determines when signals that are spatially transmitted are not separable, and if separable, the quality of each link. The quality of each link may be evaluated using, for example, Signal to Interference Noise Ratio (SINR). The resultant traditional mode datastream(s) 182 is passed through the decoder. In the decoder the conversion from symbols to associated bit sequences is implemented. As shown above in FIG. 3, the output of the decoder is passed to an associated combiner. The configuration of the configurable spatial processor under the control of control unit 746 takes place as a result of in/out of band control signals. These signals may be generated during call setup or during an actual call session by SM_MA processes/logic 104.

In FIG. 7B, the configurable nature of the spatial processor is evident by comparison to FIG. 7A. Composite signals 640-642 are presented to the first fabric switch 700. Responsive to signals from the control unit 746, the first fabric switch generates output signals for each of the composite input signals. Composite signal 640 is passed to a first pair of logic sub-modules within the first logic unit 702. Composite signal 642 is passed to a second pair of logic sub-modules within the first logic unit 702. The first pair of logic sub-modules include: multiplier 704 together with associated weight register 712, and multiplier 706 together with associated weight register 714. The second pair of logic sub-modules include: multiplier 708 together with associated weight register 716, and multiplier 710 together with associated weight register 718. Multipliers 704-706 receive as inputs the composite signal 640. Multipliers 708-710 receive as inputs the composite signal 642. The weight registers may contain weights obtained during transmission of a training sequence which allow training sequences to be separated. These are multiplied by the corresponding composite signal inputs and the four products are cross-coupled to summers 734-736 of the second logic unit 732 by the second fabric switch. The output of summers 734-736 is, respectively, the estimated substreams 454-456. In the embodiment shown, these are passed through an evaluator 740 to the decoder 388. Subsequently, the estimated substreams are combined into the original datastream 176 (not shown). The decoder 388 performs the above-mentioned function of mapping the summer output into symbols and from the symbols, into the appropriate binary sequences. In an alternate embodiment of the invention, the evaluator may be placed downstream of the decoder and perform a similar function at that location.

Exhibit 1002
Page 0401 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

The evaluator monitors the estimated substreams to determine if they are appropriately separated, and if separable, the quality of the link(s). This determination might, for example, be made during the transmission of a training sequence. When the evaluator determines it is no longer possible to spatially separate the corresponding substreams, that determination may be passed to the upstream processes/logic 104, e.g. the MSC 106 (see FIG. 1). This results in an alteration of the spatial configuration of the transmission. A change in spatial transmission may be implemented in any number of ways. These include: a change in the antenna selection and/or number at a single base, a change from traditional to spatial mode broadcasting at a single base, a change from single-base to multi-base transmission. Similarly, when the evaluator determines that the substreams are separable, it may pass on the link quality parameters to the upstream processes/logic 104, e.g. the MSC 106. This can help the BTS/MSC/CO side of the processes/logic 104_ choose the modulation rate (bits per symbol) of each substream, and carry out parsing accordingly.

FIGS. 7C-D show an embodiment of space-time processor. To the capabilities of the above-discussed spatial processor is added the ability to remove the interference in the composite signal caused by the delayed versions of the composite signal over time. To account for these perturbations, one or more delay elements may be introduced into the signal paths in the first logic unit to account for these effects. An exploded view of an embodiment of a time logic sub-module is shown in FIG. 7D. In the embodiment shown, each time sub-module is coupled to the output of a corresponding multiplier in the first logic unit. Time sub-modules 720-726 are coupled to the outputs of multipliers 704-710, respectively. Each time module may consist of a plurality of delay elements. In the exploded view, a sub-module includes delay modules 760-762; multipliers 770-772 together with associated weight registers 780-782, as well as a summer 790. The output of multiplier 704 is an input both to delay module 760 and summer 790. The output of delay module 760 is an input both to delay module 762 and to multiplier 770. The output of delay module 762 is an input to multiplier 772. The outputs of the multipliers provide additional inputs to the summer 790. The output of the summer is presented to the second fabric switch 730. Each time module may include additional multipliers with associative delay units and weight registers. As was the case in FIGS. 7A-B, the space-time processor in FIGS. 7C-D is configurable. FIG. 7C shows the processor configured for a single input

composite signal 750. FIG. 7D shows the space-time processor configured for two composite input signals 640-642.

The spatial/space-time processor of FIGS. 7A-D is configurable; e.g. capable of processing a variable number of composite signals and outputting a corresponding number of estimated subscriber substreams. In another embodiment of the invention, the spatial/space-time processor is not configurable; accepting instead a fixed number of substreams and outputting a corresponding fixed number of estimated subscriber substreams.

As will be obvious to those skilled in the art, any of a number of other processing techniques may be used to implement the current invention, including: space-time, space- frequency, space- code, etc. In turn, these may further utilize any, or a combination of techniques including, but not limited to: linear or non-linear processing, Maximum Likelihood (ML) techniques, Iterative decoding/interference canceling, Multi-user detection (MUD) techniques, etc., without departing from the scope of this invention.

FIG. 8 shows a datastream interspersed with the training sequences consistent with a non-blind embodiment of the current invention. Training sequences 800-802 and data sequences 850-852 are shown. Suitable training sequences include orthogonal Walsh codes transmitted by the spatially separate antennas. The spatial/space-time processor of the receiver attempts to generate weights which separate the known Walsh code sequences. Those weights are then used in processing the subsequent datastream(s)/substreams. In an embodiment of the invention, the training sequences are inserted into the datastream at frequency/duty cycle, which depend on the mobility of the subscriber unit. In another embodiment of the invention, the training sequences vary in duration and are constant in frequency. The training sequences may be transmitted in/out of band. As the mobility of a subscriber increases, the frequency/duty cycle of the training sequences may be increased. The mobility of the subscriber unit can, as discussed above, be detected by Doppler shift/spread detected by the mobility detector 334 (see FIG. 3) on the receive side of the base station, for example. When the subscriber unit is fixed, training may only be performed at, or before, call setup or at a relatively low frequency/duty cycle during a call/data session. In still other embodiments of the invention, no training sequences

Exhibit 1002
Page 0403 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

would be inserted into the datastream(s)/substreams, instead relying on blind training techniques discussed above.

FIGS. 9A-B to 12A-B show various access methodologies utilized to provide multiple-access spatial multiplexing in accordance with the current invention. The figures labeled with "A" show the transmit portion of each access method while the figures labeled with "B" show the receive side. FIGS. 9A-B show SM time-division multiple access (TDMA). FIGS. 10A-B show SM frequency-division multiple access (FDMA). FIGS. 11A-B show SM code-division multiple access (CDMA). FIGS. 12 A-B show SM space-division multiple access (SDMA). The modules disclosed herein on the upstream side, as well as the subscriber side, may be implemented in hardware/software. They may be implemented on a single chip, e.g. DSP or ASIC. The modules disclosed on the upstream side may be located in the BTS or further upstream, e.g. the MSC/CO. On the subscriber side the modules may be implemented in a single unit.

FIG. 9A shows a slot selector 900, a transmit processor module 314A (optional), and a final transmit stage 316A. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. The mobility detector is, in an embodiment of the invention shown in FIG. 3, part of the receive side of the BTS. It is shown in FIG. 9A for purposes of clarity, since it interacts with the training module 328 and CPU 324 to detect and generate training sequences responsive to the mobility of the subscriber unit. Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the slot selector 900. In TDMA each subscriber session is allocated a specific time segment in which to be transmitted. Time segments are assigned in round-robin fashion. In the traditional public switched telephone network (PSTN), there are twenty-four time slots (a.k.a. channels/D0). The slot selector 900, under the direct/indirect control of processes/logic 104 and implemented at, e.g. the MSC 106, assigns the related substreams 454-456 to identical channels (TDMA slots) within the separate TDMA datastream(s) 902-904, which are output by the slot selector. The traditional mode datastream 182 is assigned to a separate channel/slot within TDMA datastream 904.

Exhibit 1002
Page 0404 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Each of the TDMA datastream(s) 902-904 is, in an embodiment of the invention, provided as an input to an optional transmit processing module 314A. That module may implement any one of a number of well known prior art techniques for improving signal quality in a wireless network including: diversity, space coding, space-time coding, space-frequency coding, beam forming, interference canceling, etc.

The transmit processor 314A (optional) includes, in the embodiment shown, diversity processing, space-time coding and beam-forming. Beam-forming exploits channel knowledge to direct transmissions to the location of the corresponding subscriber. Diversity may be implemented in: frequency, time, space, polarization, space/space-time, etc. The outputs of the optional transmit processor 314A are provided as inputs to the final transmit stage 316A. That stage includes encoder modulators 924-926, operating off a common carrier 914 for processing each of the TDMA datastream(s) 902-904. These modulated datastream(s) are passed to respective RF stages 934-936 and associated antennas 134T-136T for spatially separate transmission of the individual substreams that they contain, e.g. 454-456. Additional antenna arrays 940-942, RF stages 930-932, encoder/modulator stages 920-922 are used to implement any of the optional transmit processes.

FIG. 9B shows the receive side of a subscriber unit 150 enabled for spatial multiplexing utilizing TDMA access. That unit includes: first receiver stage 382A, receive processor 384A (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, TDMA slot selector 978, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R which are coupled via, respectively, RF stages 952-950 to demodulator/sampling modules 962-960. The demodulator/sampling units operate off a common carrier 970. An additional antenna array 946, RF stage 954, demodulator/sampling module 964, and carrier generator 972 are utilized by the receive processor 384A to implement: diversity processing, space-time decoding, beam-forming, etc.

In operation, the carrier recovery module 376 synchronizes the carriers 970-972 to the carrier frequency of the incoming composite signals 990-992. The TDM slot selector 978 accepts a channel assignment from the BTS(s) and synchronizes the

Exhibit 1002
Page 0405 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

receive processes accordingly. The composite signals from each antenna are demodulated and sampled by the corresponding one of the demodulator/sampling modules 964-960. The outputs of these modules provide inputs to the receive processor 384A. The receive processor implements signal processing techniques which may complement one or more of the optional processes discussed above for the transmit side (see FIG. 9A). Each composite signal output by the receive processes/logic 384A provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived from the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams, e.g. 996-998. In configurable embodiments of the spatial/space-time processor, information received from the BTS(s) at the start of, or during, a call session configures the processor to generate a number of substreams that correspond to the actual number of substreams transmitted. Next, the estimated subscriber substreams are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as for example, an audio signal, a video signal, a data file, etc.

FIGS. 10A-B show a BTS implementing SM frequency-division multiple access (FDMA). In FDMA, each subscriber session, whether traditional or spatially processed, is provided with a single frequency slot within the total bandwidth available for transmission. The BTS includes: a frequency slot selector 1000, a transmit processor module 314B (optional), and a final transmit stage 316B. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the frequency slot selector 900. The selector 1000, under the direct or indirect control of the MSC 106, selects the appropriate frequency slot for

the datastream(s)/substreams. This is represented in FIG. 10A by a final transmit stage which includes encoder/modulator clusters (1020-1022), (1024-1026), and (1028-1030), each of which modulates about a unique center frequency as determined by respective associated carriers 1010-1014. Intermediate the frequency selector 1000 and the final transmit stage 316B, is an optional transmit processing unit 314B which may impose on the datastream(s)/substreams additional signal processing utilizing antenna arrays 1040-1042 in conjunction with antennas 134T-136T, as discussed above in connection with FIG. 9A.

Within the final transmit stage two spatially separate antennas 134T-136T are shown. These are coupled via, respectively, RF stages 1034-1036 and summers (1002-1004),(1006-1008), to separate outputs of each of three encoder/modulator clusters. Each encoder/modulator cluster operates about a distinct center frequency. Each cluster contains a number of encoder/modulator outputs at least equivalent to the number of spatially separate antennas in the final transmit stage. Since there are two antennas in the example shown, each cluster contains at least encoding/modulating capability for processing two distinct substreams and for outputting each separately onto a corresponding one of the antennas for spatially separate transmission. The traditional mode datastream 182 is assigned to the first cluster with a center frequency determined by carrier 1010. That datastream is output via summer 1006 on antenna 136T. Each of the substreams 454-456, parsed from a common datastream 176 (see FIGS. 4A-J) is passed to a single cluster for spatially separate transmission on a single center frequency corresponding, in the example shown, to the center frequency determined by carrier 1012. The modules disclosed herein may be implemented in the BTS or further upstream, e.g. the mobile switching center. They may be implemented as hardware or software. They may be implemented on a single chip, e.g. DSP or ASIC.

FIG. 10B shows a subscriber unit 150 enabled for spatial multiplexing utilizing FDMA access methodology. That unit includes: first receiver stage 382B, receive processor 384B (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, frequency selector 1078, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are coupled via RF stages 1052-1050, respectively, to demodulator/sampling modules 1062-1060. The

demodulator/sampling units operate off a common frequency synthesizer 1070. Additional antenna array 1046, RF unit 1054, demodulator/sampling unit 1064, and frequency synthesizer 1072 are shown. Optionally, these may be utilized by receive processing unit 384B to implement any of the receive processes discussed above in connection with FIG. 9B.

In operation, the carrier recovery module 376 synchronizes the carriers 1070-1072 to the carrier frequency assigned by the BTS for the subscriber session, i.e. the carrier frequency at which the composite signals 1090-1092 are transmitted. The composite signals from each antenna are demodulated and sampled by the corresponding one of the demodulator/sampling modules 1064-1060. The outputs of these modules provide inputs to the receive processor/logic 384B. The receive processor implements signal processing techniques which may complement one or more of those discussed on the transmit side (see FIG. 10A). Each composite signal output by the receive processor/logic 384B provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1096-1098. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during a call session, configures the processor to generate a number of substreams/datastream(s) which correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams in their binary equivalent 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

FIGS. 11A-B show a BTS implementing SM code-division multiple access (CDMA). In CDMA, each subscriber session, whether traditional (unparsed) or spatially processed (parsed), is provided with a distinct code sequence. The datastream/substreams are modulated (spread) onto the distinct code sequence/key code (Kn), and the spread signal is, in turn, modulated onto a common carrier. This has the effect of spreading each session across the entire transmission bandwidth. The BTS includes a key/code selector 1100, a transmit processor module 314C (optional), and a final transmit stage 316C. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Shown here for ease of explanation, the mobility detector, as discussed above, is actually implemented on the receive side of the BTS and interacts with the training module 328 to inject training sequences into the SM_CDMA transmissions.

Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the key/code selector 1100. The selector 1100, under the direct or indirect control of the MSC 106, selects the appropriate key/code sequence for the datastream(s)/substreams. This is represented in FIG. 11A by a final transmit stage which includes spreader and encoder/modulator clusters, (1110-1111,1120-1121), (1112-1113,1122-1123), and (1114-1115,1124-1125) each of which modulates over a unique key code, respectively 1116-1118, and all of which modulate on a common carrier 1126. Intermediate the code/key selector 1100 and the final transmit stage 316C is the optional transmit processing unit 314C, which may impose on the datastream(s)/substreams additional signal processing, such as that described and discussed above in connection with FIG. 9A.

Within the final transmit stage, two spatially separate antennas 134T-136T are shown, along with an optional antenna array 1140-1142 associated with transmit processing. These are coupled via, respectively, RF stages 1134-1136 and summers (1102-1104),(1106-1108) to separate outputs of each of three spreader encoder/modulator clusters. Each spreader encoder/modulator cluster operates about a distinct key code. Each cluster contains a number of encoder/modulator outputs at least equivalent to the number of spatially separate antennas in the final transmit

stage. Since there are two antennas in the example shown, each cluster contains at least encoding/modulating capability for processing two distinct substreams and for outputting each separately onto a corresponding one of the antennas for spatially separate transmission. The traditional mode datastream 182 is assigned to the second cluster with the key code 1117. That datastream is output via summer 1104 on antenna 134T. Each of the substreams 454-456, parsed from a common datastream 176 (see FIGS. 4A-J), is passed to a single cluster for spatially separate transmission with a single key code 1116.

FIG. 11B shows a subscriber unit 150 enabled for spatial multiplexing utilizing CDMA access methodology. That unit includes: first receiver stage 382C, receive processor 384C (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, key/code selector 1182, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are coupled via, respectively, RF stages 1152-1150 to demodulator/sampling modules 1168-1166. Demodulator/sampling modules 1168-1166 operate off a carrier 1172. The output of these is passed to de-spreaders 1162-1160, respectively, which operate off of key code 1176, assigned by the key/code selector 1182 on the basis of control information passed between subscriber unit and base station. Carrier recovery and synchronization may be handled by carrier recovery module 376, operating in conjunction with carrier generator 1172. Additionally, first receiver stage 382C includes optional antenna array 1146, RF stage 1154, demodulator/sampling unit 1170, carrier generator 1174, de-spreader 1164, and key/code generator 1178. These may be utilized in conjunction with the optional receive processor 384C in the manner discussed above in FIGS. 9B and 10B.

In operation, the carrier recovery module 376 synchronizes the carriers 1172-1174 to the carrier assigned by the BTS for the subscriber session, i.e. the carrier at which the composite signals 1190-1192 were transmitted. The composite signals from each antenna are then demodulated and sampled by the corresponding one of the demodulator/sampling modules 1168-1166. Respectively, the outputs of these modules provide inputs to de-spreaders 1162-1160, where they are de-spread using the key code 1176 assigned for the session. The outputs of the de-spreaders provide inputs to the optional receive processor 384C. The receive processor may implement signal processing techniques which complement one or more of those discussed on

the transmit side (see FIG. 11A). Each composite signal output by the receive processes/logic 384C provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1196-1198. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during, a call session configures the processor to generate a number of substreams/datastream(s) which correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams 454-456 in their binary equivalent to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as, for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

FIGS. 12A-B show a BTS implementing space-division multiple access (SDMA). In SDMA, each subscriber session, whether traditional (unparsed) or spatially processed (parsed), is transmitted as a shaped beam; a high gain portion of which is electronically directed using beam forming toward a known subscriber, at a known location, within a cell. This has the effect of allowing channel re-use within a single cell by beam forming each subscriber session to a separate segment of a cell.

The BTS includes a beam steering selector 1200, a transmit processor module 314D (optional), and a final transmit stage 316D. In the embodiment shown, these are a part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Subscriber datastream 182 and substreams 454-456, derived from subscriber datastream 176 (See FIGS. 4A-J), are shown as inputs to the beam steering selector 1200. The selector 1200, under the direct/indirect

Exhibit 1002
Page 0411 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

control of the MSC 106, selects the appropriate direction in which beam steering is to be carried out for each subscriber session and its associated datastream/substreams. Intermediate the beam steering selector 1200 and the final transmit stage 316D is the optional transmit processing unit 314D, which may impose on the datastream(s)/substreams additional signal processing, such as that described and discussed above in connection with FIG. 9A, with the exception of beam forming.

Within the final transmit stage, two pairs of spatially separate antennas 134TA/B-136TA/B are shown. Additionally, antenna array 1240 associated with transmit processes 314D is shown. The two pairs of antennas are coupled via, respectively, RF stages 1234,1230,1236,1232 to beam steering module 1202. The beam steering module accepts as inputs the separately encoded and modulated outputs from encoder modulators 1220-1226, each of which operated on a common carrier 1210, and each of which handles a different substream/datastream. The steering of datastream 182 to subscriber 144 (see FIG. 1B), and of substreams 454-456 to subscriber 150, is accomplished by beam steering unit 1202. That unit, operating with a known location/channel for each subscriber, steers the output beams from the antennas so that they interfere in a manner which maximizes the gain appropriately. At the location of subscriber 144, beam steering results in the composite signal corresponding to datastream 182 reaching a relative maximum, while the gain of the composite signals corresponding to the substreams 454-456 at that location is minimized. Beam steering also accomplishes the opposite effect at the location of subscriber unit 150.

FIG. 12B shows a subscriber unit 150 enabled for spatial multiplexing utilizing SDMA access methodology. That unit includes: first receiver stage 382D, receive processor 384D (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are respectively coupled via RF stages 1252-1250 to demodulator/sampling modules 1262-1260. Demodulator/sampling modules 1262-1260 operate off of a common carrier 1270. Carrier recovery and synchronization may be handled by carrier recovery module 376 operating in conjunction with carrier generator 1270. Additionally, the first receiver stage may also include: an antenna array 1246, coupled via RF stage 1254 to a demodulator/sampler 1264, and associated carrier module

Exhibit 1002
Page 0412 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

1272. These operate under the control of receive processes 384D to implement any of the receive processes discussed above in connection with FIG. 9B, 10B and 11B.

In operation, the carrier recovery module 376 synchronizes the carriers 1270-1272 to the carrier at which beam forming is conducted by the BTS(s). The composite signals from each antenna are then demodulated and sampled by the corresponding one of the demodulator/sampling modules 1268-1266. The outputs of these modules provide inputs to the receive processor 384D. Each composite signal output by the receive processes/logic 384B provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1296-1298. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during, a call session configures the processor to generate a number of substreams/datastream(s) that correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams in their binary equivalent 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as, for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

Although FIGS. 9-12 show four distinct multiple access methods, it will be obvious to those skilled in the art that each of these may be combined with one or more of the others without departing from the scope of this invention, as well as with such multiple access methods as: orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access, or any other orthogonal division multiple access/quasi-orthogonal division multiple access (ODMA) techniques.

FIGS. 13A-B show the process flow for transmit and receive processing/logic 104_ associated with an embodiment of the current invention. These processes/logic may be carried out across multiple datastreams, either in parallel, serially, or both. Processing begins at process block 1300 in which the next datastream is detected. Control then passes to decision process 1302. In decision process 1302 a determination is made as to the mode of the datastream. As discussed above, the mode determination may distinguish traditional/spatial, quality of service, bit rate, etc. as well as various combinations thereof. If a determination is made that the mode is traditional, control passes to process 1304. In process 1304 a routing determination is made for the datastream. The routing decision may involve the MSC directing the datastream to an appropriate one of the base stations for transmission. Control then passes to process 1306. In process 1306, the datastream is placed on the appropriate channel within the access protocol implemented on the wireless network. Channel assignment may also be made by the MSC. Control then passes to process 1308 in which the subscriber datastream is transmitted. Next, in decision process 1310, a determination is made as to whether any handoff from one BTS to another is appropriate. If this determination is in the affirmative, control returns to process 1304 for re-routing of the datastream. Alternately, if a negative determination is made in process 1310 that the subscriber is fixed, or still within the cell associated with the transmitting BTS, then control returns to process 1300 for the processing of the next datastream.

If, alternately, in decision process 1302 the mode of the next datastream is determined to be spatial, control passes to process 1320. In process 1320 the datastream is split into a configurable number of substreams. Control is then passed to process 1322. In process 1322 the individual substreams are routed and to one or more base stations for transmission to the subscriber. Control then passes to process 1324. In process 1324, under the direct or indirect control the MSC (see FIG. 1A), the access channel on which to transmit the substreams is selected. That information is communicated to the BTS(s) which are involved in the transmission of the substreams. Control then passes to decision process 1326. In decision process 1326 a determination is made as to whether the intended subscriber is mobile or fixed. If a negative determination is reached, i.e. that the subscriber is fixed, control passes to process 1328. In process 1328, a training sequence either at set-up or during a call

session is generated provided non-blind training protocols are being utilized. The receipt of these training sequences by the subscriber unit allows that unit to derive appropriate weight parameters in the first logic unit of the spatial/space-time processor for separating the composite signals into individual estimated substreams (see FIGS. 7A-D). Alternately, if in decision process 1326 an affirmative determination is reached, i.e. that the subscriber is mobile, then control is passed to process 1330. In process 1330, the frequency or duration of the training sequences inserted into the datastream is increased appropriately. This allows the subscriber unit to continually re-train its spatial/space-time parameters to account for possible changes in the spatial environment brought about by its motion. Control is then passed to process 1332. In process 1332 a determination is made as to the number of substreams that are to be transmitted. The subscriber unit is then signaled as to the number of substreams for which it should configure its spatial/space-time processor and other modules. Control is then passed to process 1334. In process 1334 the selected BTS(s) transmit the selected substreams to the corresponding subscriber unit. Control is then passed to decision process 1336.

In decision process 1336, a decision is made as to whether signal separation at the subscriber unit is adequate. As discussed above, this determination may, for example, be based on feedback from the subscriber unit by monitoring the received signal stream from the subscriber unit, or by monitoring bit error rate (BER) at the transmitting BTS(s). Numerous other methods will be evident to those skilled in the art for making this determination. If this decision is in the negative, i.e. that the subscriber unit is unable to separate the substreams, control returns to process 1320. The process 1320 may now parse the data stream into lesser number of substreams than before, or may do parsing as before, then pass the control to process 1322 for re-routing of the datastream's substreams. Re-routing might, for example, include a change of spatial configuration on a single BTS, or a changeover from single-base to multi-base transmission, as discussed above in connection with FIGS. 4A-J. Alternately, if in decision process 1336 an affirmative determination is reached that the subscriber unit is able to separate the substreams, control passes to decision process 1338. In decision process 1338 a determination is made as to whether a handoff is required. This may result in a partial or full handoff. If that determination is in the negative, e.g. the subscriber unit is fixed, or still within the cell and is capable

Exhibit 1002
Page 0415 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

of separating the substreams, then control returns to process 1300 for the interception of the next datastream. Alternately, if that decision is in the affirmative, control returns to process 1320. The process 1320 parses the datastreams as before, and passes the control to process 1322 for re-routing of the substreams to one or more base stations.

FIG. 13B shows the receive processes/logic of a subscriber unit associated with an embodiment of the invention. Processing begins at process 1350, in which the next datastream in his detected. Control is then passed to decision process 1352. In decision process 1352, a control signal from the BTS is received indicating the mode of the transmitted signal, e.g. traditional/spatial, and in the latter case, the number of substreams to be generated from the composite signals received. If the composite signals are to be treated as carrying a traditional datastream, control is passed to process 1354. In process 1354 the appropriate channel on which to receive the composite signal is assigned. Channel assignment may occur: during call setup, during a change in spatial configuration, or during a change from single-base to multi-base transmission, for example. Control is then passed to process 1356. In process 1356 the composite signals are received and appropriately processed by the associated modules of the subscriber unit (see FIG. 3). Control is then passed to decision process 1358. In decision process 1358, any training sequences and update of signal processing parameters that may be required are performed. Control is then passed to decision process 1360 for a determination as to whether signal quality and/or strength is adequate. If an affirmative determination is reached, e.g. that quality and/or strength is adequate, then control returns to process 1350 for the processing of the next datastream. Alternately, if a negative determination is reached, then control is passed to process 1362. In process 1362 signaling of the BTS(s) that signal strength or quality is not acceptable is accomplished. In an embodiment of the invention, the subscriber unit signals the BTS that signal strength is no longer suitable for reception, or that signal separation, in the case of spatial transmissions, is no longer adequate. Control then returns to process 1350 for the processing of the next datastream.

If, alternately, in decision process 1352 the control signal from the BTS indicates that the mode of the incoming composite signals is spatial, control is passed to process 1370. In process 1370, control information received by the subscriber unit indicates the number of substreams for which the spatial processor, and other modules

Exhibit 1002
Page 0416 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

of the receive portion of the subscriber unit, are to be configured. Control is then passed to process 1372. In process 1372 access parameters, e.g. channel, for the transmission from the BTS(s) to the subscriber unit are passed to the subscriber unit. Control then passes to process 1374. In process 1374 the composite signals are received and processed into corresponding estimated subscriber substreams. Control then passes to decision process 1376. In decision process 1376 a determination is made as to whether any training sequence is present in the datastream. This embodiment of the invention therefore implements non-blind training. Other embodiments of the invention implementing blind training methods need not implement this particular act. If, in decision process 1376 a negative determination is reached, i.e. that no training sequences are present, control returns to process 1350. Alternately, if in decision process 1376 an affirmative determination is reached, i.e. that a training sequence is present, then control is passed to process 1378. In process 1378, evaluation of the training sequence is performed and new weights registered within the spatial/space-time processor for separating the training sequences. Control is then passed to decision process 1380 for evaluation of the training sequences, then passed to decision process 1382 for a determination of whether the training sequences can be separated adequately. If an affirmative decision is reached, then control returns to decision process 1350. Alternately, if the separation is not adequate, then control passes to process 1384. In process 1384, a control signal is sent to the BTS indicating that a change in spatial configuration is required. The BTS(s) might respond by changing spatial configuration from single to multi-base, by changing the number or spatial configuration of the antennas utilized at a single base, by changing a channel, etc. Control then returns to process 1350 for processing of the next datastream.

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

It should also be apparent that the described subscriber units may be used in a wide variety of other applications without departing from the scope of the present

Exhibit 1002
Page 0417 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

invention. One such application contemplates the use of the described subscriber units in network access units that are used provision extend or otherwise supplement the range of existing high speed telephone or cable networks. By way of example, a hybrid DSL/wireless link is diagrammatically illustrated in Fig. 14. As is well known in the telecommunications art, in conventional high speed xDSL networks, high speed communications are made between a head end DSL modem (typically located at a central office (CO) or optical network unit (ONU)) and a remote DSL modem located on a customer's premises. The link between the central and remote modems is made on ordinary twisted pair wires. Thus xDSL system have the strong advantage of allowing high speed communications using existing wiring infrastructure. However, twisted pair wiring has significant signal attenuation and therefore, it is typically difficult or impossible to provide DSL service to customers who are located too far (e.g. more than 2 or 3 miles) from the central office/ONU. Further, even among customers within the coverage area, the loading coils and the bridge taps which are used around the binders of twisted pair wires that connect the modems, as well as other potential obstacles may make DSL technology difficult to implement in many circumstances.

In the embodiment illustrated in Figure 14, the range and/or accessibility of the DSL network is extended by placing a head end DSL modem 1430 in proximity to the remote DSL modem 1425. A suitable xDSL protocol (such as ADSL, VDSL, etc.) and modulation technique (such as DMT, DWMT, CAPs, etc.) is used to communicate between the remote DSL modem 1425 located at the customer premises and the head end DSL modem 1430 located at an appropriate location that is within range of the customer premises. By way of example, the head end DSL modem 1430 may be located at the terminal server 1410 on a nearby telephone pole 1432 from which the twisted pair drop 1435 originates that serves the customer premises. The head end DSL modem 1430 then provides the raw input data stream to the network access unit (subscriber unit) 1440 that communicates with appropriate BTSs 1445 as described above. Of course, in embodiments where a plurality of different remote DSL modems within the same neighborhood are being serviced, the head end DSL modem may multiplex the data streams from the various xDSL connections.

It is noted that the location of the described network access units may be widely varied based on the needs of a particular system. One advantage to placing the

Exhibit 1002
Page 0418 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

network access units at the terminal servers is that it provides a readily accessible location where installation is relatively easy. Also, terminal servers are often located on a telephone pole as illustrated in Figure 14. This may be advantageous in that top telephone poles are relatively higher as compared to many other potential deployment locations, which may provide a clearer path between the network access unit 1440 and the BTS transceiver. This, of course may result in increased data speeds. It should be appreciated that the described arrangements can bring DSL service to a wide variety of locations using the POTS (plain old telephone service) infrastructure.

Referring next to Fig. 15 another embodiment of the present invention is illustrated. In this embodiment, the network access unit 1440 is connected to a plurality of cable modems 1460 via an appropriate cable 1470. Any suitable cable including hybrid fiber co-axial (HFC) cables, co-axial cables or fiber cables may be used as cable 1470. Like the previously described hybrid DSL link, the illustrated hybrid cable link provides the possibility of expanding the range of high speed data communications using existing infrastructure.

As suggested above, the described subscriber unit can be used as a node in virtually any network to facilitate communications between that network and other devices and/or networks. For example, with the growing popularity of home networks, a subscriber unit can be used as a node in a home network. Alternatively, a subscriber can be used in office networks and/or any other type of local area, wide area, or other networks.

Another networking concept that has attracted some attention lately is vehicle based networking. For example, people have contemplated wiring carriers such as buses, airplanes, ships and other vehicles with networks that provide multiple nodes within the vehicle for use by passengers. The described spatial multiplexing based subscriber units which take advantage of a wireless link are particularly well adapted to providing high speed access for any vehicle based network.

Referring next to Fig. 16, yet another deployment possibility for the subscriber units will be described. In the embodiment illustrated in Fig. 16, the subscriber unit 1601 is utilized as a wireless interface for a repeater BTS 1610 in a cellular network. Various parties have proposed and implemented the concept of using repeater BTSs in cellular networks. Generally, a repeater BTS 1610 is designed to extend the coverage

Exhibit 1002
Page 0419 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

area of a master BTS 1620 and/or cover dead spots in the master BTS's coverage area. The repeater BTS simply repeats the signals being transmitted by the master BTS. The link between the master BTS and the repeater link can be either a wireless link or a wired link. Given the high data rates that are possible using the spatial multiplexing based subscriber units, it should be apparent that the described subscriber units are particularly well suited for use in repeater BTSs.

Although a few specific deployments have been described, it should be appreciated that the described spatial multiplexing based subscriber units may be deployed in a wide variety of other situations as well.

Exhibit 1002
Page 0420 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

CLAIMS

1. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

base stations each including spatially separate transmitters for transmitting in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for assigning an available channel on which to transmit each subscriber datastream, for routing at least a substream of each datastream to at least a selected one of the base stations and for generating control signals to configure the at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel.

2. The wireless cellular network of Claim 1 wherein the logic is arranged for changing a spatial transmission configuration from a first transmitting base station to at least the first base station together with a second transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

3. The wireless cellular network of either of claims 1 and 2 wherein the logic is arranged for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

4. The wireless cellular network of any of the preceding claims wherein the logic further comprises a parser for parsing each datastream into substreams.

Exhibit 1002
Page 0421 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

5. The wireless cellular network of Claim 4, wherein:

the parser includes responsiveness to a mode signal to parse each datastream into a variable number of substreams and to avoid parsing of each datastream; and

the parser is responsive to a modulation rate of each substream.

6. The wireless cellular network of Claim 4, wherein the logic further comprises a router for routing the substreams to at least a selected one of the base stations and each of the base stations further comprises a selector responsive to the control signals generated by the logic to inject a routed one of the substreams onto the channel assigned by the logic.

7. The wireless cellular network of Claim 6, wherein each of the base stations further comprises a selector responsive to the control signals generated by the logic to inject routed ones of the substreams onto both the channel assigned by the logic as well as onto selected ones of the spatially separate transmitters.

8. The wireless cellular network of any of the preceding claims wherein the logic further comprises:

a detector to detect modes of the subscriber datastreams from the first network and to generate a mode signal corresponding to the mode of each of the subscriber datastreams;

a parser responsive to the mode signal to parse the datastream into a variable number of substreams and to avoid parsing of the datastream; and

a router for routing both an unparsed datastream as well as a variable number of substreams to at least a selected one of the base stations.

9. The wireless cellular network of Claim 8, wherein the modes of the datastreams include voice mode and data mode and wherein further the parser is

Exhibit 1002
Page 0422 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

responsive to a voice mode signal avoids parsing of the datastream, and responsive to a data mode signal parses the datastream into a variable number of substreams.

10. The wireless cellular network of Claim 8, wherein the modes of the datastreams include high bit rate and low bit rate and wherein further the parser avoids parsing of a low bit rate datastream, and parses a high bit rate datastream into a variable number of substreams.

11. The wireless cellular network of Claim 8, wherein the modes of the datastreams include low QoS requirement and high QoS requirement and wherein further the parser avoids parsing a datastream with a low QoS requirement, and parses a datastream with a high QoS requirement into a variable number of substreams.

12. The wireless cellular network of any of Claims 8-11, wherein each of the base stations further comprises:

a selector responsive to the control signals generated by the logic to inject routed ones of the substreams as well as the unparsed datastream onto both the channel assigned by the logic as well as a selected one of the spatially separate transmitters.

13. The wireless cellular network of any of the preceding claims wherein each of the base stations further comprises a training module for injecting a training sequence into the transmissions of the spatially separable transmitters.

14. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprises:

spatially separate receivers for receiving composite signals resulting from the spatially separate transmission of spatially separate source signals corresponding to

Exhibit 1002
Page 0423 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

selected substreams of an uplink subscriber datastream from selected ones of the subscriber units, on an assigned channel of the multiple access protocol;

a spatial processor configurable in response to the control signal to separate the composite signals into estimated source signals based on information obtained during the transmission of known data patterns from the selected ones of the subscriber units; and

a combiner for combining the estimated source signals into a corresponding uplink subscriber datastream.

15. The wireless cellular network of Claim 14, wherein the spatial processor further comprises:

a configurable logic responsive to the control signal to vary both a number of the composite signals separated as well as the number of the estimated source signals.

16. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprise:

mobility detectors for determining a mobility of each of the subscriber units and generating a mobility signal; and

a training module responsive to the mobility signal for varying at least one of: an injection interval and duration of a training sequence into the transmissions of the spatially separable transmitters.

17. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprises transmit processes selected from at least one of a group of transmit processes consisting of: diversity, space coding, space time coding and beam forming.

18. A subscriber unit for use in a cellular system with base stations each including spatially separate transmitters for transmitting selected substreams of at least one of a

Exhibit 1002
Page 0424 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

plurality of subscriber downlink datastreams on an assigned channel of a multiple access protocol, and the subscriber unit comprising:

spatially separate receivers for receiving on the assigned channel of the multiple access protocol composite signals resulting from the spatially separate transmission the selected substreams;

a spatial processor to separate the composite signals into estimated subscriber substreams, and to signal the base stations when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams; and

a combiner for combining the estimated substreams into a corresponding subscriber datastream.

19. The arrangement of Claim 18, wherein the spatial processor further comprises responsiveness to a control signal from the base station to vary a number of estimated subscriber substreams.

20. The arrangement of Claim 18 or 19, wherein the spatially separate receivers further comprise:

a first selector responsive to the control signal to assign a channel on which to operate said spatially separate receivers; and

a second selector responsive to the control signal to enable selected ones of the spatially separate receivers on the assigned channel to receive the composite signals.

21. The arrangement of any of Claims 18-20, wherein the spatial processor further comprises a configurable logic responsive to the control signal to vary both a number of the composite signals separated as well as the number of the estimated source signals and to evaluate the composite signals over time.

Exhibit 1002
Page 0425 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

22. The arrangement of any of Claims 18-21, wherein the spatial processor further comprises an evaluator to evaluate the estimated source signals during a transmission interval in which at least one of the base stations transmits the known data patterns and to initiate the signal to the at least one of the base stations when a change of the spatial transmission configuration is required.

23. The arrangement of any of Claims 18-22, wherein the combiner includes responsiveness to the control signal to vary a number of estimated source signals combined into a corresponding subscriber datastream.

24. The arrangement of any of Claims 18-23, further comprising:

a parser for parsing an uplink subscriber datastream into substreams; and

spatially separate transmitters for transmitting the substreams of the uplink subscriber datastream on an assigned channel of a multiple access protocol.

25. The arrangement of any of Claims 18-24, wherein the subscriber unit further comprises receive processors from at least one of a group of receive processes consisting of diversity, space decoding, space-time decoding, beam forming and interference canceling.

26. A wireless cellular network for transmitting subscriber downlink datastreams from a first network to subscribers located within the wireless cellular network, and said wireless cellular network comprising:

base stations each configured for spatially separate transmission of selected substreams of each subscriber downlink datastream on an assigned channel of a multiple access protocol;

subscriber units each configured for spatially separate reception on the assigned channel of the selected substreams and for combining the substreams into the corresponding subscriber datastream; and

Exhibit 1002
Page 0426 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a logic communicating with each of the base stations and to the first network and the logic configured to route at least a substream of each subscriber downlink datastream to at least a selected one of the base stations and further configured to vary the routing between a single base station and multiple base stations to vary a spatial transmission configuration of the selected substreams.

27. A wireless cellular network for receiving subscriber datastreams at corresponding ones among a plurality of base stations located within the cellular network, and said wireless cellular network comprising:

a plurality of subscriber units each including spatially separate transmitters for transmitting, in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for generating control signals to configure selected ones of the base stations to receive composite signals resulting from the spatially separate transmission of the selected substreams from a corresponding one among the plurality of subscriber units on the assigned channel, for converting the composite signals into estimate substreams and for combining the estimated substreams of each subscriber datastream into each subscriber datastream.

28. The logic of Claim 27, further for changing the spatial reception configuration from a first receiving base station to at least the first base station together with a second base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the composite signals into estimated substreams.

28. The logic of Claim 27 or 28 , further for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the composite signals into estimated substreams.

Exhibit 1002
Page 0427 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

29. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

base stations each including at least one transmitter for transmitting, in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for assigning an available channel on which to transmit each subscriber datastream, for routing at least a substream of each datastream to at least a selected one of the base stations and for generating control signals to configure the at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel.

30. The arrangement of Claim 29, wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station to at least the first base station together with a second transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

31. The arrangement of Claim 29 or 30, wherein the logic is further arranged for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

32. The arrangement of any one of Claims 29-31 wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station together with a second transmitting base station to at least the first

Exhibit 1002
Page 0428 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

transmitting base station together with a third transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

33. The arrangement of any one of Claims 29-32, wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station together with a second transmitting base station to at least the third transmitting base station together with a fourth transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

34. A method for transmitting subscriber downlink datastreams from base stations to corresponding ones among a plurality of subscriber units, and said method for transmitting comprising the acts of:

routing at least a substream of each subscriber downlink datastream to selected ones of the base stations;

transmitting the at least a substream of each subscriber downlink datastream from the selected ones of the base stations on an assigned channel of a multiple access protocol; and

re-routing at least a substream of each subscriber downlink datastream between a single base station and multiple base stations responsive to a determination that a change of a spatial transmission configuration of the at least a substream of each subscriber downlink datastream signal is required.

35. The method of Claim 34, wherein the at least a substream comprises at least one of: a whole subscriber downlink datastream and substreams of the subscriber downlink datastream.

Exhibit 1002
Page 0429 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

36. The method of Claim 34 or 35, wherein the routing act and re-routing acts further comprise the acts of:

parsing each of the subscriber downlink datastreams into a configurable number of substreams; and

configuring the at least a selected one of the base stations to transmit selected substreams of each subscriber downlink datastream to a corresponding one among the plurality of subscriber units on the assigned channel.

37. The method of Claim 36, wherein the parsing act further comprises the acts of:

determining a mode for each of the subscriber downlink datastreams;

parsing the subscriber downlink datastream into a plurality of substreams responsive to a first mode determination in said act of determining; and

avoiding the parsing of the subscriber downlink datastream responsive to a second mode determination in said act of determining.

38. The method of Claim 37, wherein the first mode and the second mode correspond to at least one of: a transmission rate of each of the subscriber downlink datastreams, and a data type of each of the subscriber downlink datastreams.

39. The method as recited in any of Claims 34-38, wherein the determination that a change of a spatial transmission configuration is required corresponds to a signal generated by a corresponding one of the subscriber units.

40. The method as recited in any of Claims 34-39, further comprising the acts of:

receiving at a corresponding one among the plurality of subscriber units signals generated in said transmitting act;

determining a number of substreams to be derived from the signals;

separating the signals into the number of substreams determined in said act of determining; and

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

combining the substreams into a corresponding subscriber downlink datastream.

41. A method of receiving subscriber downlink datastreams transmitted from a plurality of spatially separate transmitters, comprising the acts of:

receiving signals generated from at least one of the plurality of spatially separate transmitters;

determining a number of substreams to be derived from the signals;

separating the signals into the number of substreams determined in said act of determining; and

combining the substreams into a corresponding subscriber downlink datastream.

42. The method Claim 41, wherein said separating act further comprises the acts of:

determining that a change of a spatial transmission configuration is required in order to separate the number of substreams; and

changing the spatial transmission configuration responsive to said act of determining.

43. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

means for routing at least a substream of each subscriber downlink datastream to selected ones of the base stations;

means for transmitting the at least a substream of each subscriber downlink datastream from the selected ones of the base stations on an assigned channel of a multiple access protocol; and

Exhibit 1002
Page 0431 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

means for re-routing the at least a substream of each subscriber downlink datastream between a single base station and multiple base stations responsive to a signal from a corresponding one of the subscriber units requesting a change of spatial transmission configuration.

44. A subscriber unit for use in a cellular system with base stations each including spatially separate transmitters for transmitting selected substreams of at least one of a plurality of subscriber downlink datastreams on an assigned channel of a multiple access protocol, and the subscriber unit comprising:

means for receiving signals generated from at least one of the plurality of spatially separate transmitters;

means for determining a number of substreams to be derived from the signals;

means for separating the signals into the number of substreams determined in said act of determining;

means for combining the substreams into a corresponding subscriber downlink datastream; and

means for signaling the base when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams.

45. A wireless cellular remote unit for transmitting a datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas, the transmitter further being responsive to a control signal from the base station to vary the number of applied substreams.

Exhibit 1002
Page 0432 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

46. The unit of Claim 45, wherein the remote unit communicates with a first network to provide the first network with access to the cellular network.

47. The unit of Claim 46 wherein the first network is one selected from the group consisting of a home network, a vehicle based network and a local area network.

48. A unit as recited in any one of claims 45-47 wherein the subscriber unit is incorporated into a bridge or router to provide a wireless bridge or router.

49. The unit of any one of claims 45-48, wherein the remote unit is one of a fixed unit and a mobile unit.

50. The unit of any one of claims 45-49, wherein the remote unit further comprises transmit processes from at least one of a group of transmit processes consisting of diversity, space coding, space-time coding, space frequency coding, beam forming and interference canceling.

51. The unit of any one of claims 45-50, wherein the transmitter includes a parser for parsing the datastream into the substreams.

52. The wireless cellular remote unit of Claim 51, wherein the parser is responsive to at least one of:

a mode signal to parse the datastream into a variable number of substreams and to avoid parsing of each datastream; and

a modulation rate of each substream.

53. The unit of any one of claims 45-52 further comprising a selector arranged to inject a routed one of the substreams onto the assigned channel.

Exhibit 1002
Page 0433 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

54. A wireless cellular remote unit for transmitting a datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas;

a detector to detect a mode of the datastream and to generate a corresponding mode signal; and

a parser responsive to the mode signal to parse the datastream into a variable number of substreams and to avoid parsing of the datastream.

55. The wireless cellular remote unit of Claim 54, wherein the modes of the datastream includes at least one of:

voice mode and data mode and wherein further the parser responsive to a voice mode signal avoids parsing of the datastream, and responsive to a data mode signal parses the datastream into a variable number of substreams;

high bit rate and low bit rate and wherein further the parser avoids parsing of a low bit rate datastream, and parses a high bit rate datastream into a variable number of substreams; and

low QoS requirement and high QoS requirement and wherein further the parser avoids parsing a datastream with a low QoS requirement, and parses a datastream with a high QoS requirement into a variable number of substreams.

56. A wireless cellular remote unit for receiving a downlink datastream from and transmitting an uplink datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

Exhibit 1002
Page 0434 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a transmitter for transmitting a plurality of uplink substreams of the uplink datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each uplink substream to an associated one of the spatially separate antennas;

a receiver including a spatial processor arranged to separate a composite downlink signal received by the spatially separate antennas into estimated substreams, and a combiner for combining the estimated substreams into a corresponding subscriber datastream, the receiver being arranged to signal the base stations when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams.

57. A wireless cellular remote unit as recited in claim 56 wherein the remote unit takes the form of a network access unit that is a node in a network that facilitates communication outside of the network.

58. A method of transmitting a datastream from a remote unit to at least one cellular base station in a cellular network, the method comprising:

forming a plurality of substreams from the datastream, wherein the number of substreams formed is determined in response to a control signal received from one of the base stations; and

transmitting the substreams in parallel from spatially separate antennas on an assigned channel or slot using a multiple access protocol.

59. A method of communicating between a remote location and one or more base stations in a cellular network, the method comprising:

transmitting a datastream from the remote location to a wireless access unit over a wired connection using a communications protocol selected from the group consisting of an xDSL protocol, a cable modem protocol and a networking protocol;

forming a plurality of substreams from the datastream; and

Exhibit 1002
Page 0435 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

transmitting the substreams to the one or more base stations in parallel from spatially separate antennas on an assigned channel or slot using a multiple access protocol.

60. A wireless cellular remote unit for receiving a downlink datastream from and transmitting an uplink datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

transmission means for transmitting a plurality of uplink substreams of the uplink datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each uplink substream to an associated one of the spatially separate antennas; and

receiver means arranged to separate a composite downlink signal received by the spatially separate antennas into estimated substreams, and combine the estimated substreams into a corresponding subscriber datastream.

61. A wireless cellular remote unit as recited in claim 60 wherein:

the remote unit is arranged to signal the base stations when a change of a spatial transmission configuration is required by the receiver in order to resolve the composite signals into estimated substreams; and

the transmitter is responsive to a control signal from the base station to vary the number of applied substreams.

62. A repeater base station suitable for use in conjunction with a master base station that is part of a cellular network, the repeater base station including:

a slave base station; and

a wireless interface unit comprising,

a plurality of spatially separate antennas; and

Exhibit 1002
Page 0436 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a transmitter for transmitting a plurality of substreams of a datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas, the transmitter further being responsive to a control signal from the master base station to vary the number of applied substreams.

63. A communications network comprising:

a master station controller;

at least one base station controller that communicates with the master station controller;

a plurality of base station, each base station being arranged to communicate with an associated one of the base station controllers, wherein at least one of the base stations is designated as a master base station; and

a repeater base station as recited in claim 62.

64. A unit for use in a communications network that delivers DSL service to customers, the unit comprising:

a head end DSL modem arranged to communicate with a remotely located DSL modem using a DSL protocol; and

a wireless access unit comprising arranged to receive a datastream from the head end DSL modem, the wireless access unit including, a plurality of spatially separate antennas and a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas.

65. A unit for use in a communications network that delivers DSL service to customers, the unit comprising:

Exhibit 1002
Page 0437 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a head end DSL modem arranged to communicate with a remotely located DSL modem using a DSL protocol; and

a wireless access unit comprising,

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a base station in the communications network;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the head end DSL modem for transmission to a remotely located DSL modem using a DSL protocol.

66. A unit for use in a communications network that delivers high speed data delivery service to customers, the unit comprising:

a head end cable modem unit arranged to communicate with a remotely located cable modem over a cable;

a wireless access unit comprising arranged to receive a datastream from the head end cable modem, the wireless access unit including, a plurality of spatially separate antennas and a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas.

67. A unit for use in a communications network that delivers high speed data delivery service to customers, the unit comprising:

a head end cable modem unit arranged to communicate with a remotely located cable modem over a cable;

a wireless access unit comprising,

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a base station in the communications network;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the head end cable modem for transmission to a remotely located cable modem.

68. A unit as recited in claim 66 or 67 wherein the cable is one selected from the group consisting of a hybrid fiber co-axial cable, a co-axial cable and a fiber cable.

69. A repeater base station suitable for use in conjuction with a master base station that is part of a cellular network, the repeater base station including:

a slave base station; and

a wireless interface unit comprising,

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a master base station;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the slave base station for transmission by the slave base station.

70. A communications network comprising:

a master station controller;

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

at least one base station controller that communicates with the master station controller;

a plurality of base station, each base station being arranged to communicate with an associated one of the base station controllers, wherein at least one of the base stations is designated as a master base station; and

a repeater base station as recited in claim 69.

71. A unit as recited in claim 64 or 65 wherein the unit is coupled to a terminal server in a POTS communications network such that a first link between the remotely located DSL modem and the head end DSL modem takes the form of twisted pair wiring and a second link between the wireless access unit and a base station takes the form of a wireless link.

72. An arrangement as recited in any of the preceding claims, wherein the multiple access protocol is selected from at least one of a group of multiple access protocols consisting of: code-division multiple access, frequency-division multiple access, time-division multiple access, space-division multiple access, orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access, orthogonal division multiple access (ODMA) and quasi-orthogonal division multiple access (ODMA) techniques.

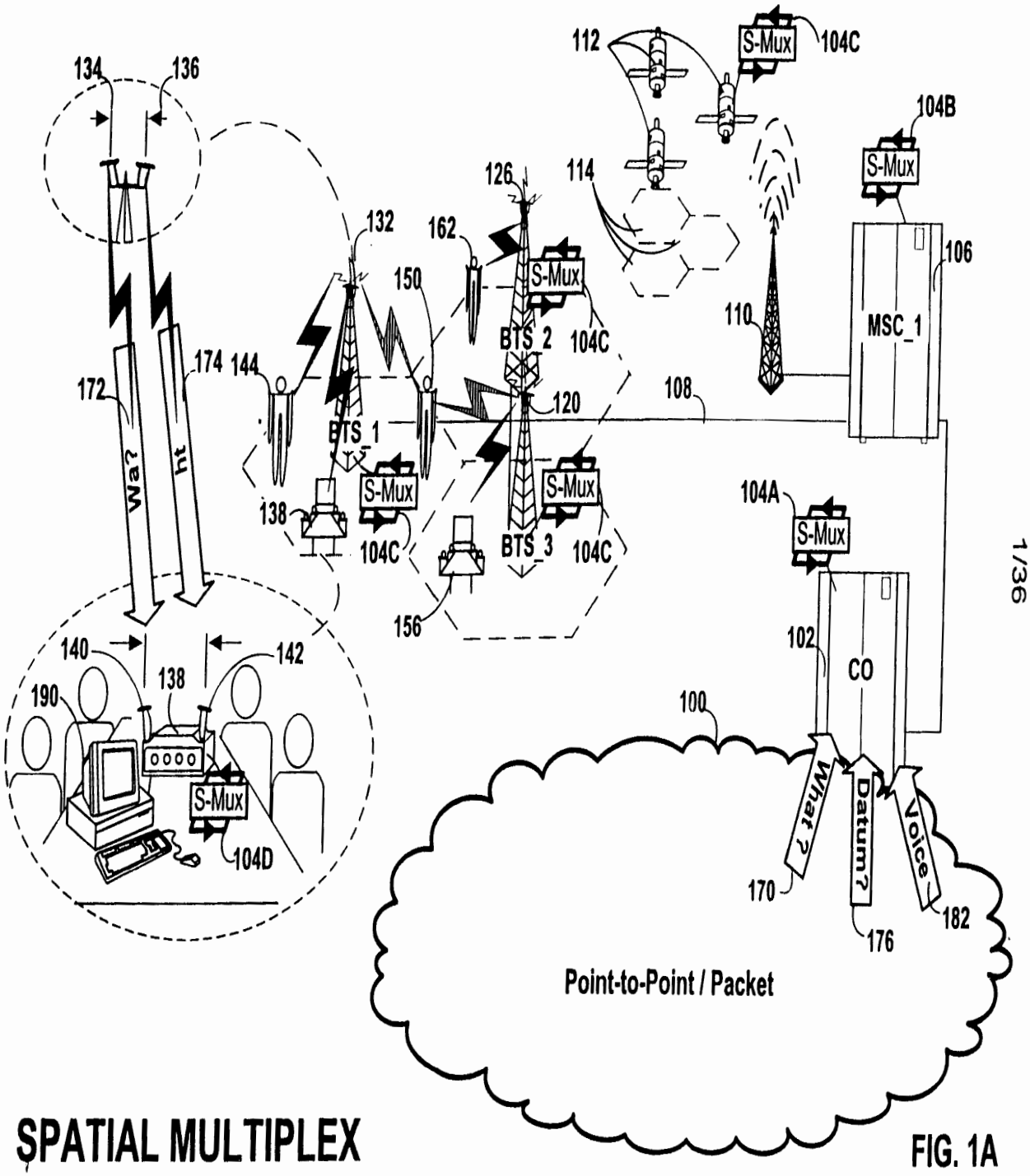
73. An arrangement as recited in any of the preceding claims, wherein the assigned channel comprises, within a transmission bandwidth, at least one of: a frequency-division, a time-division, a spatial-division, a code-division, orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access or any other orthogonal division multiple access (ODMA)/quasi-orthogonal division multiple access techniques.

74. The arrangement of any of the preceding claims wherein the base stations receive the plurality of subscriber downlink datastreams from at least one of a group of networks consisting of: a public switched telephone network, a local area network, a wide area network, a satellite network, an adhoc network, a virtual private network, an intranet and an internet.

75. The arrangement of any of the preceding claims, wherein the base stations include satellites.

76. An arrangement as recited in any of the preceding claims wherein the subscriber unit is incorporated into a bridge or router to provide a wireless bridge or router.

Exhibit 1002
Page 0441 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148



SPATIAL MULTIPLEX

FIG. 1A

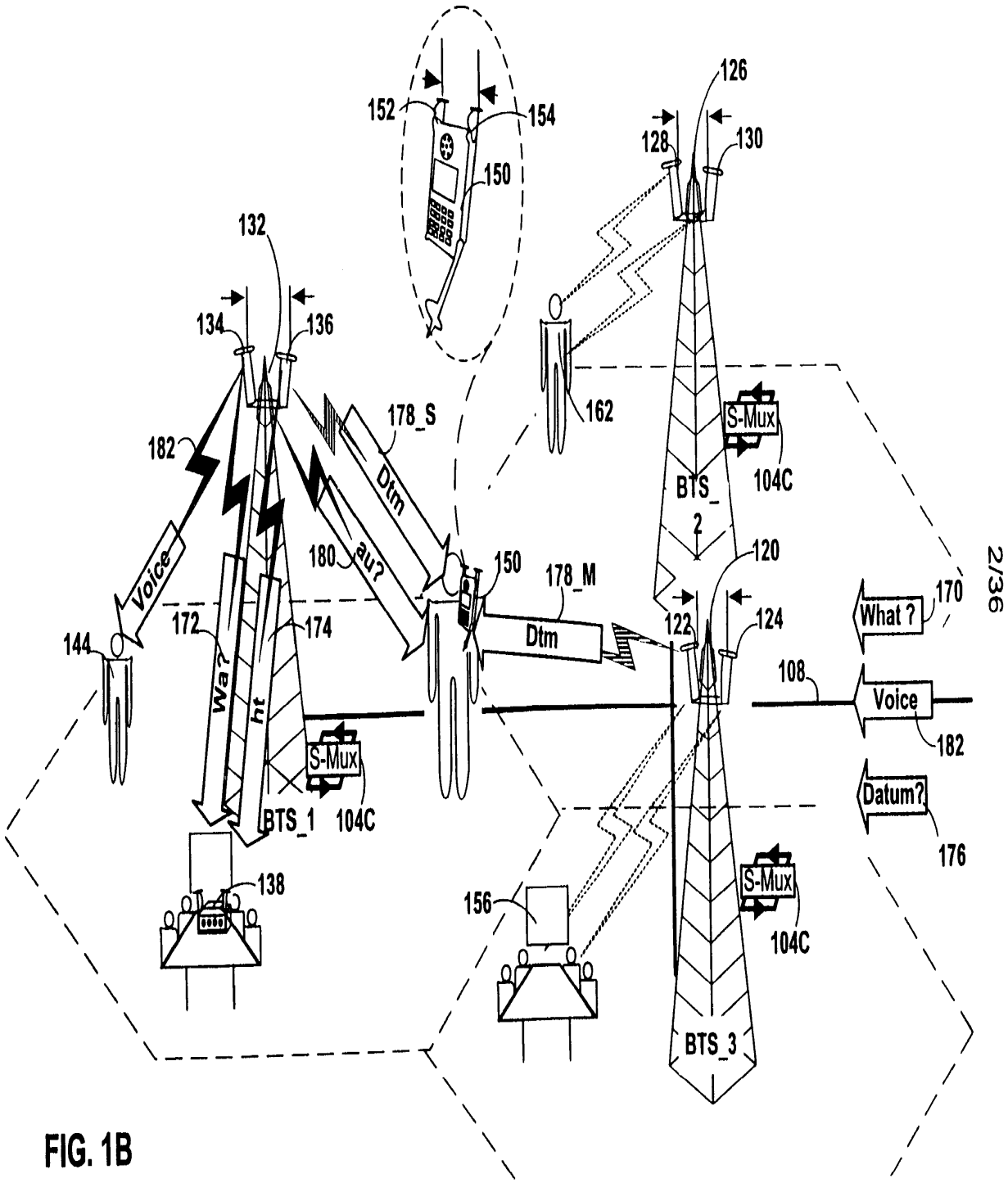

152
154
150
126
128
130
132
134
136
162
178_S
182
Dtm
S-Mux
104C
BTS_
2
180
au?
150
178_M
120
Voice
172
174
122
124
What ?
170
144
Wa?
ht
Dtm
108
Voice
182
S-Mux
BTS_1
104C
Datum?
176
138
156
S-Mux
104C
BTS_3

FIG. 1B

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FIG.1C

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FIG. 2D

FIG. 2E

FIG. 2F

FIG. 2A

FIG. 2B

FIG. 2C

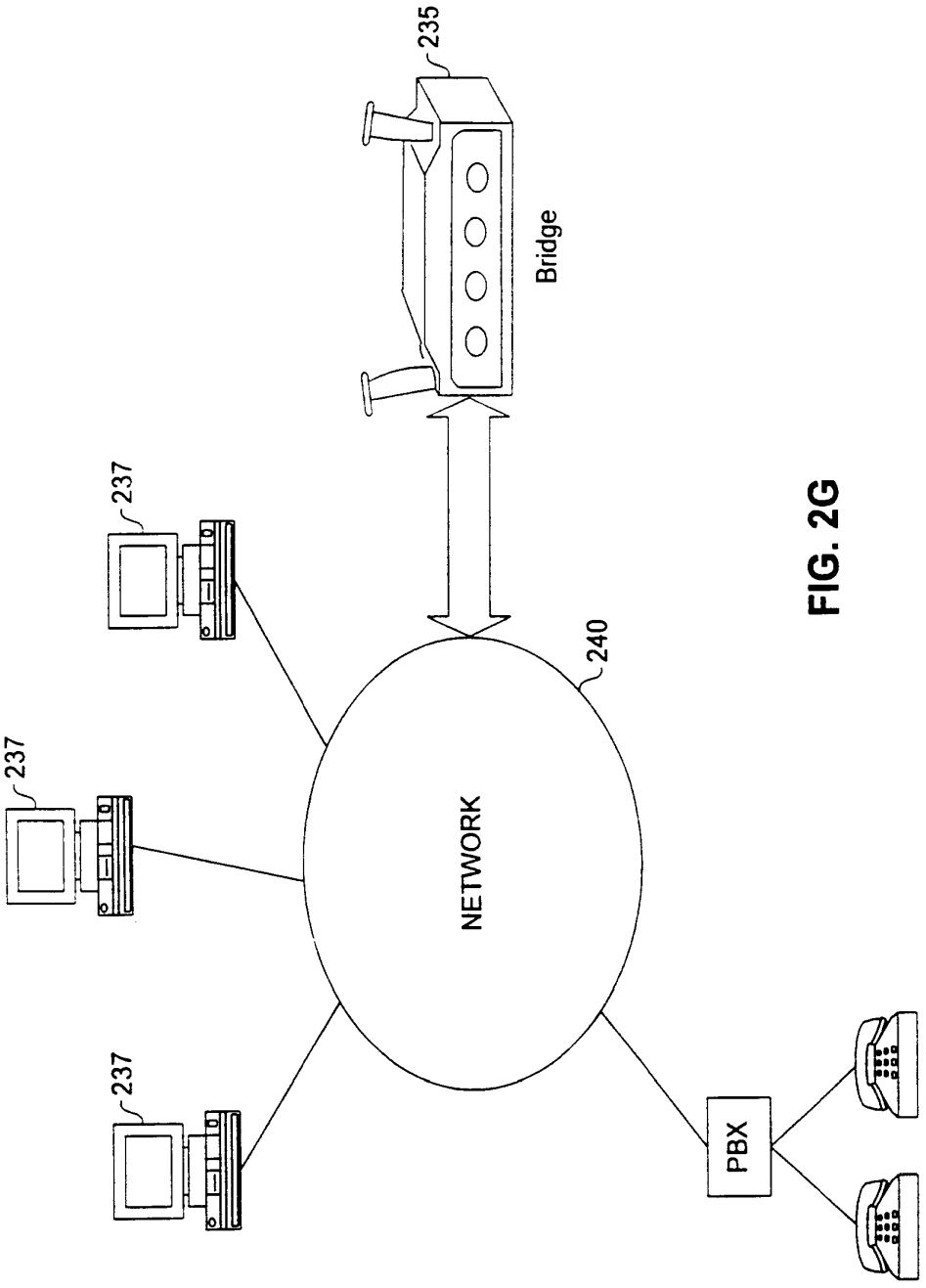
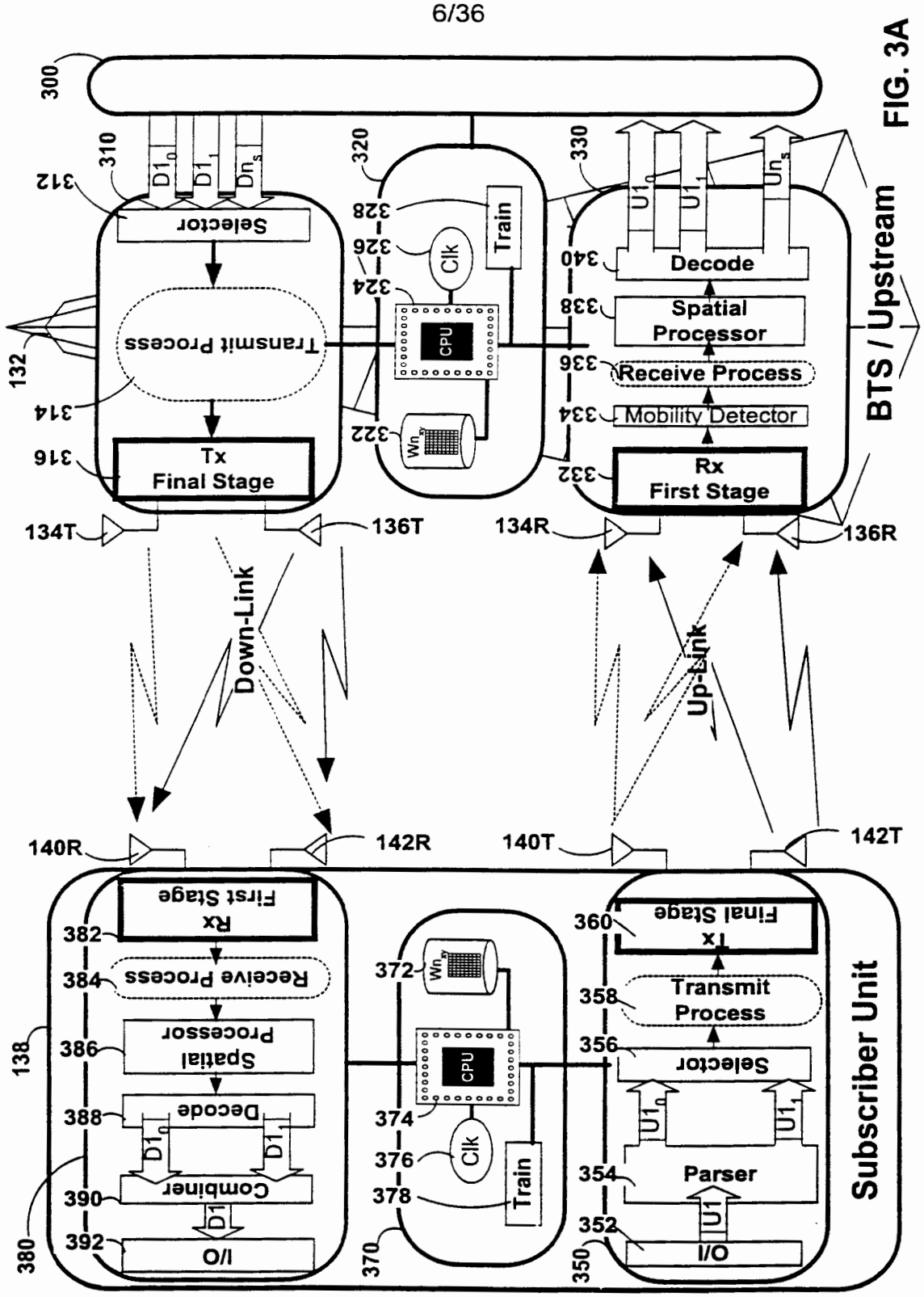


FIG. 2G



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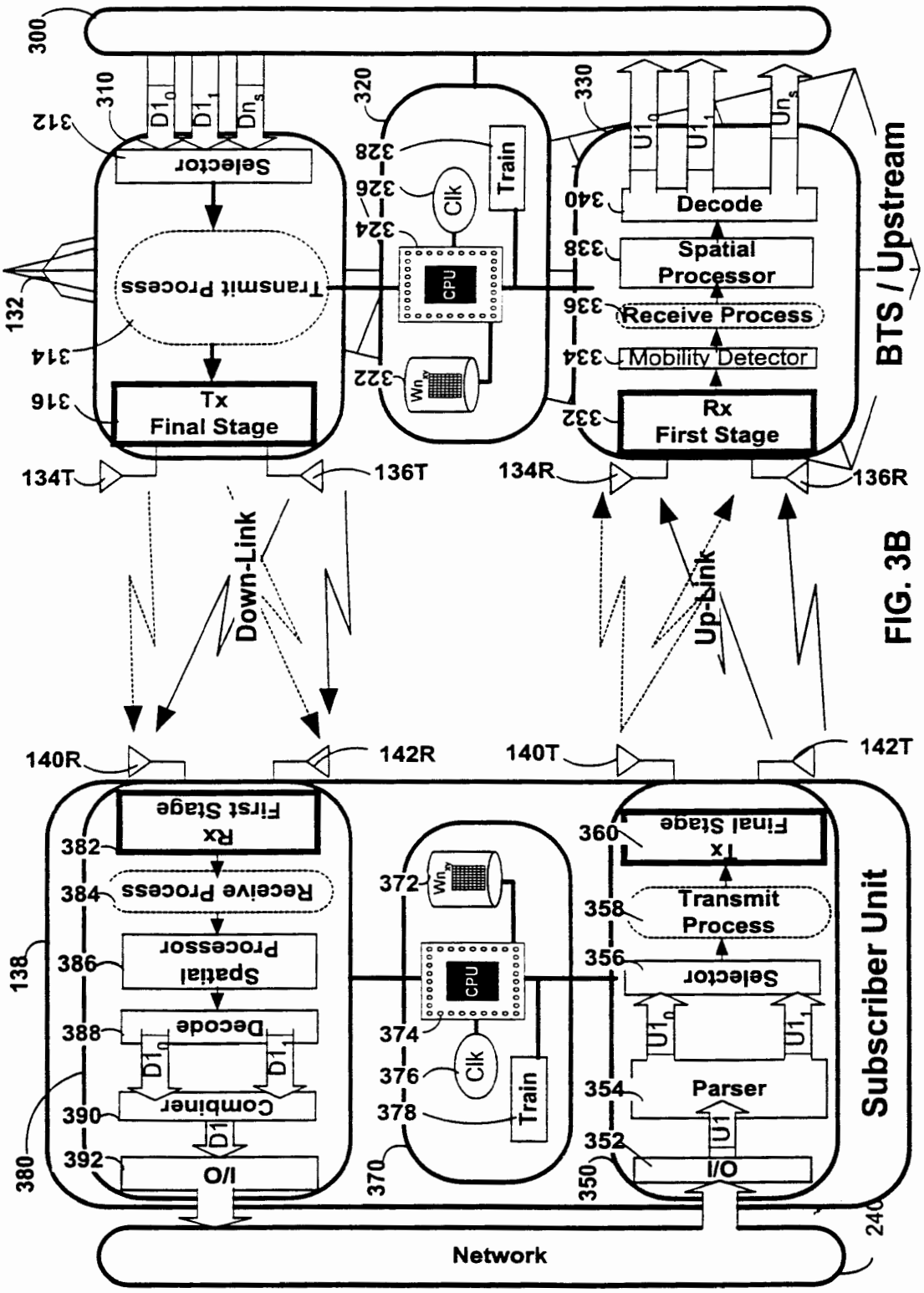
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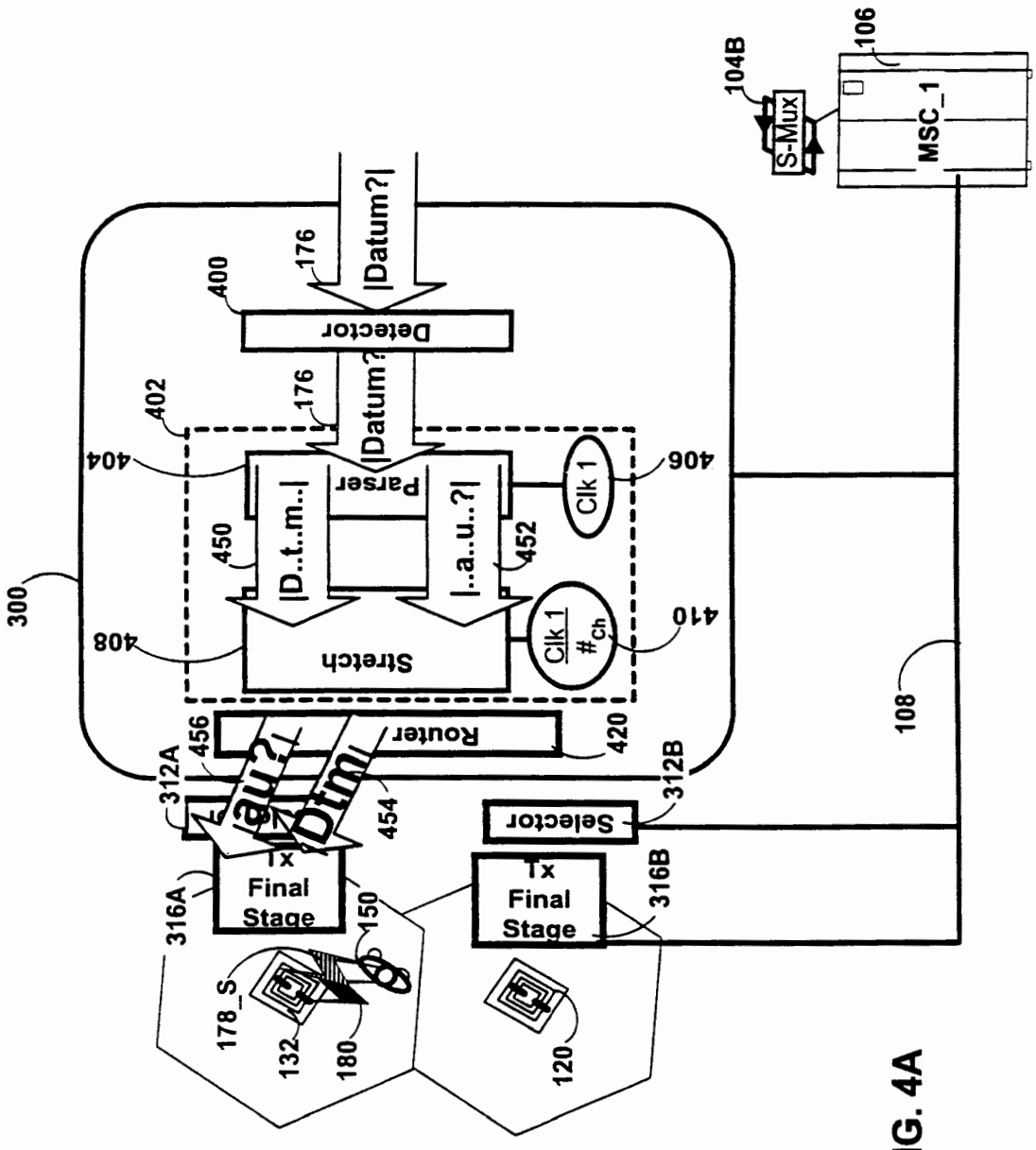
310
312
Selector
320
328
Train
326
Clk
324
CPU
330
340
Decode
338
Spatial Processor
336
Receive Process
334
Mobility Detector
332
Rx First Stage
BTS / Upstream
132
Transmit Process
314
316
Tx Final Stage
322
134T
136T
134R
136R
Down-Link
Up-Link
140R
142R
140T
142T
Rx First Stage
382
Receive Process
384
Spatial Processor
386
Decode
388
Combiner
390
I/O
392
380
138
372
374
376
Clk
378
Train
370
CPU
360
Final Stage
Tx
358
Transmit Process
356
Selector
354
Parser
352
I/O
350
Subscriber Unit
240
Network

FIG. 3B


104B
106
S-Mux
MSC_1
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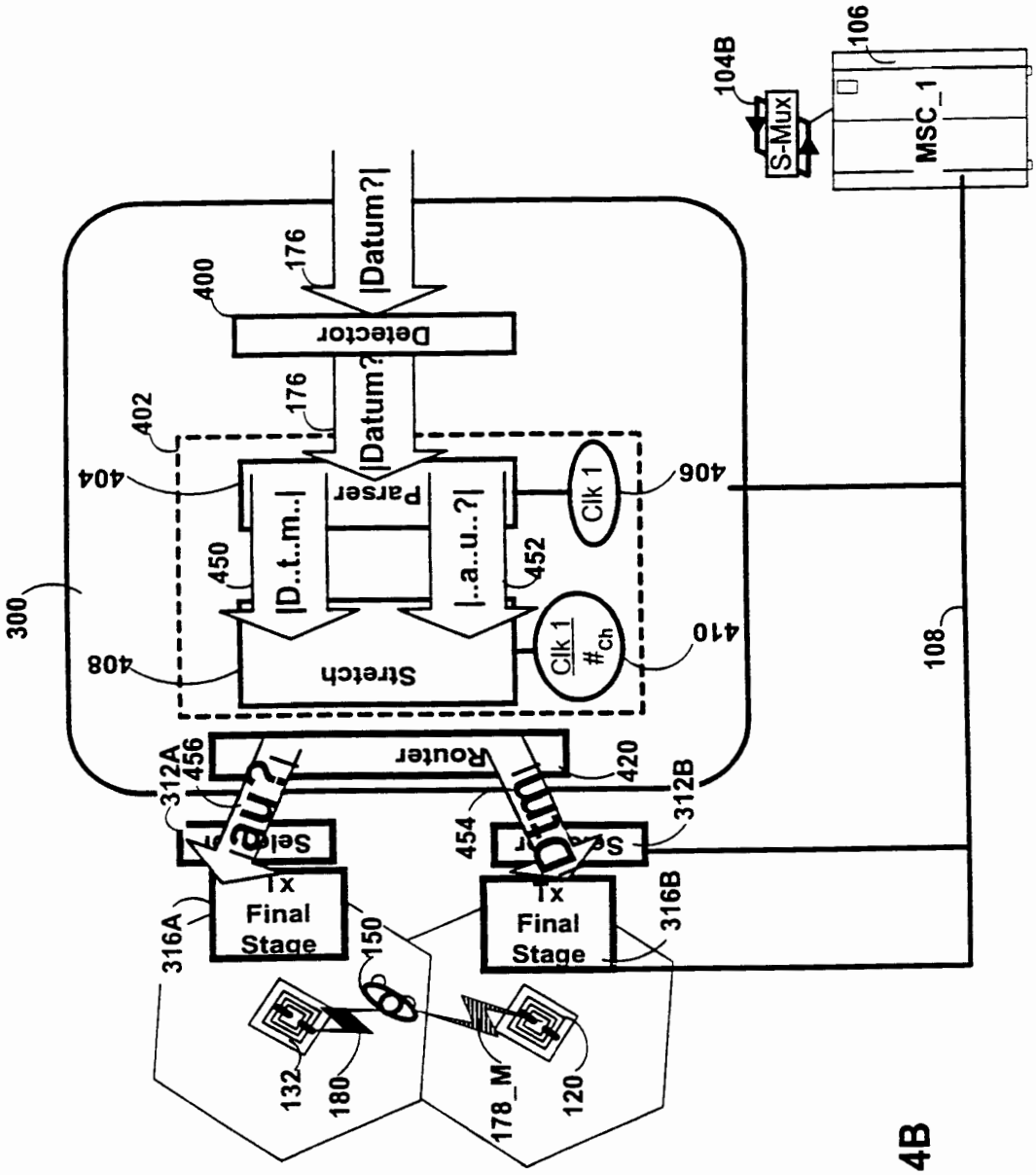
176
400
Detector
402
404
406
Parser
Clk 1
450
452
|D..t..m..|
|..a..u..?|
300
408
410
Stretch
Clk 1
#Ch
456
Router
420
108
312A
312B
454
Selector
Tx
Final
Stage
316A
316B
150
178_S
132
180
120

FIG. 4A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Detector
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402
404
Parser
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|..a..u..?|
450
452
406
Clk 1
408
Stretch
410
Clk 1
#Ch
Router
420
312A
456
312B
454
Tx
Final
Stage
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132
180
178_M
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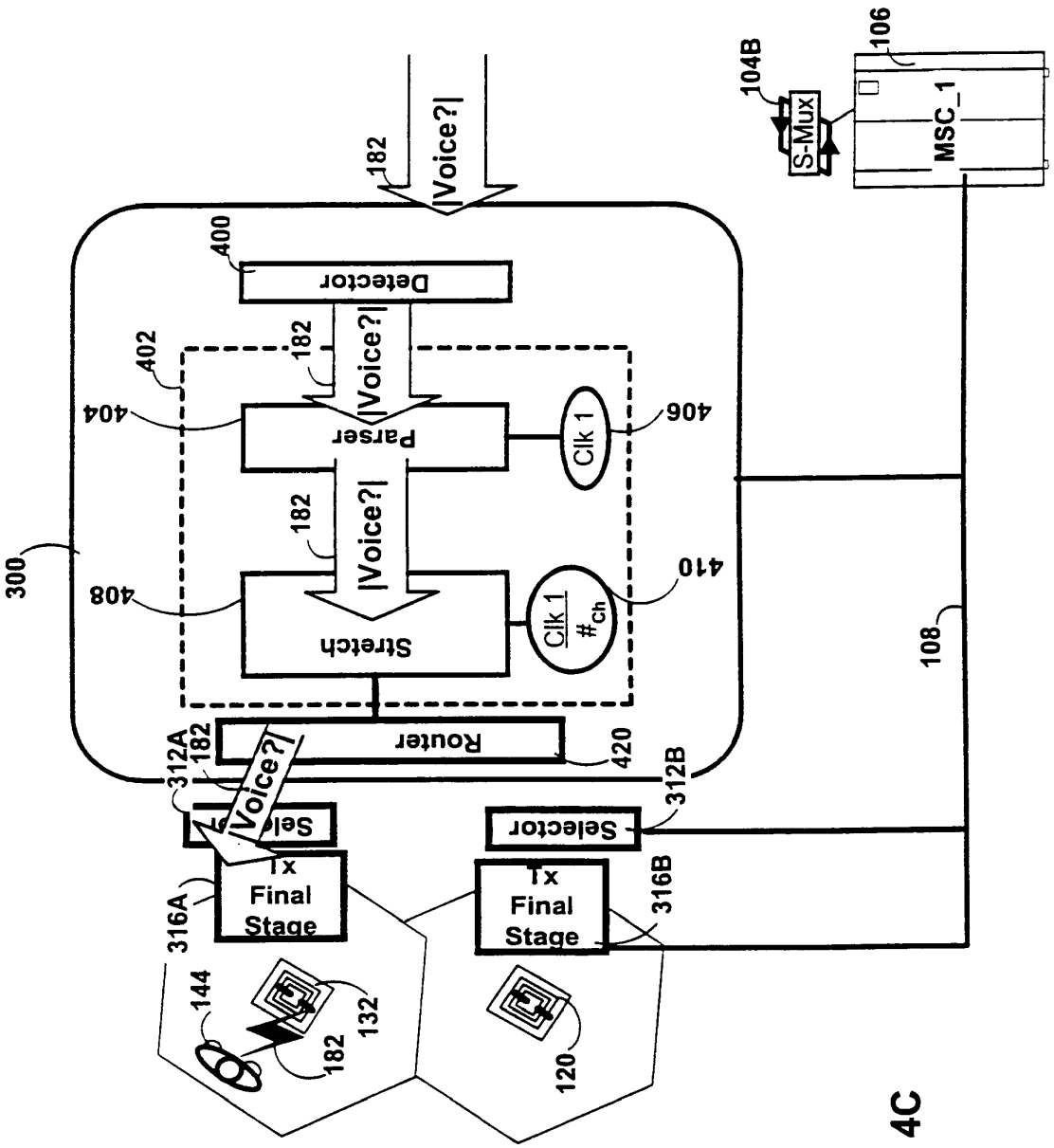
108
104B
S-Mux
106
MSC_1

FIG. 4B


104B
106
S-Mux
MSC_1
182
Voice?
400
Detector
402
182
Voice?
404
Parser
Clk 1
406
182
Voice?
300
408
Stretch
Clk 1 / #Ch
410
108
Router
420
312A
182
Voice?
312B
Selector
Selector
Tx Final Stage
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Tx Final Stage
316B
144
132
182
120

FIG. 4C

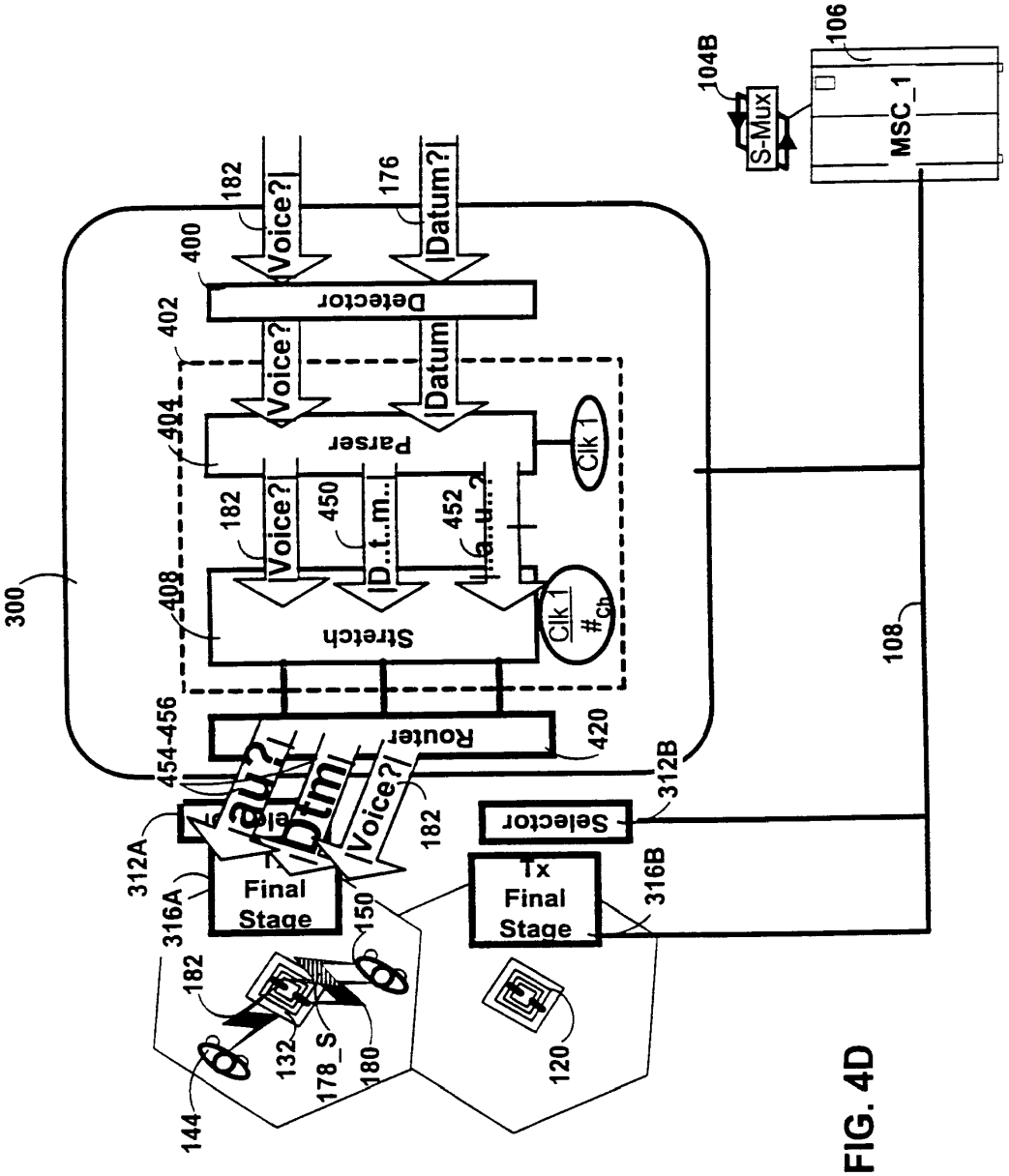

FIG. 4D

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0452 of 1285

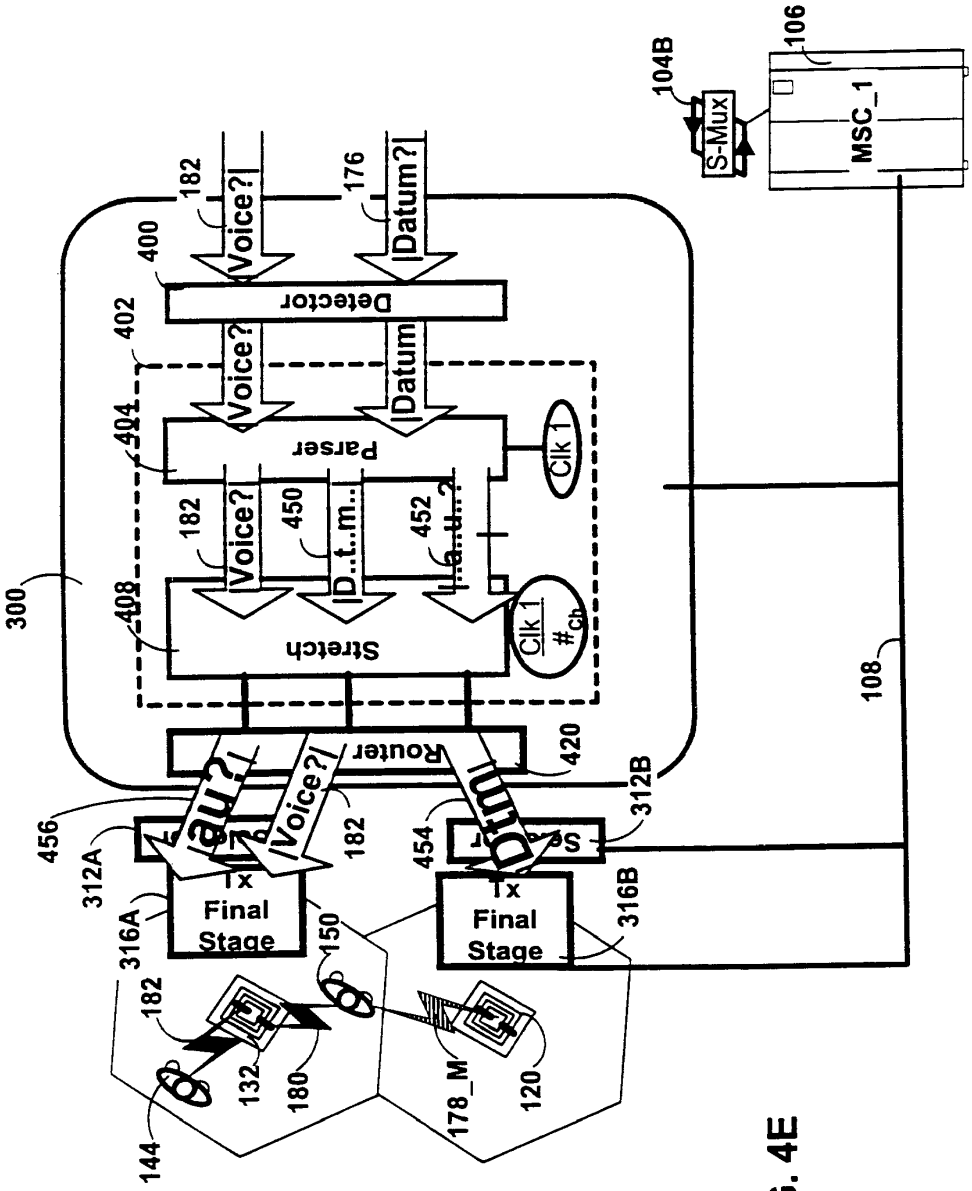

FIG. 4E

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0453 of 1285

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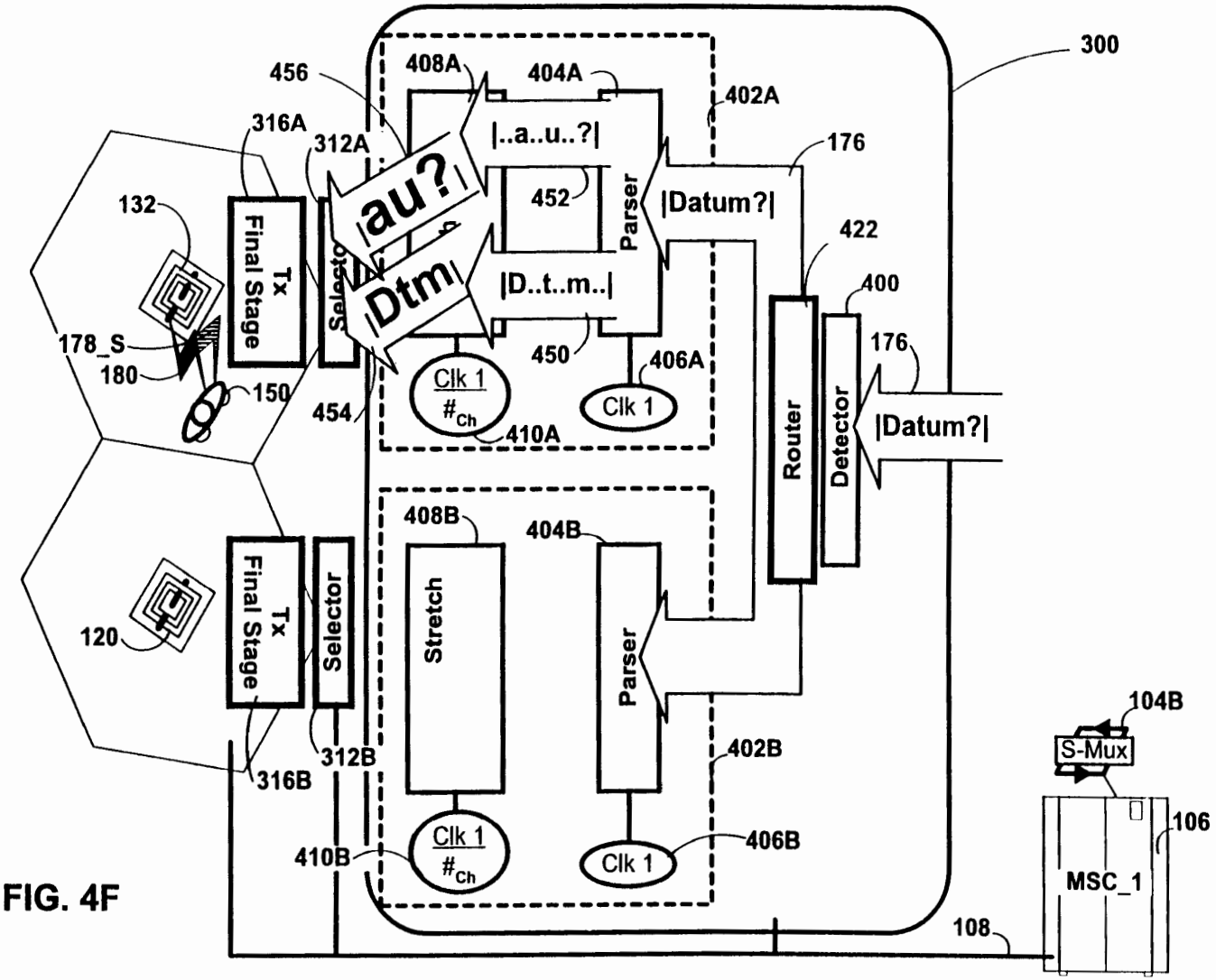
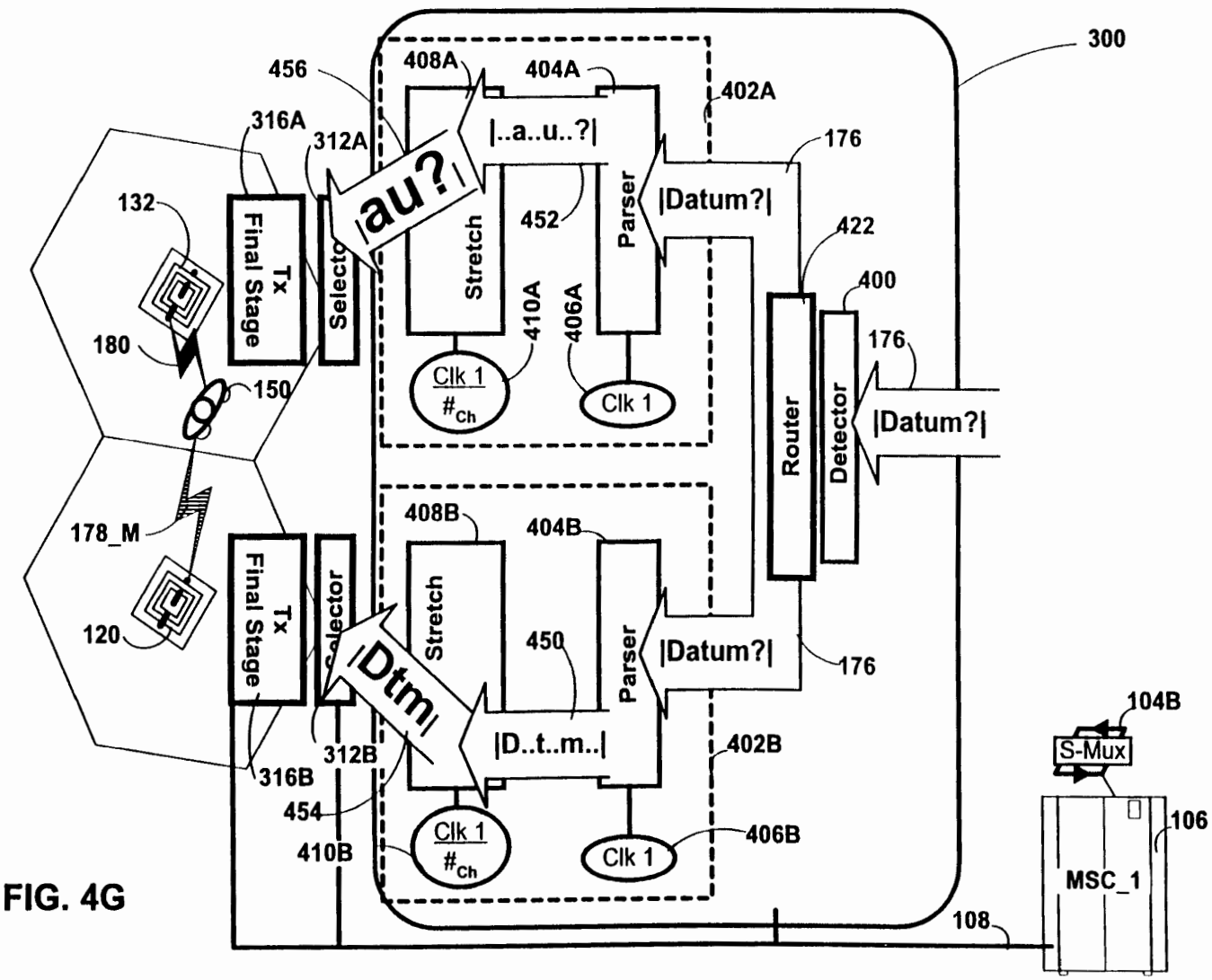


FIG. 4F

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148


300
456
408A
404A
402A
316A
312A
|..a..u..?|
|au?|
176
132
Tx Final Stage
Selector
Stretch
452
Parser
|Datum?|
422
400
180
410A
406A
176
150
Clk 1 #Ch
Clk 1
Router
Detector
|Datum?|
408B
404B
178_M
Tx Final Stage
Selector
Stretch
450
Parser
|Datum?|
176
120
|Dtm|
|D..t..m..|
104B
S-Mux
312B
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402B
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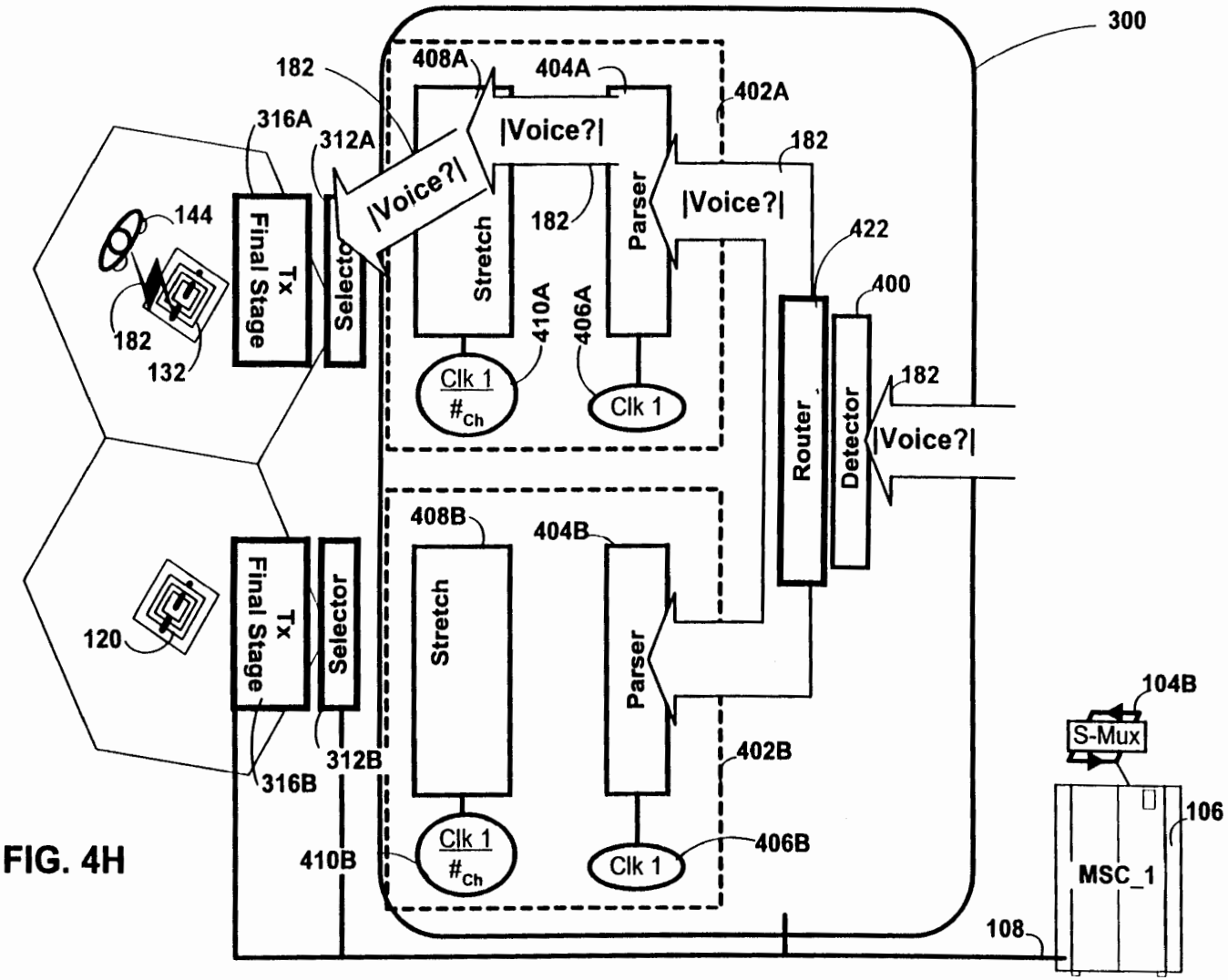
106
410B
Clk 1 #Ch
Clk 1
406B
MSC_1
108

FIG. 4G


300
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|Voice?|
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Tx Final Stage
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Stretch
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Parser
|Voice?|
422
400
182
132
410A
406A
Clk 1 #Ch
Clk 1
Router
Detector
182
|Voice?|
408B
404B
120
Tx Final Stage
Selector
Stretch
Parser
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106
Clk 1 #Ch
410B
Clk 1
406B
MSC_1
108

FIG. 4H

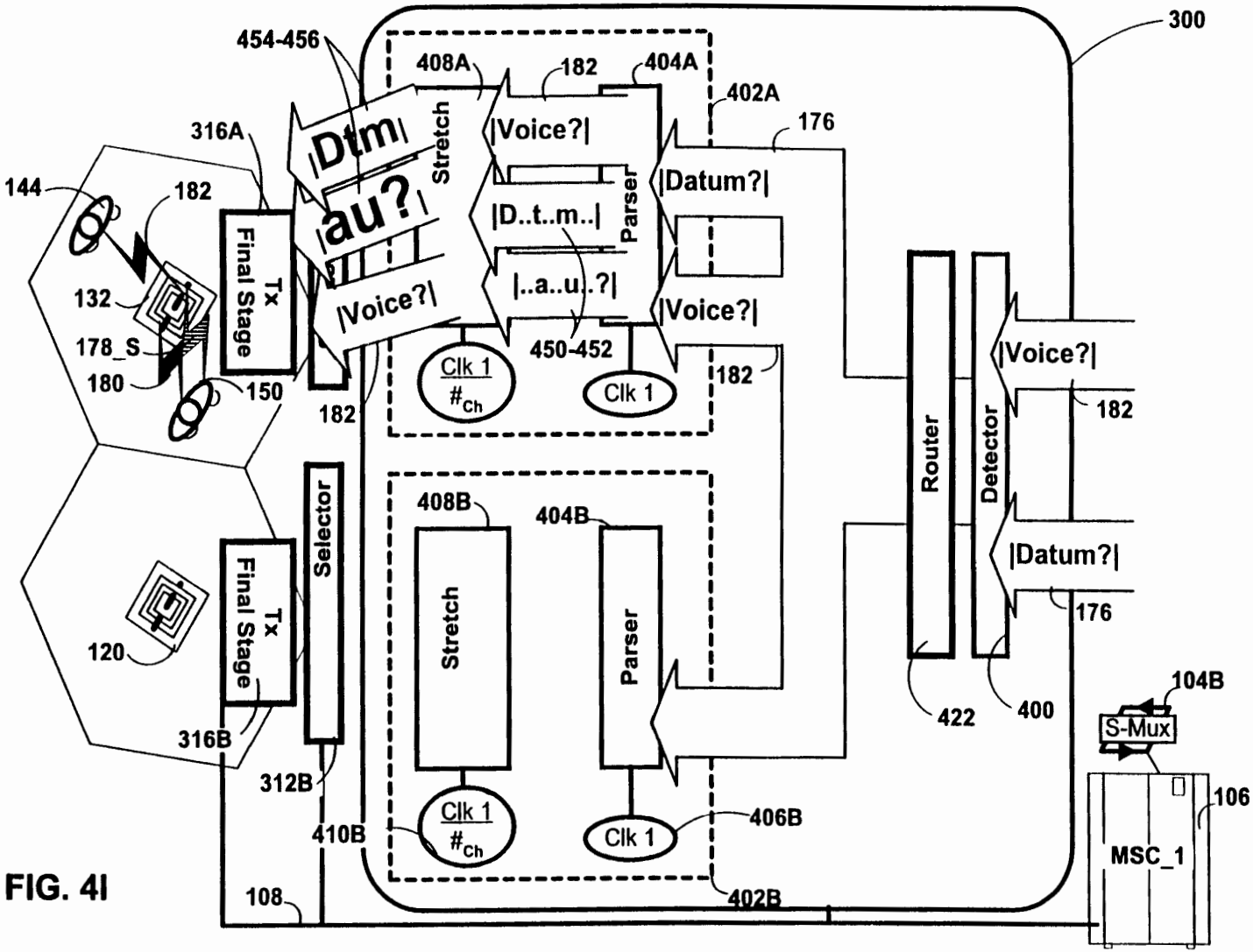

FIG. 4I

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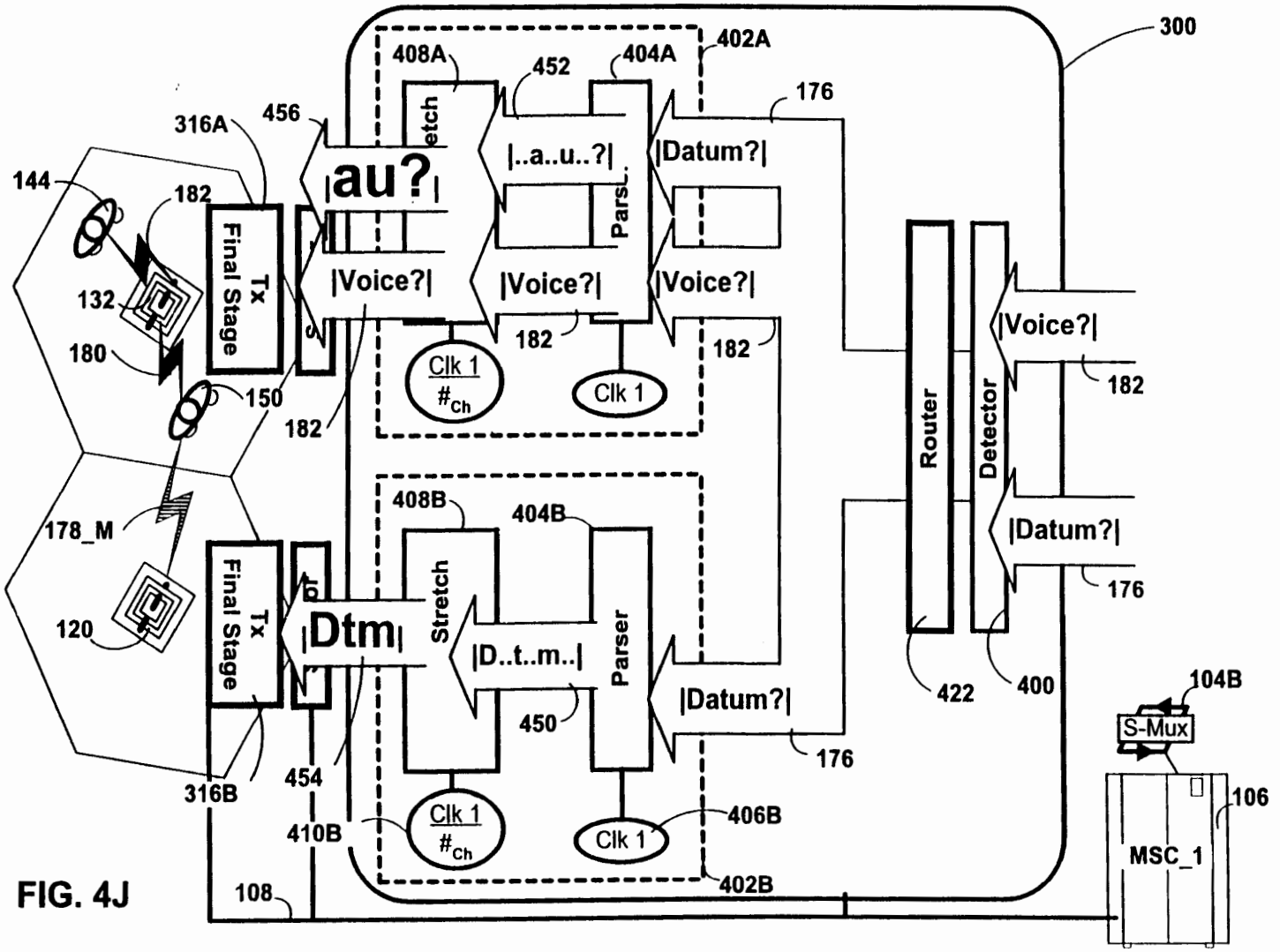
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404A
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316A
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|Datum?|
Tx Final Stage
Parser
|Voice?|
|Voice?|
|Voice?|
132
180
150
182
182
182
Clk 1
#Ch
Clk 1
Router
Detector
|Voice?|
182
178_M
408B
404B
|Datum?|
176
120
Tx Final Stage
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Stretch
|D..t..m..|
Parser
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FIG. 4J

SUBSTITUTE SHEET (RULE 26)

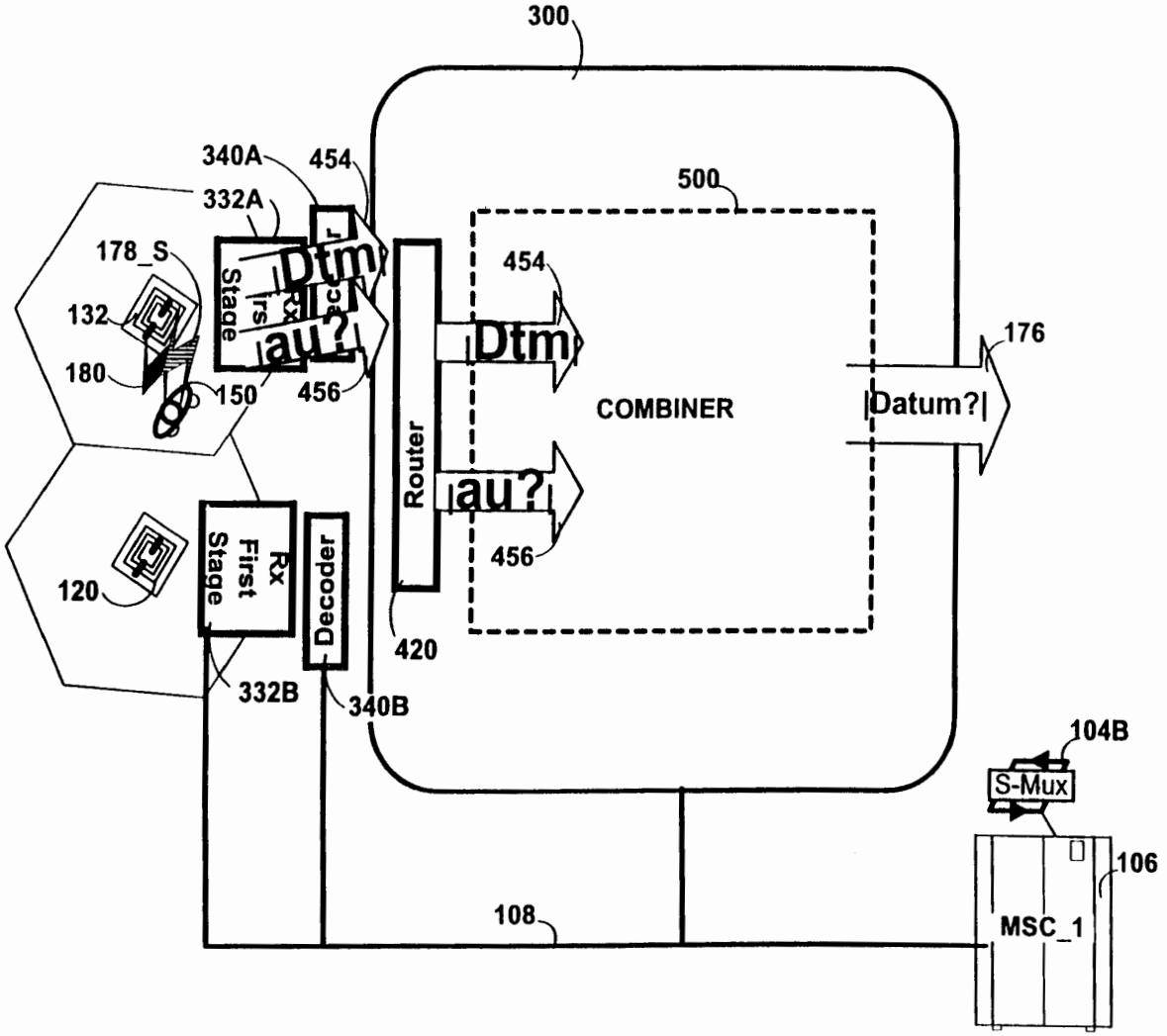
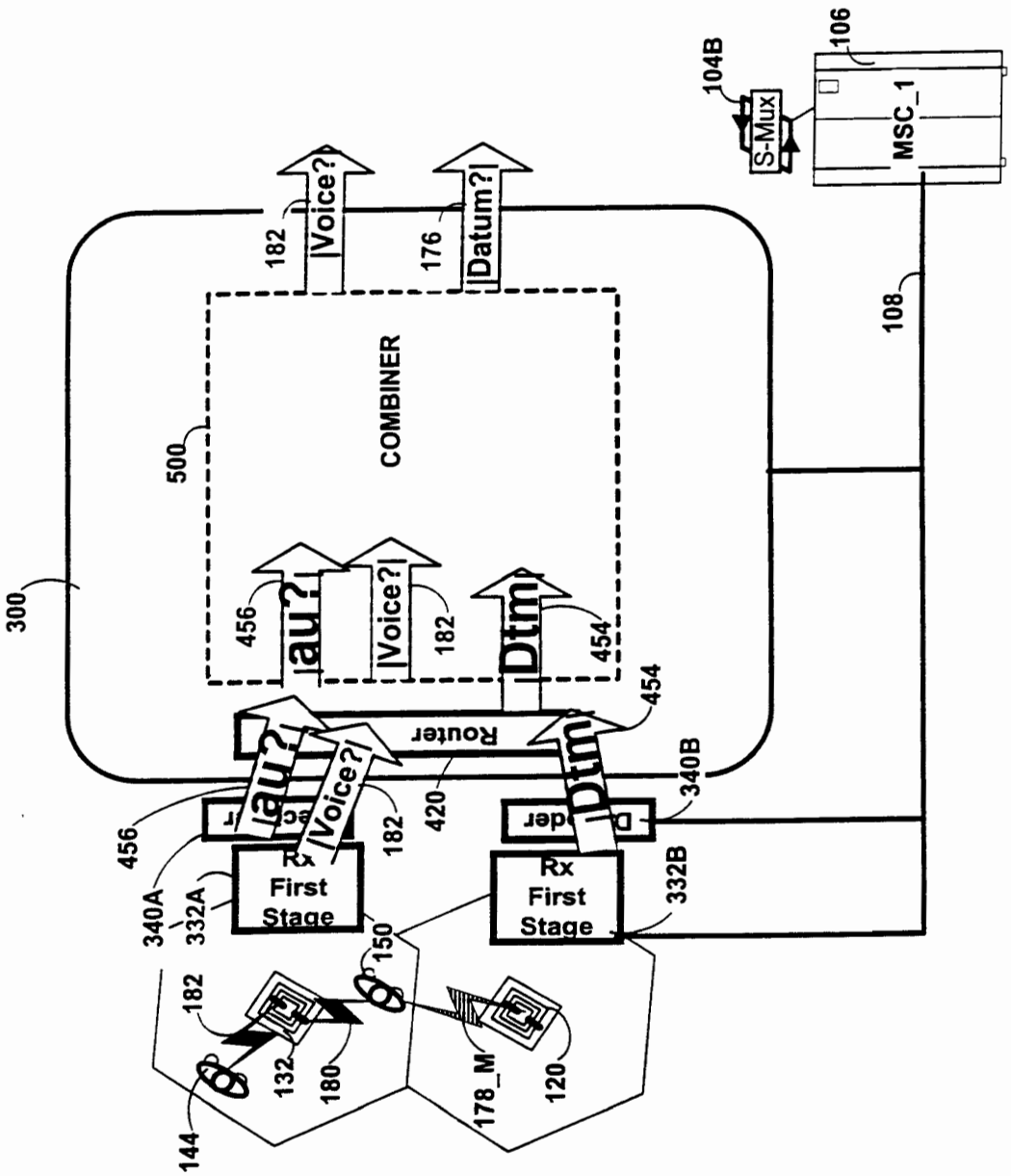


FIG. 5A

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 5B



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Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

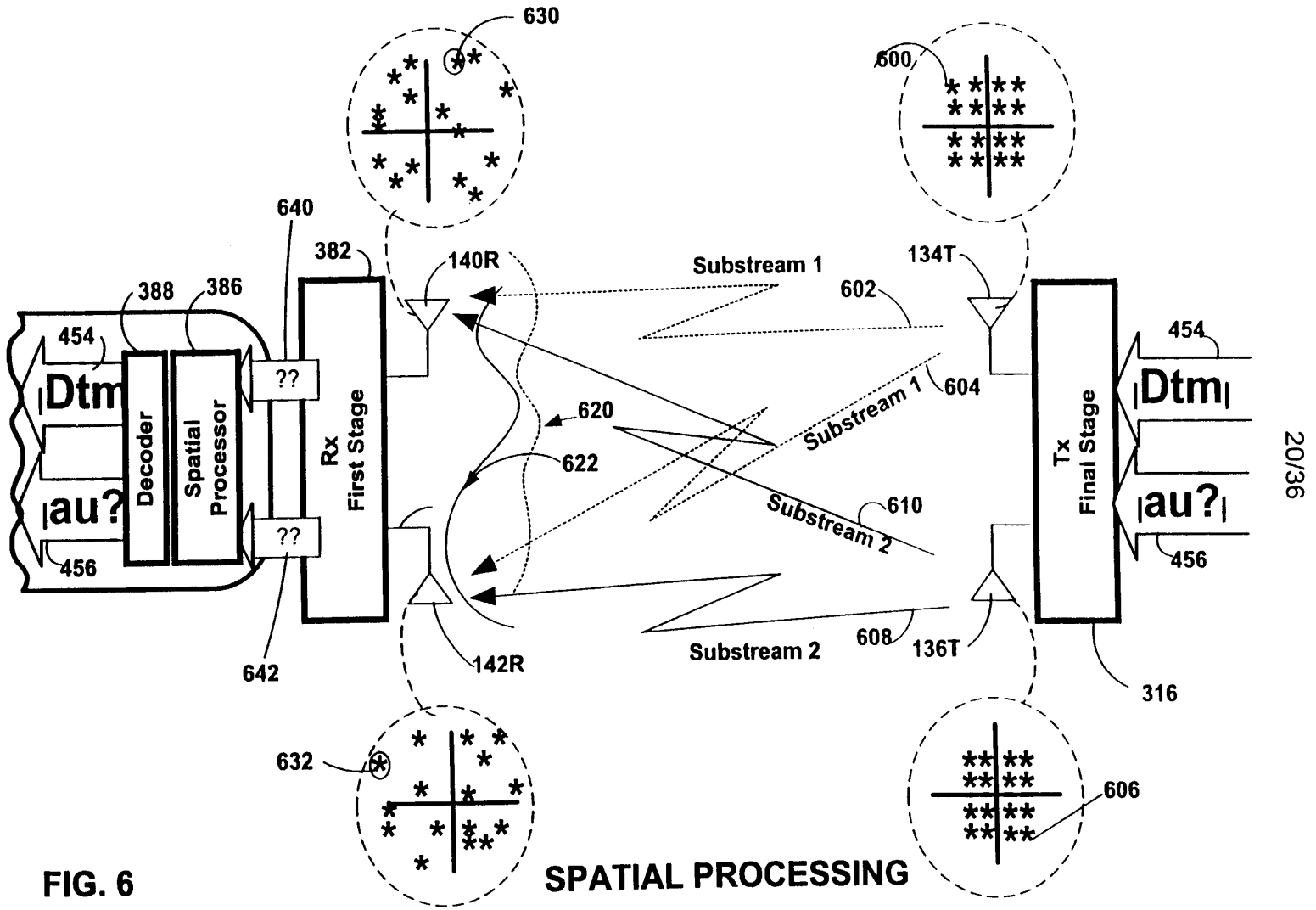
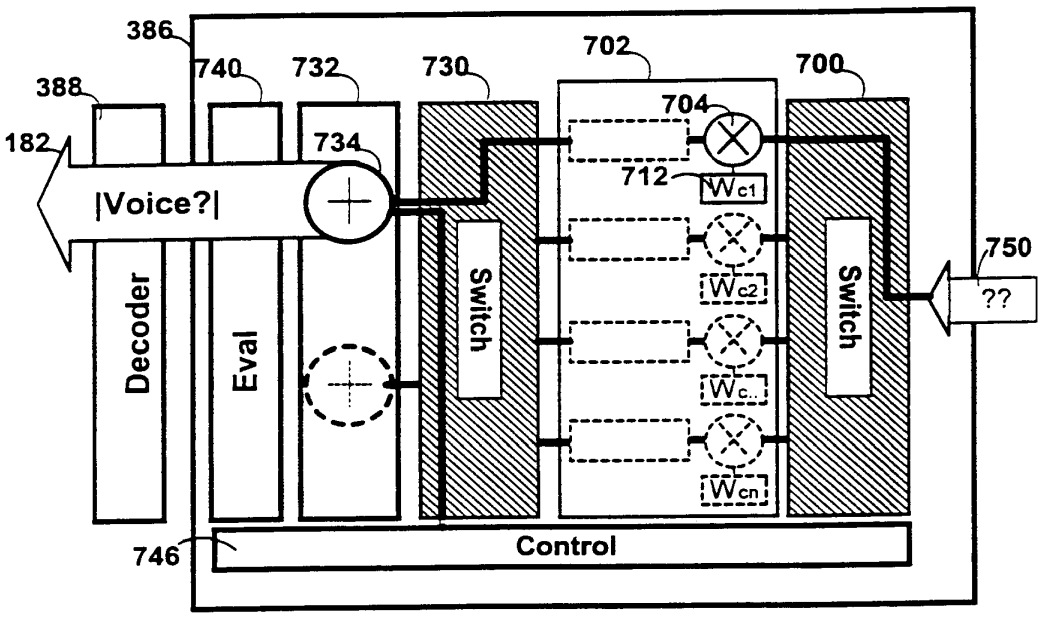
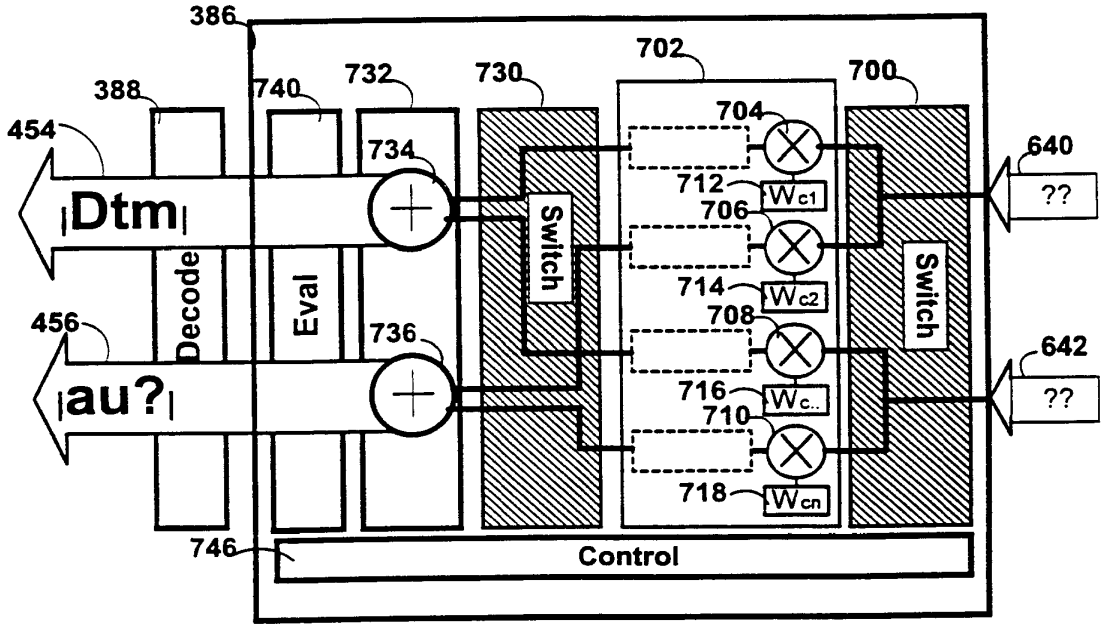


FIG. 6 SPATIAL PROCESSING

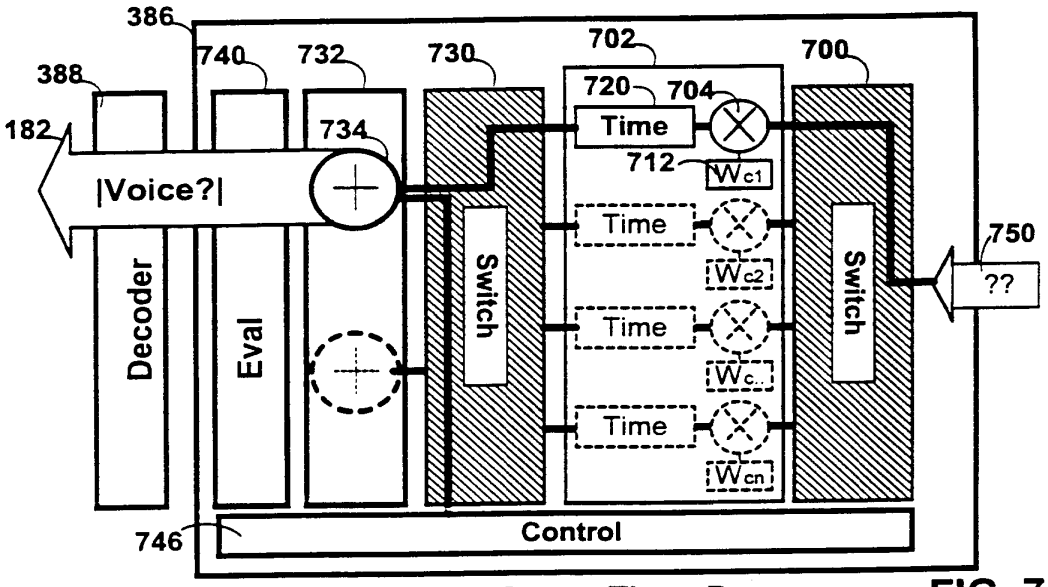


Spatial Processor FIG. 7A

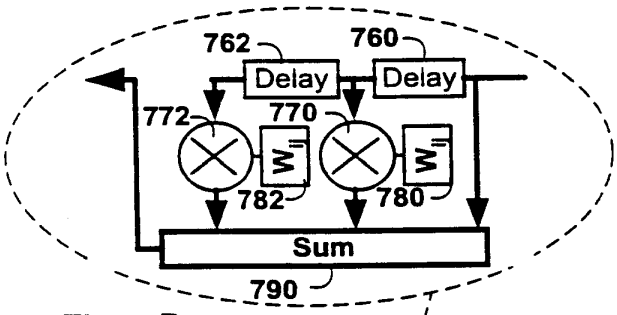


Spatial Processor

FIG. 7B



Space-Time Processor FIG. 7C



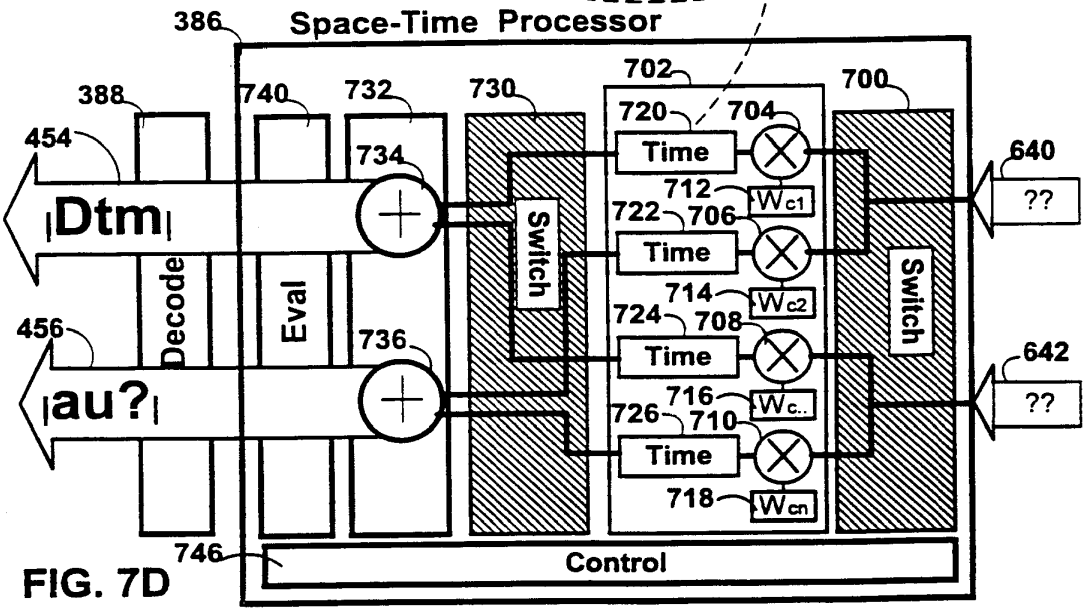


FIG. 7D

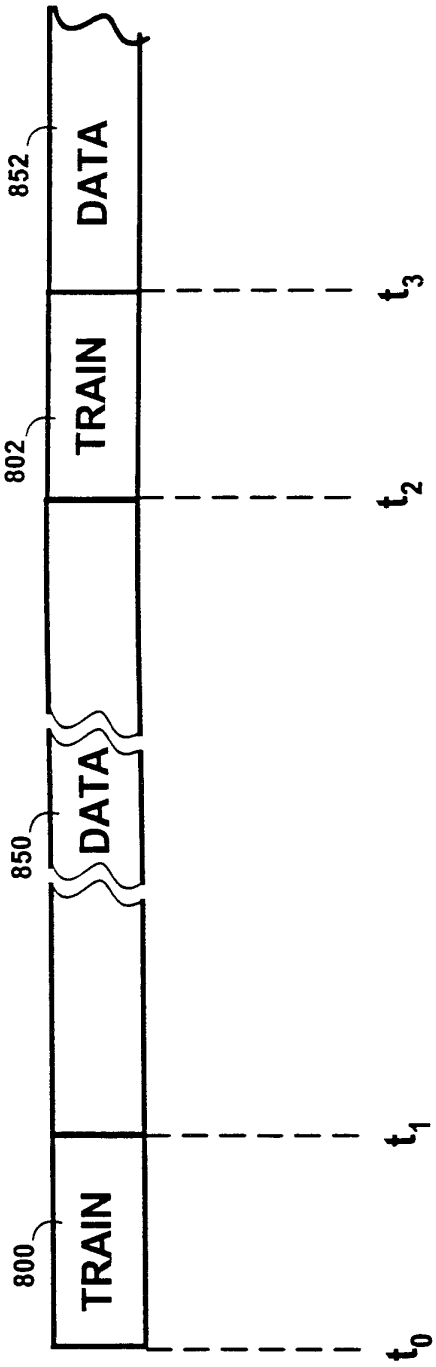


FIG. 8

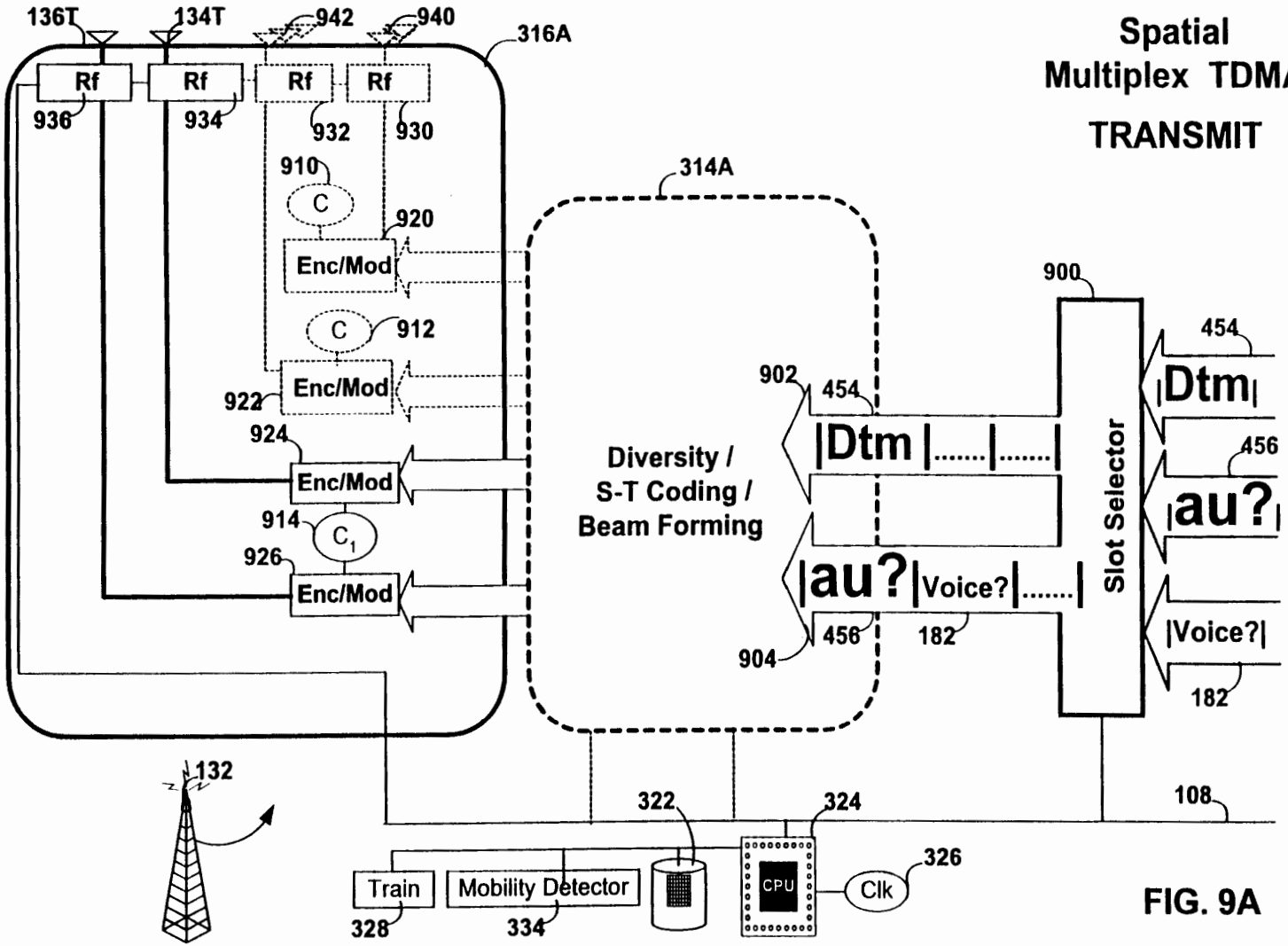

Spatial
Multiplex TDMA
TRANSMIT
136T
134T
942
940
316A
Rf
936
934
932
930
910
C
920
Enc/Mod
912
922
924
914
C_1
926
314A
Diversity /
S-T Coding /
Beam Forming
900
902
454
Dtm
456
au?
Voice?
904
182
Slot Selector
132
322
324
108
326
Clk
CPU
Train
328
Mobility Detector
334

FIG. 9A

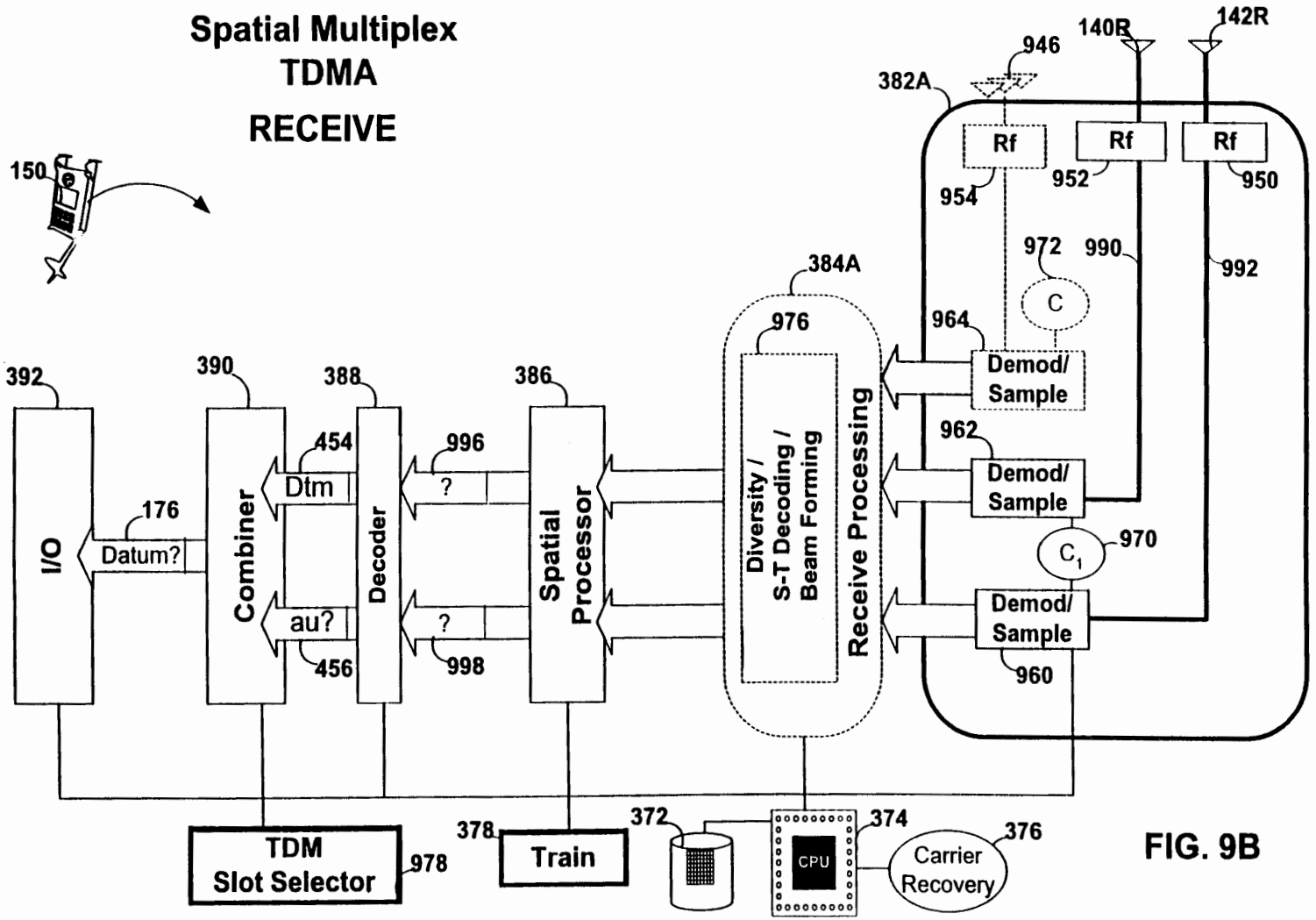

Spatial Multiplex
TDMA
RECEIVE
150
946
140R
142R
382A
Rf
Rf
Rf
954
952
950
972
990
992
384A
C
976
964
Demod/
Sample
962
Demod/
Sample
970
C1
Demod/
Sample
960
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
392
390
388
386
I/O
Datum?
176
Combiner
454
Dtm
au?
456
Decoder
996
?
?
998
Spatial
Processor
TDM
Slot Selector
978
378
Train
372
CPU
374
Carrier
Recovery
376

FIG. 9B

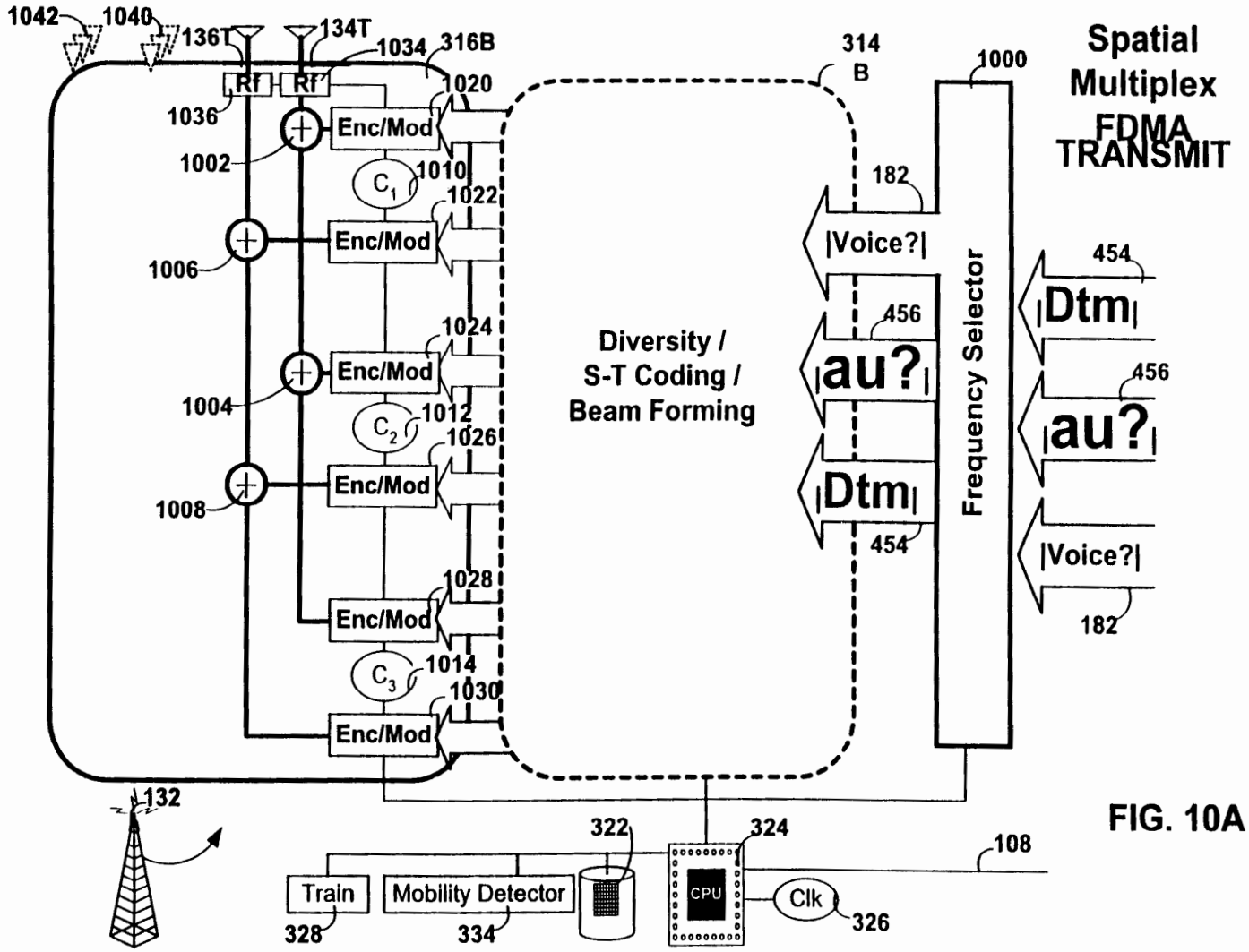

1042
1040
136T
134T
1034
316B
314
B
1000
Spatial
Multiplex
FDMA
TRANSMIT
Rf
Rf
1020
1036
Enc/Mod
1002
C1
1010
1022
Enc/Mod
1006
182
|Voice?|
454
|Dtm|
456
1024
Enc/Mod
Diversity /
S-T Coding /
Beam Forming
|au?|
456
1004
C2
1012
1026
Enc/Mod
|Dtm|
|au?|
1008
454
Frequency Selector
|Voice?|
182
1028
Enc/Mod
C3
1014
1030
Enc/Mod
132
322
324
108
Train
Mobility Detector
CPU
Clk
328
334
326

FIG. 10A

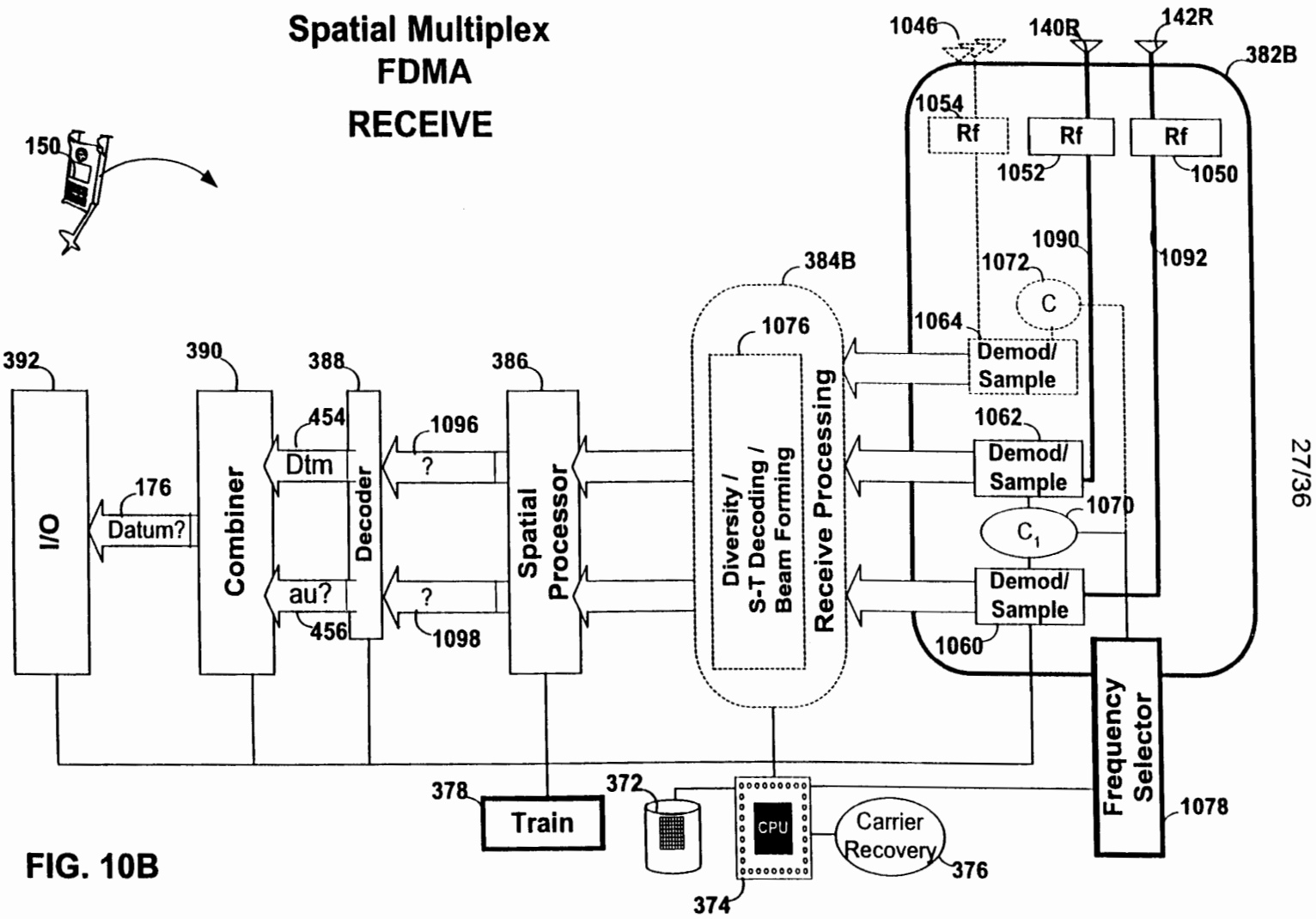

Spatial Multiplex
FDMA
RECEIVE
150
1046
140R
142R
382B
1054
Rf
Rf
Rf
1052
1050
1090
1092
1072
C
384B
1076
1064
Demod/
Sample
392
390
388
386
454
1096
Dtm
?
176
Datum?
I/O
Combiner
Decoder
Spatial
Processor
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
1062
Demod/
Sample
1070
C1
au?
?
456
1098
Demod/
Sample
1060
Frequency
Selector
1078
378
Train
372
CPU
Carrier
Recovery
376
374

FIG. 10B

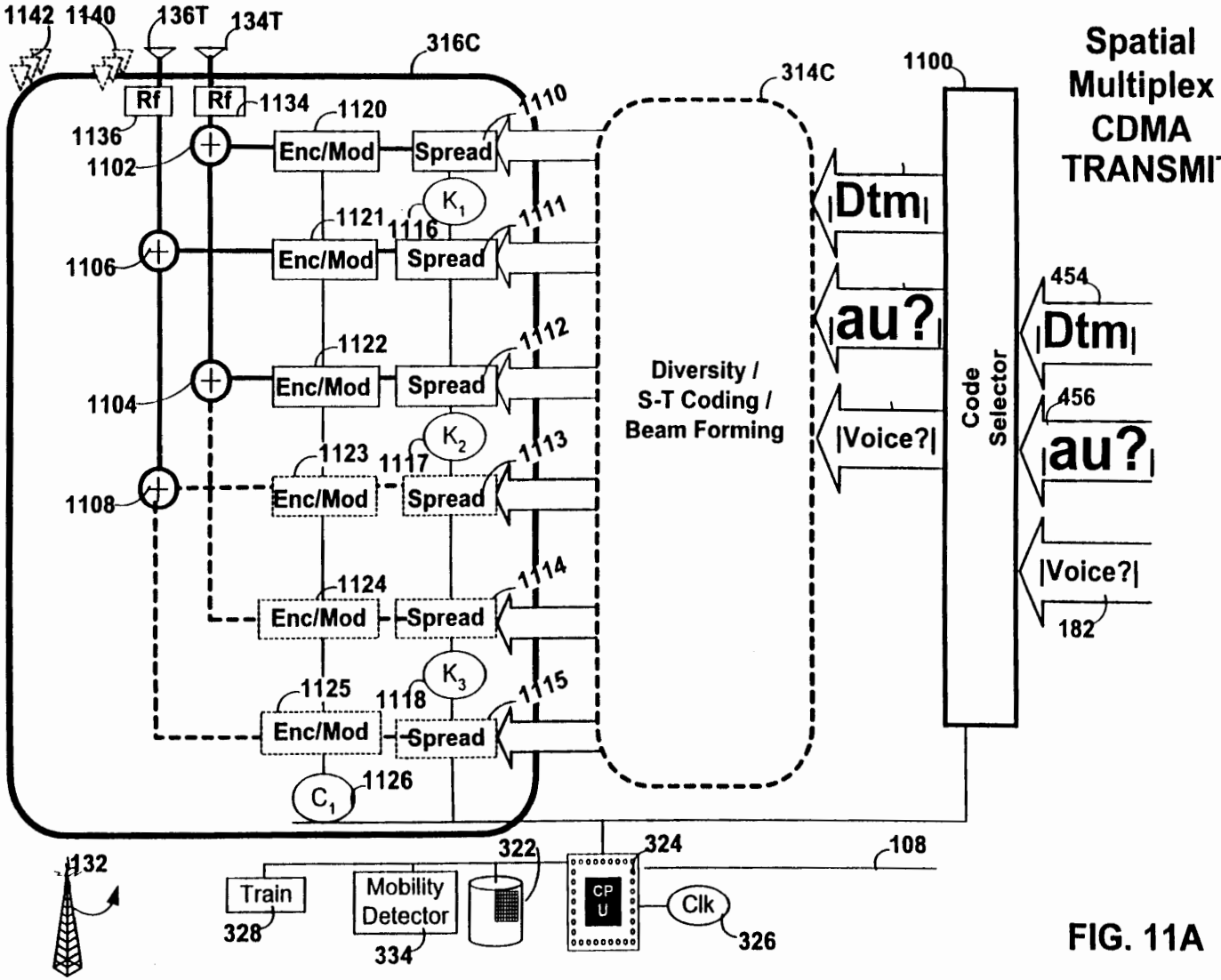
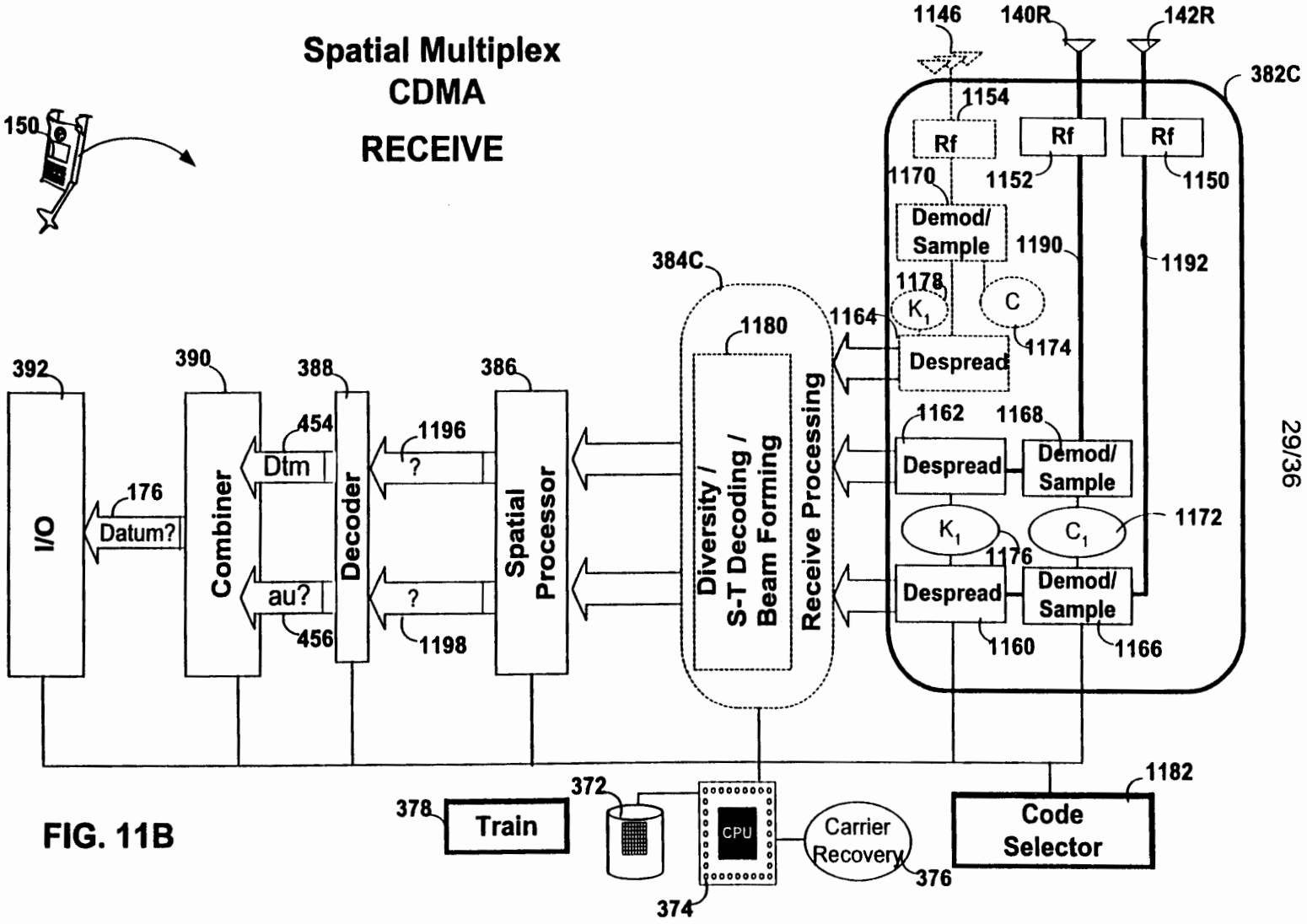

Spatial Multiplex CDMA TRANSMIT
1142
1140
136T
134T
316C
314C
1100
Rf
Rf
1134
1120
1136
1102
Enc/Mod
Spread
1110
K1
1121
1116
1111
1106
Enc/Mod
Spread
1122
1112
1104
Enc/Mod
Spread
K2
1123
1117
1113
1108
Enc/Mod
Spread
1124
1114
Enc/Mod
Spread
K3
1125
1118
1115
Enc/Mod
Spread
C1
1126
Diversity / S-T Coding / Beam Forming
|Dtm|
|au?|
|Voice?|
Code Selector
454
|Dtm|
456
|au?|
|Voice?|
182
132
Train
328
Mobility Detector
334
322
CP U
324
Clk
326
108

FIG. 11A


Spatial Multiplex
CDMA
RECEIVE
150
1146
140R
142R
382C
1154
Rf
Rf
Rf
1170
1152
1150
Demod/
Sample
1190
1192
384C
1178
K_1
C
1180
1164
1174
Despread
392
390
388
386
454
1196
1162
1168
I/O
Combiner
Decoder
Spatial
Processor
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
Despread
Demod/
Sample
176
Dtm
?
K_1
C_1
1172
Datum?
1176
au?
?
Despread
Demod/
Sample
456
1198
1160
1166
1182
372
378
Train
CPU
Carrier
Recovery
Code
Selector
376
374
FIG. 11B

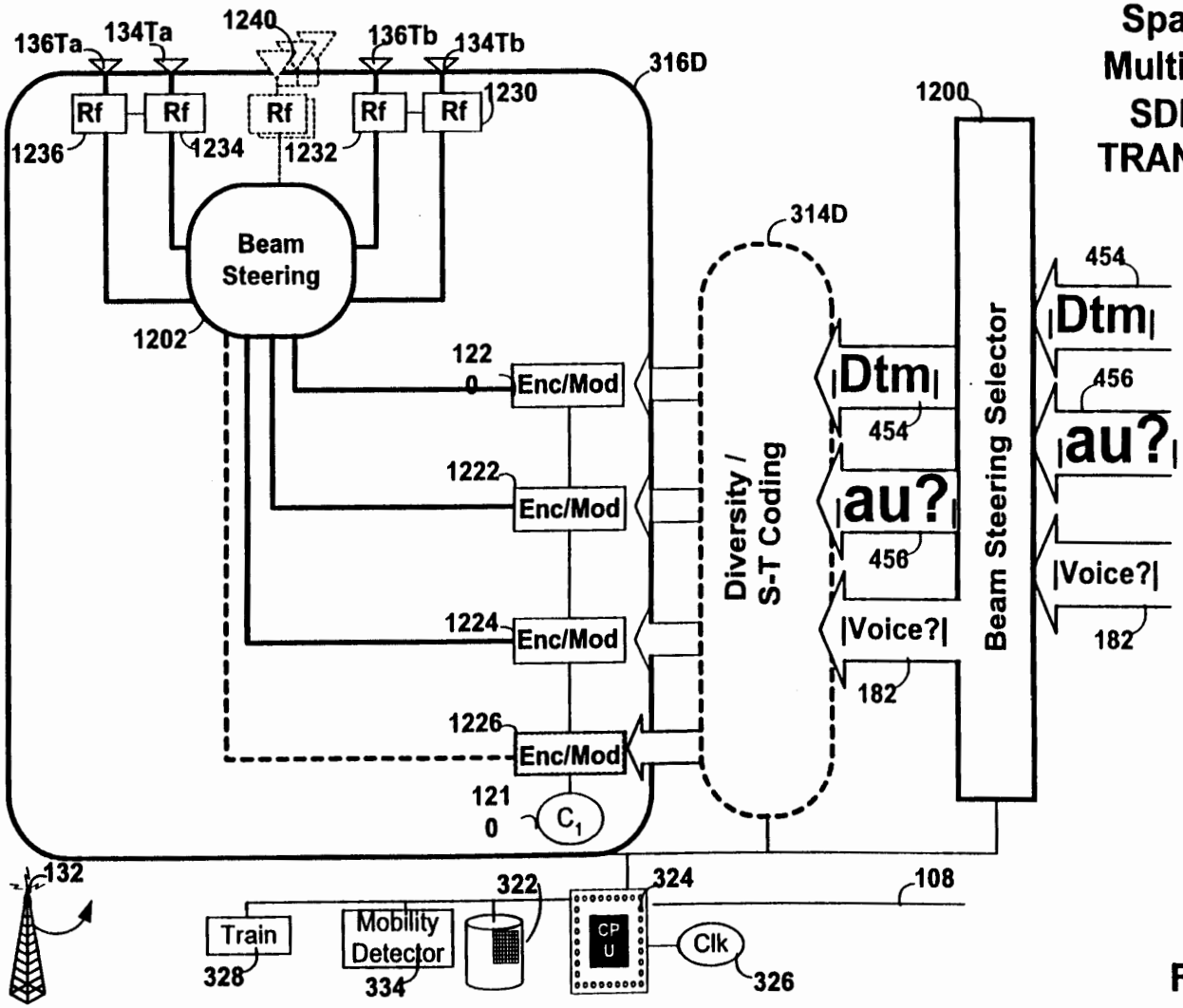

Spatial
Multiplex
SDMA
TRANSMIT
136Ta
134Ta
1240
136Tb
134Tb
316D
1200
1230
Rf
1236
1234
1232
Beam
Steering
1202
314D
454
Dtm
456
au?
Voice?
182
122
0
Enc/Mod
1222
1224
1226
121
0
C1
Diversity /
S-T Coding
Beam Steering Selector
132
322
324
108
Train
328
Mobility
Detector
334
CP
U
Clk
326

FIG. 12A

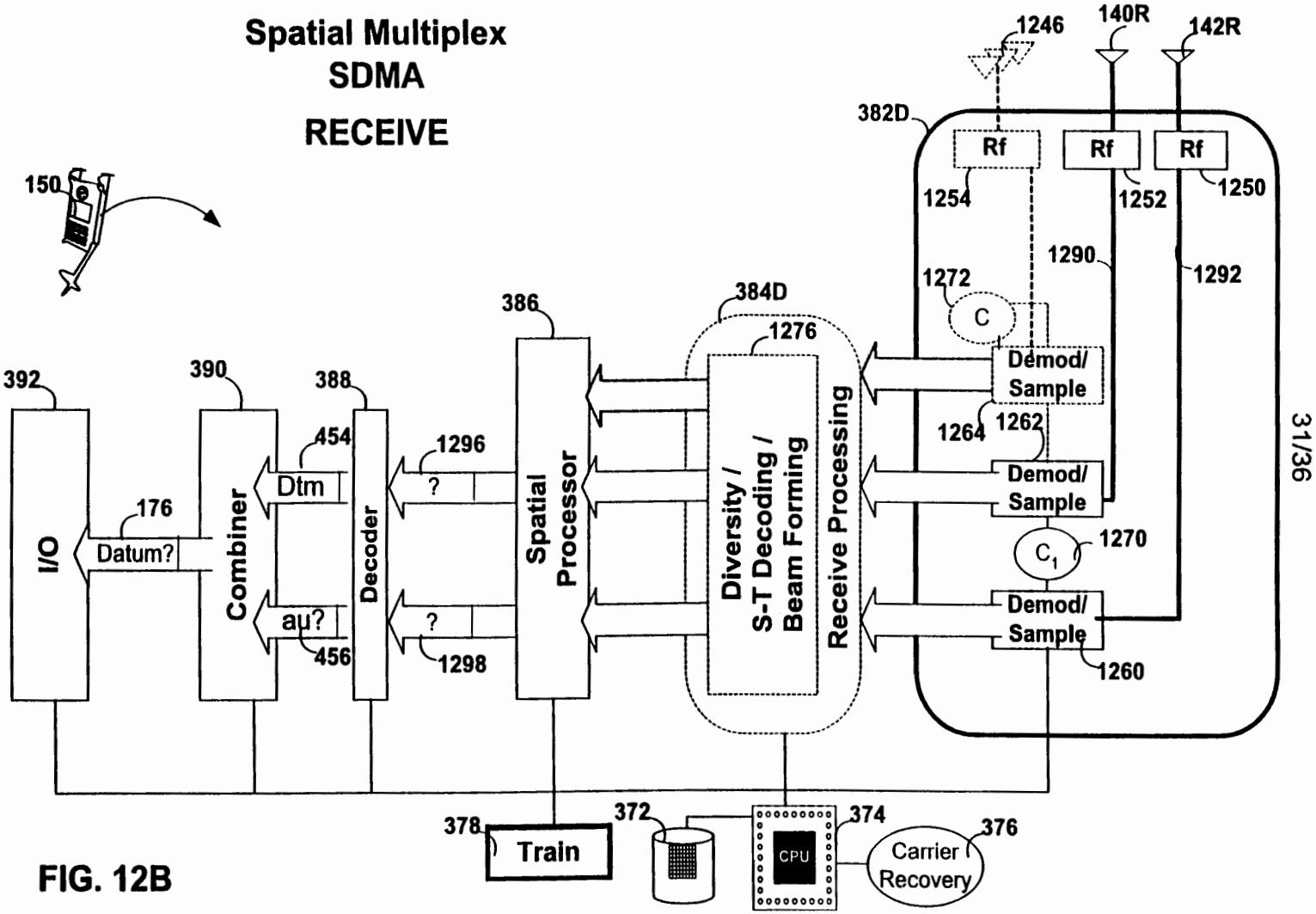

Spatial Multiplex
SDMA
RECEIVE
150
1246
140R
142R
382D
Rf
Rf
Rf
1254
1252
1250
1290
1292
1272
C
384D
386
1276
Demod/
Sample
1264
1262
Demod/
Sample
C1
1270
Demod/
Sample
1260
392
390
388
454
1296
176
Datum?
Dtm
?
I/O
Combiner
Decoder
Spatial
Processor
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
au?
456
?
1298
31/36
378
Train
372
CPU
374
Carrier
Recovery
376

FIG. 12B

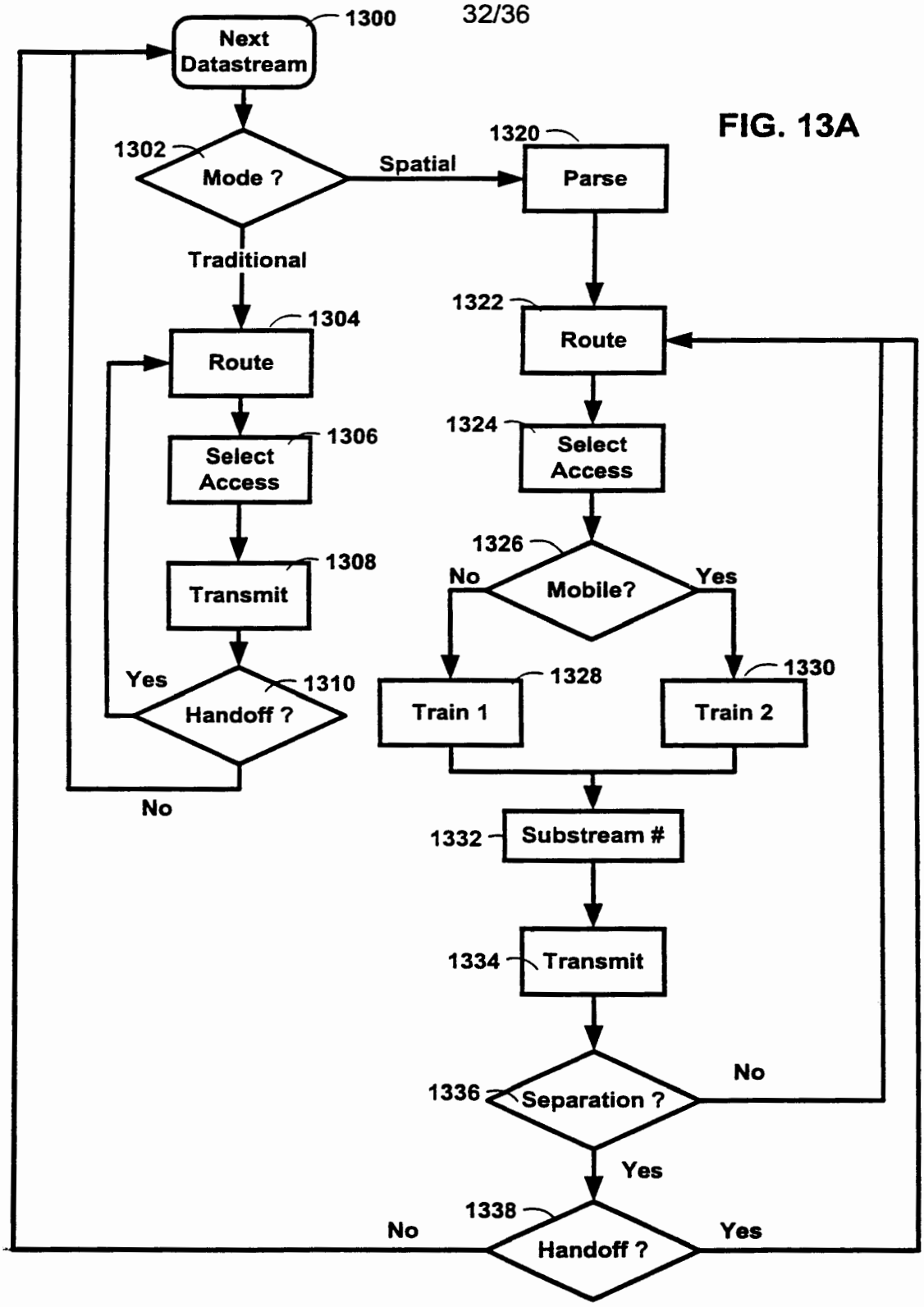
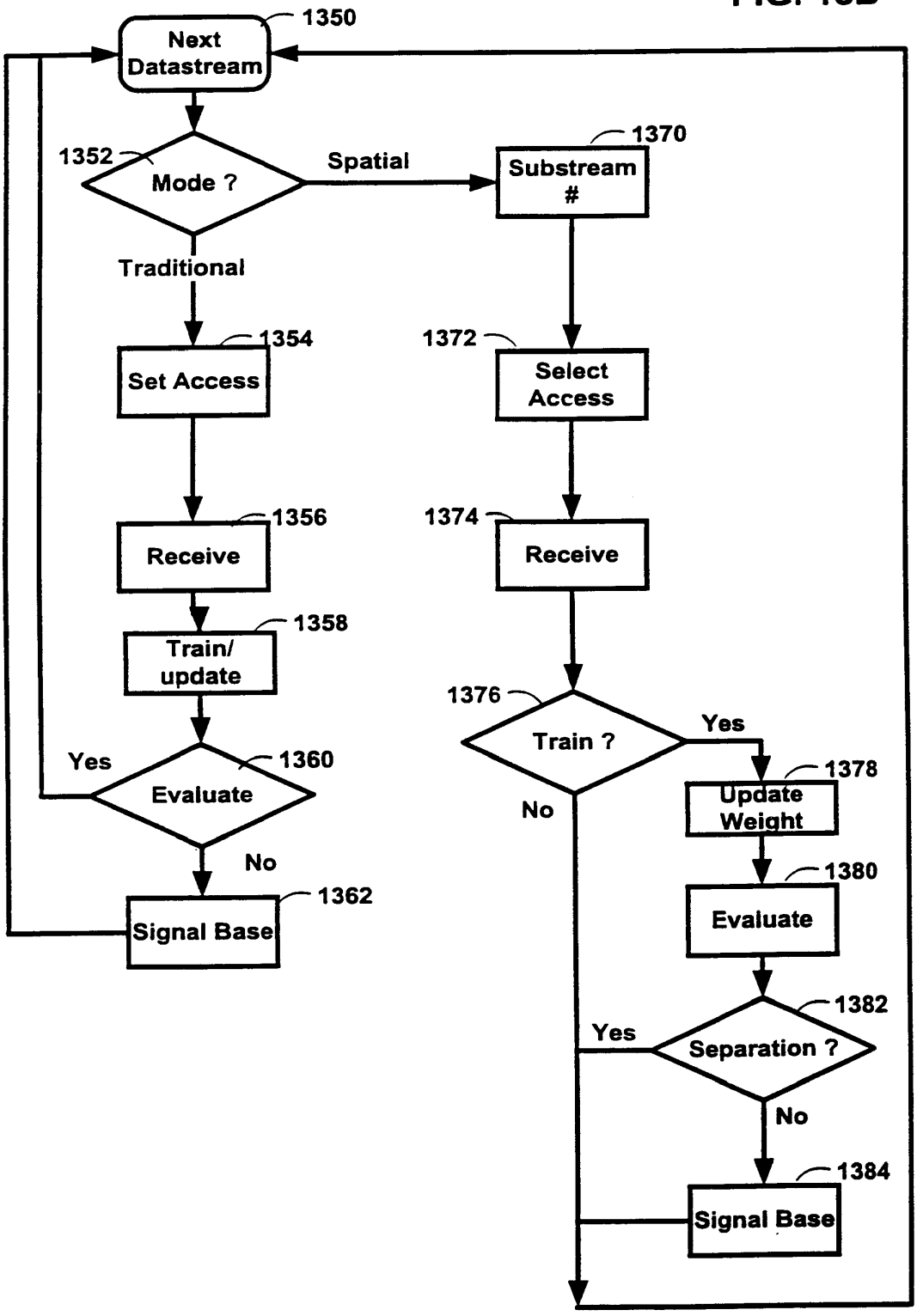
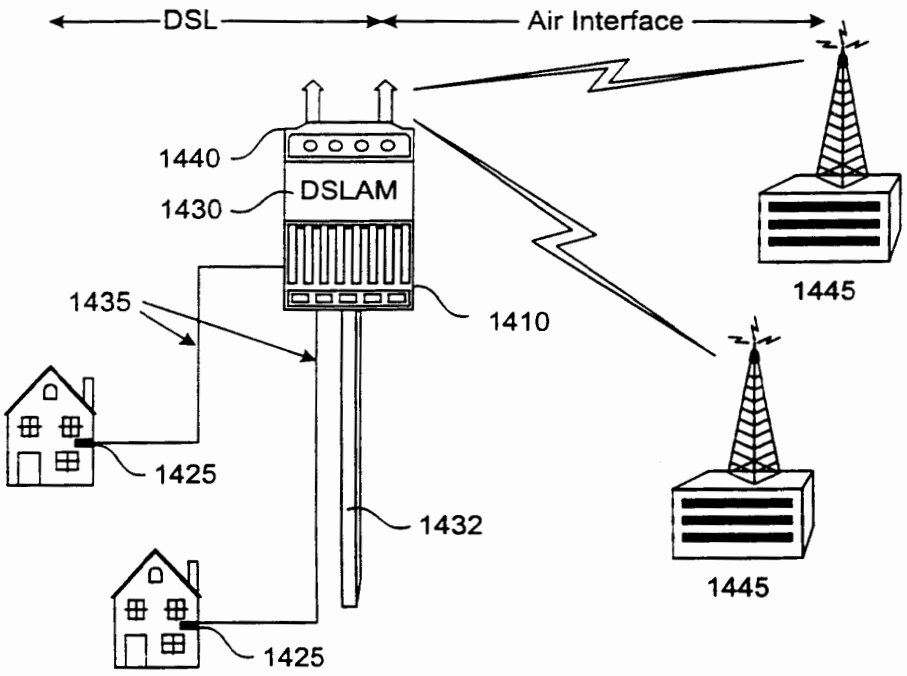

1300
Next Datastream
1302
Mode ?
Spatial
Traditional
1320
Parse
1322
Route
1324
Select Access
1326
Mobile?
No
Yes
1328
Train 1
1330
Train 2
1332
Substream #
1334
Transmit
1336
Separation ?
No
Yes
1338
Handoff ?
No
Yes
1304
Route
1306
Select Access
1308
Transmit
1310
Handoff ?
Yes
No

FIG. 13A

FIG. 13B



SUBSTITUTE SHEET (RULE 26)


DSL
Air Interface
1440
DSLAM
1430
1435
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1445
1425

FIG. 14

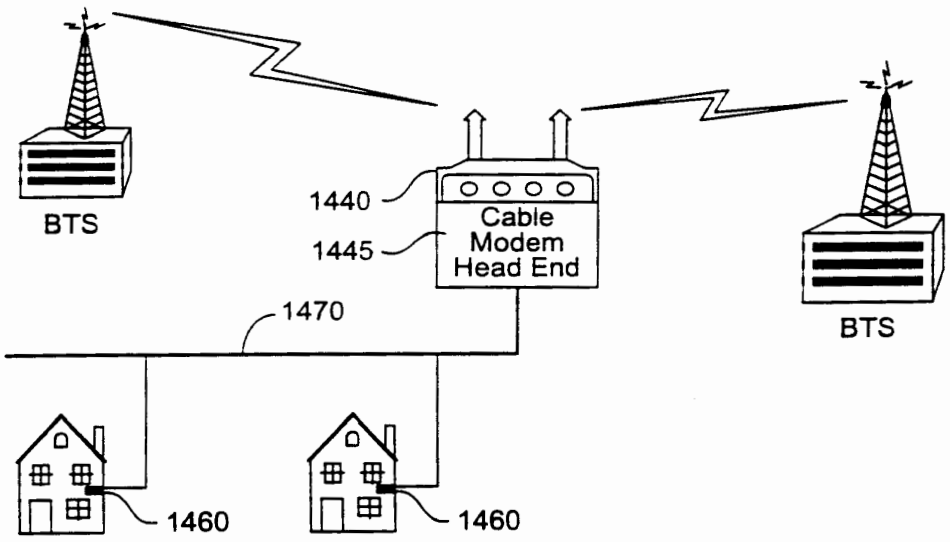

FIG. 15

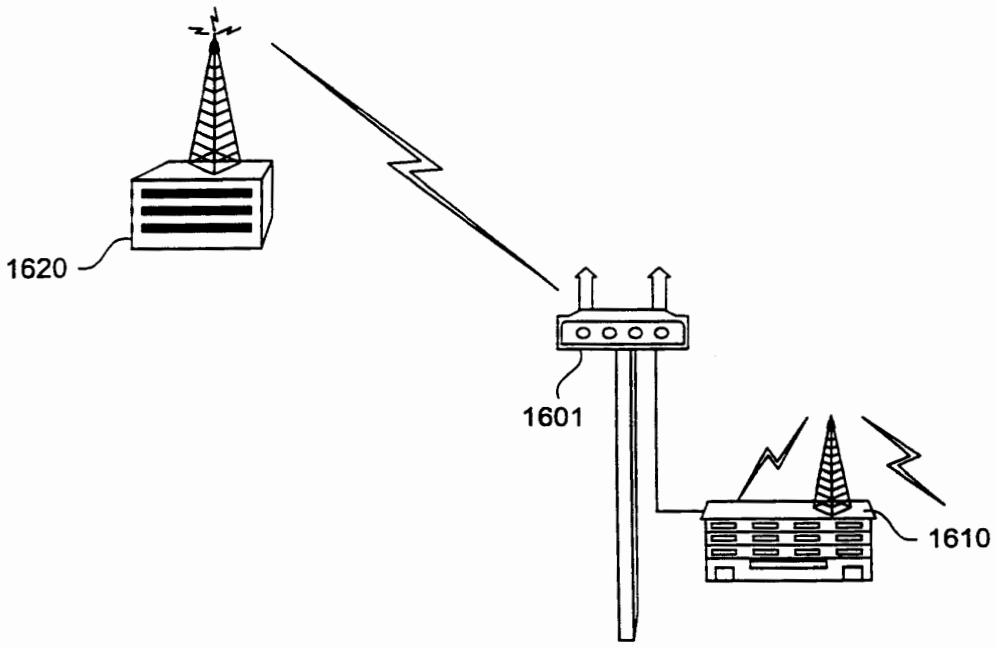

FIG. 16

INTERNATIONAL SEARCH REPORT

Int. ional Application No
PCT/US 00/20706

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q7/36 H04B7/005

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04Q H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PAULRAJ A J ET AL: "TAXONOMY OF SPACE-TIME PROCESSING FOR WIRELESS NETWORKS" IEE PROCEEDINGS: RADAR, SONAR & NAVIGATION,GB,INSTITUTION OF ELECTRICAL ENGINEERS, vol. 145, no. 1, 1 February 1998 (1998-02-01), pages 25-31, XP000769921 ISSN: 1350-2395 page 25, paragraph 2.1 -page 26 page 26, paragraph 2.2.2 -page 27 page 27, paragraph 3.1 page 28, column 1 --- -/--	1-76

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 October 2000	25/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Dheere, R

Form PCT/ISA/210 (second sheet) (July 1992)

Exhibit 1002
Page 0478 of 1285

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/20706

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 98 09381 A (RALEIGH) 5 March 1998 (1998-03-05) page 1, line 14 - line 18 page 2, line 5 -page 3, line 6 page 6, line 5 - line 25 page 7, line 2 - line 17 page 9, line 22 - line 35 page 10 page 11 page 15, line 5 - line 24 page 19, line 5 -page 20, line 15 figure 5A	1-76
A	WO 98 34424 A (AT&T) 6 August 1998 (1998-08-06) page 3, line 8 - line 13 page 5, line 17 - line 21	1,18,26, 27,29, 34,41, 43-45, 54,56, 58-60, 62-67, 69,70
A	US 5 592 490 A (ARRAYCOMM) 7 January 1997 (1997-01-07) column 11, line 10 - line 15 abstract figure 1	1,18,26, 27,29, 34,41, 43-45, 54,56, 58-60, 62-67, 69,70
P,X	US 6 067 290 A (GIGABIT WIRELESS) 23 May 2000 (2000-05-23) the whole document	1-76

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int[illegible]ional Application No
PCT/US 00/20706

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9809381 A	05-03-1998	AU 4238697 A	19-03-1998
		EP 0920738 A	09-06-1999
		EP 0931388 A	28-07-1999
		WO 9809385 A	05-03-1998
		WO 9809395 A	05-03-1998
WO 9834424 A	06-08-1998	US 6052599 A	18-04-2000
		EP 0956722 A	17-11-1999
US 5592490 A	07-01-1997	US 5515378 A	07-05-1996
		US 5546090 A	13-08-1996
		AU 701764 B	04-02-1999
		AU 4595296 A	07-08-1996
		BR 9510197 A	23-12-1997
		CA 2210859 A	25-07-1996
		CN 1173265 A	11-02-1998
		EP 0804858 A	05-11-1997
		FI 973076 A	16-09-1997
		JP 11504169 T	06-04-1999
		WO 9622662 A	25-07-1996
		WO 9818272 A	30-04-1998
		US 5828658 A	27-10-1998
		AT 183865 T	15-09-1999
		AU 670766 B	01-08-1996
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		CA 2125571 A	24-06-1993
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		DE 69229876 T	30-12-1999
		EP 0616742 A	28-09-1994
		EP 0926916 A	30-06-1999
		ES 2137197 T	16-12-1999
		FI 942771 A	10-06-1994
		JP 7505017 T	01-06-1995
		WO 9312590 A	24-06-1993
		US 5625880 A	29-04-1997
		US 5642353 A	24-06-1997
US 6067290 A	23-05-2000	NONE	

Form PCT/ISA/210 (patent family annex) (July 1992)

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

CORRECTED VERSION

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 February 2001 (08.02.2001)

PCT

(10) International Publication Number
WO 01/010156 A1

(51) International Patent Classification[7]: H04Q 7/36, H04B 7/005

(21) International Application Number: PCT/US00/20706

(22) International Filing Date: 28 July 2000 (28.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

09/364,146	30 July 1999 (30.07.1999)	US
09/545,434	7 April 2000 (07.04.2000)	US
09/564,770	3 May 2000 (03.05.2000)	US

(71) Applicant: **IOSPAN WIRELESS, INC.** [US/US]; 3099 N. First Street, San Jose, CA 95134 (US).

(72) Inventors: **PAULRAJ, Arogyaswami, J.**; 59 Peter Coutts Hill, Stanford, CA 94305 (US). **HEATH, Robert, W., Jr.**; 1875 Capistrano Way, Los Altos, CA 94024 (US). **SEBASTIAN, Peroor, K.**; 262 Higdon Avenue, #4, Mountain View, CA 94041 (US). **GESBERT, David, J.**; 180 Beatrice Street, Mountain View, CA 94041 (US). **CHOPRA, Rahul**; 1180 Fewtrell Street, Campbell, CA 95008 (US).

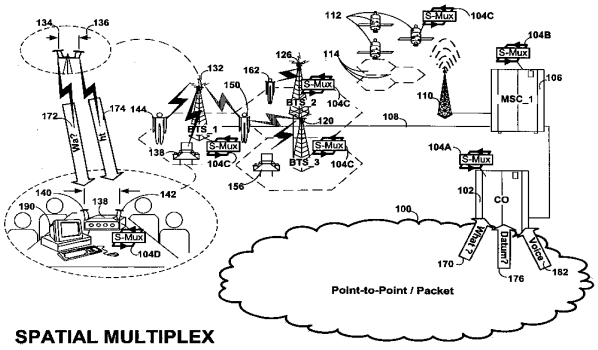
(74) Agent: **VILLENEUVE, Joseph, M.**; Beyer Weaver & Thomas, LLP, P.O. Box 130, Mountain View, CA 94042-0130 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,

[Continued on next page]

(54) Title: SPATIAL MULTIPLEXING IN A CELLULAR NETWORK



SPATIAL MULTIPLEX

(57) Abstract: The present invention provides methods and apparatus for implementing spatial multiplexing in conjunction with the one or more multiple access protocols during the broadcast of information in a wireless network. A wireless cellular network for transmitting subscriber datastream(s) to corresponding ones among a plurality of subscriber units located within the cellular network is disclosed. The wireless cellular network includes base stations and a logic. The base stations each include spatially separate transmitters for transmitting, in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol. The logic assigns an available channel on which to transmit each subscriber datastream. The logic routes at least a substream of each datastream to at least a selected one of the base stations. The logic also generates control signals to configure the at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel. A subscriber unit for use in a cellular system is also disclosed. The subscriber unit includes a plurality of spatially separate antennas and a transmitter for transmitting a plurality of substreams of a datastream on an assigned channel or slot of a multiple access protocol. The transmitter is arranged to apply each substream to an associated one of the spatially separate antennas.

WO 01/010156 A1

IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(48) Date of publication of this corrected version:
6 September 2002

(15) Information about Correction:
see PCT Gazette No. 36/2002 of 6 September 2002, Section II

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

SPATIAL MULTIPLEXING IN A CELLULAR NETWORK

BACKGROUND OF THE INVENTION

1. Field of Invention

The field of the present invention relates in general to the field of wireless broadcast of information using one or more multiple access protocols and in particular to methods and apparatus for implementing spatial multiplexing in conjunction with the one or more multiple access protocols during the broadcast of information.

2. Description of the Related Art

In wireless broadcast systems, information generated by a source is transmitted by wireless means to a plurality of receivers within a particular service area. The transmission of such information requires a finite amount of bandwidth, and in current state of the art transmission of information from different sources, must occur in different channels.

Since there are quite a few services (e.g. television, FM radio, private and public mobile communications, etc.) competing for a finite amount of available spectrum, the amount of spectrum which can be allocated to each channel is severely limited. Innovative means for using the available spectrum more efficiently are of great value. In current state of the art systems, such as cellular telephone or broadcast television, a suitably modulated signal is transmitted from a single base station centrally located in the service area or cell and propagated to receiving stations in the service area surrounding the transmitter. The information transmission rate achievable by such broadcast transmission is constrained by the allocated bandwidth. Due to attenuation suffered by signals in wireless propagation, the same frequency channel can be re-used in a different geographical service area or cell. Allowable interference levels determine the minimum separation between base stations using the same channels. What is needed is a way to improve data transfer speed in the

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

multiple access environments currently utilized for wireless communications within the constraints of available bandwidth.

SUMMARY OF THE INVENTION

The present invention provides methods and apparatus for implementing spatial multiplexing in wireless networks such as cellular networks. In various embodiments unique network configuration, base stations and remote (subscriber) units are described. A wide variety of different applications of spatial multiplexing are also described.

In some embodiments the wireless cellular network includes base stations having spatially separate transmitters for transmitting in response to control signals and selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol. From the standpoint of the network, the spatially separate transmitters can be located at a single base station or may be located on multiple base stations. Logic assigns an available channel on which to transmit each subscriber datastream. The logic routes at least a substream of each datastream to at least a selected one of the base stations. The logic also generates control signals to configure at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel. Appropriate receivers are also described.

In other embodiments of the invention, subscriber units for use in cellular systems are disclosed. The subscriber units typically will have both spatially separate transmitters and receivers, although that is not a fixed requirement. In some embodiments subscriber unit includes spatially separate receivers, a spatial processor, and a combiner. The spatially separate receivers receive the assigned channel composite signals resulting from the spatially separate transmission of the subscriber downlink datastream(s). The spatial processor is configurable in response to a control signal transmitted by the base station to separate the composite signals into estimated substreams based on information obtained during the transmission of known data patterns from at least one of the base stations or by using blind training techniques. The spatial processor signals the base stations when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

downlink datastream(s). The combiner combines the estimated substreams into a corresponding subscriber datastream.

Exhibit 1002
Page 0485 of 1285

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will become more apparent to those skilled in the art from the following detailed description in conjunction with the appended drawings in which:

FIG. 1 shows a wireless cellular network incorporating spatial multiplexing and multiple access according to the current invention.

FIG. 1B is a detailed view of selected cells within the cellular network shown in FIG. 1A.

FIG. 1C shows a cell architecture that provides overlapping regions suitable for multi-base spatial multiplexing.

FIGS. 2A-G show alternate embodiments for the subscriber units utilized in the wireless cellular network shown in FIGS. 1A-B.

FIG. 3A shows a detailed hardware block diagram of a single base station and subscriber unit for use in the wireless cellular network shown in FIGS. 1A-B.

FIG. 3B shows a detailed hardware block diagram of a single base station and subscriber unit as in Fig. 3A, wherein the subscriber unit interfaces with a local area network.

FIGS. 4A-J show detailed hardware block diagrams of the multiple access hardware for controlling the transmission of subscriber datastream(s) from one or more of the base stations within the wireless network.

FIGS. 5A-B show detailed hardware block diagrams of the hardware associated with the receipt of multiple subscriber datastream(s) at the base stations of the wireless network of the current invention.

FIG. 6 shows a detailed view of the signals and the symbols associated with the transmission and receipt of spatially multiplexed signals according to an embodiment of the current invention.

FIGS. 7A-B show detailed hardware block diagrams of the configurable spatial processor associated with the receiver circuitry receiver, according to an embodiment of the current invention.

Exhibit 1002
Page 0486 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIGS. 7C-D show detailed hardware block diagrams of a configurable space and space-time processor associated with the configurable spatial receiver according to an embodiment of the current invention.

FIG. 8 shows in-band training and data signals for calibrating the spatially configurable receiver during the transmission of spatially multiplexed data, according to an embodiment of the current invention.

FIGS. 9A-B are respectively detailed hardware block diagrams of a spatially multiplexed transmitter and receiver implementing a time-division multiple access protocol (TDMA), according to an embodiment of the current invention.

FIGS. 10A-B are respectively detailed hardware block diagrams of a spatially multiplexed transmitter and receiver implementing a frequency-division multiple access protocol (FDMA), according to an embodiment of the current invention.

FIGS. 11A-B are respectively detailed hardware block diagrams of a spatially multiplexed transmitter and receiver implementing a code-division multiple access protocol (CDMA), according to an embodiment of the current invention.

FIGS. 12A-B are respectively detailed hardware block diagrams of a spatially multiplexed transmitter and receiver implementing a space-division multiple access protocol (SDMA), according to an embodiment of the current invention.

FIGS. 13A-B are process flow diagrams showing the acts associated with respectively the spatially multiplexed transmission and reception of datastream(s) in any one of a number of multiple access protocols, according to an embodiment of the invention.

FIG. 14 is a diagrammatic illustration of a hybrid DSL/wireless link that incorporates a spatially multiplexed remote wireless device.

FIG. 15 is a diagrammatic illustration of a hybrid cable/wireless link that incorporates a spatially multiplexed remote wireless device in a network access unit.

FIG. 16 is a diagrammatic illustration of a repeater BTS that utilizes a spatially multiplexed remote wireless device.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Exhibit 1002
Page 0487 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

A method and apparatus is disclosed which allows for both spatial multiplexed and non-spatial wireless communications between portable units and corresponding selected ones among a plurality of base stations. The methods and apparatus of the current invention may be implemented on a dedicated wireless infrastructure or may be superimposed on existing wireless communications systems, such as cellular telephone and paging services, which are currently in place around the world. The methods and apparatus include implementation in any of a number of multiple access protocols.

Spatial Multiplexing and Multiple Access

Spatial multiplexing (SM) is a transmission technology which exploits multiple antennas at both the base station(s) and at the subscriber units to increase the bit rate in a wireless radio link with no additional power or bandwidth consumption. Under certain conditions, spatial multiplexing offers a linear increase in spectrum efficiency with the number of antennas. Assuming, for example, N=3 antennas are used at the transmitter and receiver, the stream of possibly coded information symbols is split into three independent substreams. These substreams occupy the same channel of a multiple access (MA) protocol, the same time slot in a time-division multiple access (TDMA) protocol, the same frequency slot in frequency-division multiple access (FDMA) protocol, the same code/key sequence in code-division multiple access (CDMA) protocol or the same spatial target location in space-division multiple access (SDMA) protocol. The substreams are applied separately to the N transmit antennas and launched into the radio channel. Due to the presence of various scattering objects (buildings, cars, hills, etc.) in the environment, each signal experiences multipath propagation. The composite signals resulting from the transmission are finally captured by an array of receive antennas with random phase and amplitudes. For every substream the set of N received phases and N received amplitudes constitute its spatial signature.

At the receive array, the spatial signature of each of the N signals is estimated. Based on this information, a signal processing technique is then applied to separate the signals, recover the original substreams and finally merge the symbols back together. Linear or nonlinear receivers can be used providing a range of performance and complexity trade-offs. A linear spatial multiplexing receiver can be viewed as a

bank of superposed spatial weighting filters, where every filter aims at extracting one of the multiplexed substreams by spatially nulling the remaining ones. This assumes, of course, that the substreams have different signatures.

If the transmitter is equipped with M antennas, while the receiver has N antennas, the rate improvement factor allowed by spatial multiplexing is the minimum of these two numbers. Additional antennas on the transmit or receive side are then used for diversity purposes and further improve the link reliability by improving, for example, the signal-to-noise ratio or allowing for smaller fading margins, etc. Effectively spatial multiplexing allows a transmitter receiver pair to communicate in parallel through a single MA channel, hence allowing for a possible N-fold improvement of the link speed. More improvement is actually obtained if we take into account the diversity gain offered by the multiple antennas (for instance, in a Raleigh fading channel). Such performance factors are derived ideally under the assumption that the spatial signatures of the substreams are truly independent from each other. In reality, the level of independence between the signatures will determine the actual link performance. The performance, however, usually exceeds that obtained by a single antenna at the transmitter and receiver. For example, at two GHz, assuming the base station and the subscriber unit are spaced apart by one mile and using three antennas at each end of the link, a scattering radius of about 30 feet (both ends) is enough to achieve maximum performance.

FIG. 1A shows a plurality of subscriber units wirelessly coupled over a cellular network to a network 100. Network 100 may include: a local area network (LAN), a wide area network (WAN), a public switched telephone network (PSTN), Public Land Mobile Network (PLMN), an adhoc network, a virtual private network, an intranet or the internet. The wireless system includes: a central office (CO) 102, a master switch center (MSC) 106, a ground based relay station 110, satellites (112), base stations 120, 126 and 132 (BTS) and subscriber units 156, 138, 144, 150 and 162. The subscriber units may be mobile, fixed or portable. The base stations may be fixed or mobile. The base stations may include: a tower, satellites, balloons, planes, etc. The base station may be located indoors/outdoors. The cellular network includes one or more base stations, where each base station includes one or more spatially separate transmitters.

The central office 102 is coupled to the network 100. Network 100 may be circuit switched (e.g. point-to-point) or packet switched network. The central office is coupled to a master switching center 106. The MSC in traditional cellular systems is alternately identified as: a mobile telephone switching office (MTSO) by Bell Labs, an electronic mobile Xchange (EMX) by Motorola, an AEX by Ericcson, NEAX by NEC, a switching mobile center (SMC) and a master mobile center (MMC) by Novatel. The MSC is coupled via data/control line 108 to the satellites via relay station 110 and to the base stations. In an alternate embodiment of the invention, base station controllers (BSC) may serve as intermediary coupling points between the MSC and the base stations. In the embodiment shown, each of the BTS includes an array of spatially separate antennas for transmission and/or reception. The BTS may also include traditional antenna for whichever of the receive/transmit side of its communication capability lacks spatially separate antenna and associated circuitry. Antennas of a transmitter/receiver are defined to be spatially separate if they are capable of transmitting/receiving spatially separate signals. Physically separate antenna may be used to transmit/receive spatially separate signals. Additionally, a single antenna may be used to transmit/receive spatially separate signals provided it includes the ability to transmit/receive orthogonal radiation patterns. Hereinafter, the phrase "spatially separate" shall be understood to include any antenna or transmitter or receiver capable of communicating spatially separate signals. The base stations are configured to communicate with subscriber units of a traditional type, i.e. those lacking either spatially separate transmission/reception as well as spatially enabled subscriber units, i.e. those including either or both spatially separate reception and transmission capabilities.

In operation, distinct subscriber datastream(s) 170, 176 and 182 are received by CO 102. The CO performs the initial routing of the data streams to the appropriate one of a plurality of MSCs which may be located across the country. The MSC performs several functions. It controls the switching between the PSTN or network 100 and the BTSs for all wireline-to-subscriber, subscriber-to-wireline and subscriber-to-subscriber calls. It processes/logic data received from BTSs concerning subscriber unit status, diagnostic data and bill compiling information. In an embodiment of the invention, the MSC communicates with the base stations and/or satellites with a datalink using the X.25 protocol or IP protocol. The MSC also implements a portion

of the spatial multiplexing and multiple access processes/logic (SM_MA) 104B of the current invention. Each BTS operates under the direction of the MSC. The BTS and satellites 112 manage the channels at the site, supervise calls, turn the transmitter/receiver on/off, inject data onto the control and user channels and perform diagnostic tests on the cell-site equipment. Each BTS and satellite also implement a portion of the SM_MA processes/logic 104C. The subscriber units may be both traditional and spatially enabled and may still communicate over the system. Those subscriber units that are spatially enabled on either/both the transmit/receive side of communications implement SM_MA processes/logic 104D as well.

The SM_MA processes/logic allow high bit rate communications with any of the SM_MA enabled subscriber units within existing bandwidth constraints and within any of the multiple access (MA) protocols common to wireless communications or combinations thereof. Those MA protocols include: time-division multiple access (TDMA), frequency-division multiple access (FDMA), code-division multiple access (CDMA), space-division multiple access (SDMA) and many other multiple access protocols known to those skilled in the art. The SM_MA processes/logic include the ability to selectively allocate spatially separate downlink or uplink capability to any spatially enabled subscriber within a multiple access environment. This capability allows, as to that subscriber, the elevation of bit rates well above those currently available. Thus, a whole new range of subscribers can be anticipated to take advantage of this capability. Utilizing this invention, it will be possible to provide a wireless medium for connecting workstations, servers and tele-video conferences using the existing cellular infrastructure with the adaptations provided by this invention. The SM_MA processes/logic involve splitting subscriber datastream(s) destined for spatial multiplexing into substreams and intelligently routing and re-routing the substreams during a call session so as to maintain consistent quality of service (QoS). The substreams are communicated on the same channel using the same access protocol, thus not requiring additional resources or bandwidth to implement. The processes/logic include: access protocol assignment, channel assignment, monitoring of spatial separation, determination/re-determination of spatial signatures for each communication link, routing/re-routing between single-BTS and multi-BTS, handoff and control of substream parsing/combining.

Exhibit 1002
Page 0491 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

In FIG. 1A, datastream(s) 170, 176 and 182 are shown originating on network 100. The SM_MA processes/logic 104 have parsed and routed subscriber data stream 170 into substreams 172-174, which are transmitted on a single channel of a multiple access protocol over the spatially separate antenna 134-136 of BTS 132. Subscriber unit 138, via spatially separate antenna 140-142, receives composite signals 172-174 resulting from the substream transmission and utilizing SM_MA processes/logic 104D, derives the substream and original datastream 170 therefrom. In the embodiment shown, the data is delivered to the computer 190 to which the fixed subscriber desktop unit 138 is coupled. The cellular environment may also be implemented utilizing aerial equivalents of the base stations. In the embodiment shown, a plurality of satellites 112 generally deliver subscriber datastream(s) via spatially separate antennae on each of the satellites to a cellular network, i.e. 114.

In a circuit-switched embodiment of the invention, a call over a cellular network may require using two channels simultaneously; one called the user channel and one called the control channel. The BTS(s) transmit and receive on what is called a forward/downlink control channel and the forward/downlink voice/data channel and the subscriber unit transmit/receive on the reverse/ uplink control and voice/data channels. Completing a call within a cellular radio system is quite similar to the PSTN. When a subscriber unit is first turned on, it performs a series of startup procedures and then samples the received signal strength on all user channels. The unit automatically tunes to the channel with the strongest receive signal strength and synchronizes to the control data transmitted by the BTS(s). The subscriber unit interprets the data and continues monitoring the controlled channels. The subscriber unit automatically re-scans periodically to ensure that it is using the best control channel. Within a cellular system, calls can take place between a wireline party and a subscriber unit or between two subscriber units. For wireline-to-subscriber unit calls, the MSC receives a call from either a wireline party or in the form of a call setup packet from the network 100. The MSC determines whether the subscriber unit to which the call is destined is on/off hook. If the subscriber unit is available, the MSC directs the appropriate BTS to page the subscriber unit. The subscriber unit responds to the BTS indicating its availability and spatial multiplexing capabilities, receive and/or transmit. Following the page response from the subscriber unit, the MSC/BTS switch assigns an idle channel, configures spatial processing capability on both the

subscriber unit and BTS(s) if appropriate, and instructs the subscriber unit to tune to that channel. The subscriber unit sends a verification of channel tuning to the BTS(s) and then sends an audible call progress tone to the subscriber I/O unit causing it to ring. The switch terminates the call progress tone when it receives positive indication the subscriber has answered and the conversation or communication has begun.

Calls between two subscriber units are also possible in the cellular radio system. To originate a call to another subscriber unit, the calling party enters the called number into the unit's memory via the touch pad and then presses the send key. The MSC receives the caller's identification number and the called number then determines if the called unit is free to receive the call. The MSC switch sends a page command to all base stations and the called party, who may be anywhere in the service area, receives the page. The MSC determines the spatial multiplexing capability of both subscribers. Following a positive page from the called party, the switch assigns each party an idle user channel and instructs each party to tune into that respective channel. Then the called party's phone rings. When the system receives notice the called party has answered the phone, the switch terminates the call progress tone and a communication can begin between two subscriber units. If spatial multiplexing is enabled, the communication link will include that capability.

One of the most important features of the cellular system is its ability to transfer calls that are already in progress from one cell site/base station to another as a subscriber unit moves from cell to cell or coverage area to coverage area within the cellular network. This transfer process is called a handoff. Computers at the BTS transfer calls from cell to cell with minimal disruption and no degradation in quality of transmission. The handoff decision algorithm is based on variations in signal strength. When a call is in progress, the MSC monitors the received signal strength of each user channel. If the signal level on an occupied channel drops below a predetermined threshold for more than a given time interval, the switch performs a handoff provided there is a vacant channel. In a traditional non-SM cellular system a traditional handoff involves switching the transmission point of a subscriber session (datastream) from one BTS to another. In the current invention various types of handoff, e.g. partial and full may take place. The handoff operation may involve the MSC re-routing the call and the entire datastream or selected substreams thereof to different antennas of the same BTS or to a new BTS/BTSs in whole or in part. Where

the re-routing is partial, at least one substream communication path is left unchanged while other of the substreams are re-routed to antennas on another BTSs. Where the handoff is full the multiple substreams transmitted from one or more BTSs are re-routed to other BTS(s).

In an embodiment of the invention utilizing a packet switched architecture, call setup may be implemented using protocols including: ALOHA, slotted-ALOHA, carrier sense multiple access (CSMA), TDMA, FDMA, CDMA, SDMA, etc., or any combination thereof.

BTS 132, in the embodiment shown, includes spatially separate antenna array. There may be any number of antennas. In some spatial environments, baud rates for spatially multiplexed communications on a single channel will increase linearly with the number of antennas allocated by subscriber unit and BTSs to a call session. In the embodiment shown, each BTSs array includes at least two antennas 134 and 136. The BTS may include either or both spatial multiplexing capability on the downlink (transmit) or uplink (receive) side. In the embodiment shown, each BTS includes spatial multiplexing capability on both the downlink and uplink. Although each of the following embodiments utilizes two antennas to implement SM, any number of antennas on a single BTS or multiple BTSs may be utilized without departing from the scope of the invention.

FIG. 1B shows a more detailed view of the BTS and subscriber units shown in FIG. 1A. Each BTS includes two spatially separate antennas. BTS 120 includes antennas 122-124. BTS 126 includes antennas 128-130. BTS 132 includes antennas 134-136. In the embodiment shown, many of the subscriber units also include at least two spatially separate antennas. Subscriber unit 150 includes spatially separate antennas 152-154. In the embodiment shown, the MSC handles the routing of subscriber datastream(s) 170, 176 and 182 from network 100 to the appropriate BTSs for transmission to the appropriate subscriber unit. In an embodiment of the invention, the SM_MA processes/logic include the ability to determine whether to implement or not implement spatial multiplexing (SM), based on either the presence/absence of SM capabilities in the corresponding subscriber unit and/or on the nature of the datastream. If, for example, the subscriber lacks SM capability on either or both the uplink/downlink, then the corresponding datastream will not be

Exhibit 1002
Page 0494 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

parsed into substreams. Alternately, even if the subscriber unit and BTS have SM capability on both downlink and uplink, certain types of datastream(s) may not require SM processing. Examples of these might include: traditional voice call sessions, call sessions which require only low QoS or datastream(s) which require only very low bit rates or are susceptible to buffering and delayed transmission.

In the example shown in FIG. 1B, datastream 182 is traditional mode traffic, e.g. a subscriber telephone call between an upstream subscriber and the subscriber unit 144. Subscriber unit 144 is located within a cell serviced by BTS 132. Under the control of MSC 106, the datastream 182 is transmitted over signal line 108 directly to the corresponding base station 132 without being split or parsed into associated substreams. In the example shown, datastream(s)182 is transmitted from a single antenna, e.g. antenna 134, without any SM techniques. That transmission is received by the subscriber unit 144. As discussed above, subscriber unit 144 may be a traditional cell phone lacking SM capability. Alternately, subscriber unit 144 may be SM enabled but, nevertheless, receives the call in traditional mode after appropriately configuring itself to opt out of SM receive side processes/logic, electing instead traditional mode.

In the example shown, datastream(s) 170 is handled using SM_MA processes/logic 104_. The datastream 170 and/or substreams thereof, depending on the embodiment, is routed by the MSC to BTS 132. The processes/logic 104 provide to each antenna 134-136 of BTS 132 a single substream derived from the original datastream 170, on a common channel within the appropriate access protocol. Those substreams are received as composite signals by the spatially separate antenna 140-142 (see FIG. 2B) of subscriber unit 138. The subscriber unit 138, utilizing SM-MA processes/logic 104D, derives the substreams from the composite signals and combines these into the initially transmitted datastream(s) 170.

Datastream(s) 176 is also subject to SM_MA processes/logic 104_. The datastream 176 and/or substreams thereof, depending on the embodiment, is routed by the MSC, initially to BTS 132 for single-base transmission to subscriber unit 150. SM-MA processes/logic implemented collectively at the MSC 106 and BTS 132 result in the splitting/parsing of the datastream(s) 176 into substreams 178-180. Initially those substreams are received as composite signals by the spatially separate

antenna 152-154 (see FIG. 2C) of subscriber unit 150. The subscriber unit 150, utilizing SM_MA processes/logic 104D, derives the substreams from the composite signals and combines these into the initially transmitted datastream(s) 176.

Implementing SM or SM_MA communications between the BTS and the associated subscriber unit may be either line-of-site (LOS) or multipath. Multipath communications are likely in environments, such as a city, where buildings and other objects deflect signals transmitted from the BTS many times before their arrival at the subscriber unit. Under certain conditions, it may be the case that transmissions originating from spatially separate antennas of a single BTS may arrive at a subscriber unit along signal paths which cannot be spatially separated by the antenna array on the subscriber unit. Where this is the case, it may be necessary for the processes/logic to reconfigure the spatial transmission characteristics of the substreams so that they may be received at the corresponding portable unit in a manner which is spatially separable. In the example shown, the substreams 180 and 178_S are transmitted initially from a single BTS 132. When a determination is made, either by the BTS or subscriber unit that separation of the substreams is not possible, a spatial reconfiguration is initiated by the spatial multiplexing processes/logic 104. The determination might, for example, result from the subscriber unit signaling the BTS or from the BTS determining that the bit error rate (BER) of the transmission exceeded an acceptable level. In an alternate embodiment of the invention in which base and subscriber communicate over a common channel, the signaling from the subscriber to the base station(s) for a change of a spatial transmission configuration is simplified. The BTS may, by analyzing the received signals, determine that they can not be adequately separated and in response, alter the spatial configuration of the transmissions to the subscriber unit with which it shares a channel. In the example shown, this reconfiguration results in a change of spatial configuration to multi-base transmission. Substream 178_M is re-routed through BTS 120 and specifically antenna 122. Because subscriber unit 150 is positioned in an area in which the transmissions from BTS 120 and 132 overlap, the change in spatial configuration is possible. The increased spatial separation on the transmit side increases likelihood that the substreams can be spatially separated by the subscriber unit 150 and its associated SM-MA processes/logic 104D.

Exhibit 1002
Page 0496 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 1C shows another embodiment of the current invention in which a cell architecture which provides overlapping regions suitable for multi-base spatial multiplexing is shown. As in normal cellular structure, co-channel interference is avoided by ensuring that cells operating in the same frequency are spaced apart. In the example shown, BTSs 186A-C form an overlapping region between them in which they are shown in spatially multiplexed communication with subscriber unit 138. BTSs 186C-E form an overlapping region between them, in which they are shown in spatially multiplexed communication with subscriber unit 150A. BTSs 186C, F-G also form an overlapping region between them, in which they are shown in spatially multiplexed communication with subscriber unit 150B. The communications with subscriber units 138, 150A-B are conducted on separate channels to avoid co-channel interference. Diversity techniques can be simultaneously implemented. More distant cells may re-use the same channels provided co-channel interference is tolerable.

FIGS. 2A-G show alternate embodiments of subscriber units which may be either fixed, portable or mobile. FIG. 2A shows a mobile cellular phone 144 with a single antenna 146. In an embodiment of the invention, the single antenna includes the capability of transmitting and/or receiving spatially separable signals utilizing orthogonal di-poles. In an alternate embodiment of the invention, subscriber unit 144 is a traditional cellular phone which does not have the capability of transmitting/receiving a spatially separable signal. Either embodiment may be compatible with the system shown in FIGS. 1A-B, provided that system includes an embodiment of the invention with the ability to detect the transceiver capabilities of the subscriber units and to configure communications between that unit and the corresponding BTS accordingly.

FIG. 2B shows a fixed subscriber unit 138 coupled to a computer 190. In this embodiment, high-speed data communications between computer 190 and a wireless communication network with spatial multiplexing capabilities is enabled by fixed subscriber unit 138. Fixed subscriber unit 138 is shown with an antenna array including antennas 140-142. In the embodiment shown, additional antennas are provided. These may be utilized either for spatial multiplexing or to implement receive/transmit processing, e.g. diversity techniques, beam forming, interference cancellation, etc., the latter for the purpose of improving communication quality and

Exhibit 1002
Page 0497 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

link budget. The current state of the art requires a minimum separation between antennas 140-142, i.e. D1 equivalent to 1/2 the carrier wavelength. Further improvements in signal processing may avoid this requirement.

FIG. 2C shows a mobile subscriber unit, i.e. a cellular telephone 150, reconfigured for implementation of SM or SM_MA on either or both of the transmit (uplink) or receive (downlink) side of its communication with the BTSs. To this end, the antennas 152-154 are provided.

FIG. 2D shows a personal digital assistant (PDA) 200 and associated docking station 202 configured to implement SM or SM_MA communications on either or both the transmit and receive portions of its communications. To this end, the antenna array, which in the embodiment shown, includes two antennas 204-206 is provided. An example of personal digital assistants currently on the market that could be configured to utilize the current invention is the Palm Pilot ™ product sold by 3Com Corporation.

FIG. 2E shows a mobile subscriber unit 210 implemented as part of an automobile 216. The antenna array associated with this unit is not shown. The use of SM or SM_MA wireless communications between vehicles and base stations can provide such benefits as vehicle navigation, routing, and diagnostics.

FIG. 2F shows a notebook computer 220 configured for SM or SM_MA communication utilizing an antenna array with antennas 222-224 and associated hardware and processes/logic.

FIG. 2G shows a fixed subscriber unit 138 incorporated into a wireless router or bridge 235, which is coupled to a wired network 240. In this embodiment, the subscriber unit 138 serves as a high speed wireless connection between the wired network and the wireless communication network. The network 240 can take any suitable form including a local area network, a wide area network, an intranet, etc. It should be appreciated that in this arrangement, a wireless link is simply being used to connect two networks and such wireless links can be used in a wide variety of applications. For example, the wireless link can be used to provide high speed Internet access to the network 240. In the embodiment shown, the fixed subscriber unit 138 is shown as being incorporated into a router or bridge 235. However, it should be appreciated that the subscriber unit can readily be incorporated into a

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

variety of network components having a variety of functionalities. For example, the router or bridge can further include firewall capabilities, etc.

FIG. 3A is a detailed hardware block diagram of a subscriber unit 138 and a BTS 132. The BTS 132 includes: a multiple access spatial transmitter 310, a multiple access spatial receiver 330, a controller module 320 and upstream processes/logic 300, further details of which are provided in the accompanying FIGS. 4-5. The subscriber unit 138 includes: a multiple access spatially configured receiver 380, a multiple access spatially configured transmitter 350 and a control unit 370. The multiple access spatial transmitter 310 includes: a selector 312, a final transmission stage 316 and optionally may include transmit processes/logic 314. The final stage transmitter 316 is coupled to a spatially separate antenna array which includes antennas 134T-136T.

In operation, the subscriber datastream(s) and/or substreams thereof are provided to the selector 312 from the upstream processes/logic 300. Utilizing either in band or out of band control signals embodied in the datastream(s)/substreams themselves or separately communicated from the SM_MA processes/logic at the MSC 106 or elsewhere, the selector implements the MA protocol utilized by the wireless network. That protocol, as discussed above, may include: TDMA, FDMA, CDMA or SDMA, for example. The selector places each of the datastream(s)/substreams on the appropriate channel. Each of the datastream(s)/substreams are then passed through the optional transmit processes/logic, in which any of a number of well-known prior art signal processing techniques may be implemented to improve the quality of transmission. These techniques include, but are not limited to, diversity processing, space coding, space-time coding, space-frequency coding, and beam forming and interference canceling. The datastream(s)/substreams are then passed to the final transmit stage 316. Traditional mode traffic may be routed by the SM_MA processes/logic 104 to the appropriate antenna 134T-136T for transmission. If diversity processing is implemented, even traditional mode traffic may be transmitted using multiple antennas. Spatial mode traffic, i.e. the individual substreams thereof, will be routed to the appropriate one of the two antennas 134T-136T.

On the receive side, the subscriber unit SM_MA configurable receiver 380 includes: receiver first stage 382, optional receive processes/logic 384, spatial/space-

Exhibit 1002
Page 0499 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

time processor 386, decoder 388, combiner 390 and I/O module 392. The receiver first stage is coupled to a spatially separate antenna array, e.g. antennas 140R-142R. Utilizing in/out of band control signals, the SM_MA configurable receiver 380 of the subscriber unit 138, in the embodiment shown, may be configured for spatial/traditional mode signal reception on the requisite channel within the multiple access protocol. In the case of spatial mode communications, the antenna array, e.g. antennas 140R-142R, detect downlink composite signals derived from the spatially separate transmission of the substreams through antennas 134T-136T. These composite signals are down converted, demodulated and sampled by the receiver first stage 382. The composite signals are then passed to the receive processing module 384 and may be subject to receive side processing if implemented. From the receive processing module, the composite signals are passed to the spatial processor 386. The spatial/space-time processor via in/out band control signals is also configured to derive the appropriate number of substreams, i.e. equivalent to the number transmitted, from the BTS(s). Utilizing logic associated with space/space-time processing (see FIGS. 7A-D), that processor, in conjunction with decoder 388, generates estimated source substreams which are passed to the combiner 390. The combiner 390 via in/out band control signals is also configured to combine the substreams into an estimated subscriber datastream(s) corresponding to that transmitted from the BTS 132. The datastream(s) are passed to the I/O module for presentment/delivery as, e.g., audio, image or data. Where communications are asymmetric, the uplink may, in an embodiment of the invention, not include SM capability, leaving that capability to the downlink alone. This asymmetric capability may be implemented on either the downlink or the uplink without departing from the scope of this invention.

The uplink from the subscriber unit 138 to the BTS 132 may use the same or different hardware/firmware/processes/logic to that utilized for the downlink. In an embodiment of the invention, the uplink is traditional with no SM_MA capability. In the embodiment shown in FIG. 3A, the uplink includes both SM and MA processes/logic. The datastream(s) received by the I/O module 352 are passed to parser 354. In an embodiment of the invention, the parser is configurable to generate a traditional datastream or a variable number of substreams thereof. In another embodiment of the invention, the parser parses all datastream(s) into a fixed number

of substreams. Where there are no SM uplink capabilities there is no parser. In other embodiments of the invention, the configurable parser also includes a mode detector to determine whether the datastream(s) should be split into substreams. That determination, as discussed above, may be based on any number of criteria including, but not limited to, traditional vs. spatial mode, QoS, bit rate requirement, feasibility, etc. In such an embodiment, when the mode detector determines that spatial mode transmission of the datastream is appropriate, the parser will split the datastream(s) into a plurality of substreams, the number of which may itself be configurable. These substreams are then passed to the selector 356. The selector responsive to in/out of band control signals implements the appropriate access protocol, including the placement of the datastream(s) and/or substreams onto the appropriate channel within that protocol. The datastream(s) and/or substreams thereof are then optionally passed to transmit processes/logic 358, which may implement any number of well-known prior art signal processing techniques, including the above discussed diversity methodology, to improve signal reception. The substreams and/or datastream(s) are then passed to the final transmit stage 360 where they are encoded, modulated, and up-converted for transmission on a single channel through spatially separate transmit antennas 140T-142T. Composite signals corresponding thereto are received by antennas 134R-136R of the SM_MA configurable receiver 330 of the BTS.

As discussed above, where the uplink is asymmetric, the BTS may not implement or require SM on the uplink. Nevertheless, in the embodiment shown, the receiver 330 is SM_MA configurable. The receiver 330 includes a first stage receiver 332, mobility detector 334, receive processes/logic 336, spatial/space-time processor 338 and a decoder 340. The composite signals are passed by antennas 134 R-136 R to the first stage receiver. This is configurable to receive the communications on the appropriate channel within the MA protocol as determined by SM_MA processes/logic 104. These composite signals are down-converted/demodulated and sampled. In an embodiment of the invention, the mobility detector 334 monitors the composite signals for Doppler shift/spread. Doppler shift/spread of the composite signals correlates with the mobility or lack thereof of the subscriber unit. The absence of a Doppler shift/spread indicates that the subscriber unit is fixed. This determination on the part of the mobility detector may be used to initiate one or more of the following processes/logic: spatial reconfiguration, training/retraining of the

Exhibit 1002
Page 0501 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

spatial/space-time processors and/or handoff. In an embodiment of the invention in which non-blind in band training is implemented, training/retraining may include varying the training interval or duration or selection of a different training sequence. The composite signals are then passed to the optional receiver processes/logic 336. These processes/logic, as described above, may include any of a number of well-known techniques including diversity processing. The composite signals are then passed to the configurable space/space-time processor 338. Utilizing in/out of band control signals from the MSC and/or the subscriber unit, the space/space-time processor configures itself to generate a number of substreams or a single datastream(s) equivalent to those transmitted from the corresponding subscriber unit. These estimated subscriber substreams/datastream(s) are then passed to the decoder 340. The decoder decodes the symbols to their corresponding binary equivalent. The datastream(s) and/or substreams are then passed to upstream processes/logic 300.

Both the subscriber unit 138 and the BTS 132 are shown to include respectively control modules 370 and 320. These control modules implement a subset of the control processes/logic 104 required to implement the SM_MA processes, such as training of the space/space-time processors 338 and 386, etc.

Training

Training refers to the requirement that, in order to implement a space/space-time processing on the receive side of whichever link down/up is implementing SM, it is necessary that the space/space-time processor be equipped with an appropriate model of the spatial characteristics of the environment in which the signals will be passed between the subscriber unit and the associated BTS(s). Different types of training methodology may be appropriate, depending on whether the subscriber units are fixed/mobile, and if mobile, depending on the speed at which they are moving. Where a subscriber unit is fixed, training may be accomplished on installation of the unit, at setup of a call or during a call session. Where a subscriber unit is mobile, training/retraining must take place continuously or intermittently. Training for a fixed subscriber unit may take place intermittently as well, although generally at a lower frequency than that associated with a mobile subscriber unit.

Training is generally categorized as blind or non-blind. Training is non-blind when it is incorporated intermittently/continuously using in/out of band training

Exhibit 1002
Page 0502 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

signals, e.g. known sequences such as Walsh codes, transmitted between subscriber unit and BTS(s). Training is blind when it takes place without such signals, relying instead on non-Gaussianity, CM, FA, cyclostationarity or the spatial structure, such as the array manifold. The performance of blind methods will, of course, be sensitive to the validity of structural properties assumed. An excellent reference on the subject, which is incorporated herein by reference as if fully set forth herein, is found in: "*Space-Time Processing for Wireless Communications*", Arogyaswami J. Paulraj and Papadias, IEEE Signal Processing Magazine, November 1997, at pages 49-83. In an embodiment of the invention, non-blind training methods are utilized to configure the space/space-time processors. Further details on the space/space-time processor will be provided in the following FIGS. 7A-D and accompanying text.

Control module 320 includes: processor 324, clock 326, training module 328 and memory 322 for the storage of weights/parameters for the space/space-time processor 338. Control module 370 in the subscriber unit 138 includes: processor 374, clock 376, training module 378 and memory 372 for the storage of weights/parameters for the space/space-time processor 386. In the embodiment of the invention shown in FIG. 3, the CPU implements the training portion of the control processes/logic 104. In alternate embodiments of the invention, the CPU may be utilized to implement other of the control processes/logic. In still other embodiments of the invention, the training portion of the control processes/logic is handled upstream at such locations as the MSC or the CO.

In an embodiment of the invention which implements non-blind training, the mobility detector 334 signals the CPU 324 when a subscriber unit exhibits minimal Doppler shift/spread, e.g. is fixed. In an embodiment of the invention, the CPU 324 directs the transmit module 310 to signal subscriber unit 138 at call setup, or at the start of a call session, to use stored parameters from an earlier training session or to process a setup training session transmitted by the BTS. In another embodiment of the invention, the CPU may reduce the frequency or duration of a training sequence responsive to a determination that the Doppler shift/spread is minimal.

On the BTS side, the training module 328 inserts a known training sequence, e.g. Walsh code, into the downlink transmissions and these are processed by the CPU 374 of the subscriber unit and weights derived therefrom which allow the

Exhibit 1002
Page 0503 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

space/space-time processor 386 to separate the training sequence spatially broadcast from the antenna array of the BTS(s). Similarly, where the uplink implements SM, the subscriber unit training module 378 inserts a known training sequence into the uplink transmissions as well. These are in turn processed by the CPU 324 and appropriate weights derived therefrom stored in the spatial processor 338 for use with the uplink communications during the call/data-transfer session. Whenever training/re-training takes place, weights are recalculated and stored for use in subsequent SM communications.

Where the mobility detector 334 determines that the subscriber unit is mobile, an alternate non-blind training methodology may be implemented. In an embodiment of the invention, that methodology shown in FIG. 8 involves inserting into in/out of band downlink communications the known training sequence. This allows updating of the spatial parameters/weights by the corresponding subscriber unit and its space/space-time processor. This capability allows spatial multiplexing to be implemented in both a mobile and a fixed environment. In still another embodiment of the invention, the duration/frequency at which the training intervals are inserted into the up/down link communications may be varied depending on the mobility of the subscriber unit.

In still another embodiment of the invention, blind training methods may be implemented. These unsupervised methods do not need training signals because they exploit the inherent structure of the communication signals.

As will be obvious to those skilled in the art, the processes/logic 104 and the associated modules/blocks discussed above and in the following disclosure may be implemented in hardware, software, firmware or combinations thereof without departing from the teachings of this invention. They may be implemented on a single chip, such as a digital signal processor (DSP), or application specific integrated circuits (ASIC). On the upstream side (i.e., BTS, MSC, CO, etc.), the SM_MA processes/logic 104 may physically reside in any one or all upstream units. The processes/logic may be implemented using master-slave control relationship between CO/MSC and BTS or peer-to-peer control relationship between BTSs alone, or distributed control between CO/MSC and BTS.

FIG. 3B illustrates a detailed hardware block diagram of a subscriber unit 138 and a BTS 132 similar to the system described in FIG. 3A. The difference in this embodiment is that the subscriber unit is connected to a network 240 and thus the I/O modules 352 and 392 in the transmitter 350 and receiver 380 respectively are coupled to the network 240. Of course, the subscriber unit could readily communicate with any type of network or network device.

FIGS. 4A-F show an embodiment of the BTS/MSC/CO side of the processes/logic 104_ for implementing SM_MA. FIGS. 4A-B and 4D-E show a partial handoff.

FIG. 4A shows BTSs 120 and 132 coupled to MSC 106 and to the associated upstream processes/logic 300 of processes/logic 104_. The BTS 120 is shown with the associated final transmission stage 316B and the selector 312B. The BTS 132 is shown coupled to the final transmission stage 316A and to the selector 312A. The upstream processes/logic 300 include a detector 400, parser unit 402 and router 420. The parser unit 402 includes a parser module 404 and clock 406 as well as a stretcher 408 and its clock 410. The MSC 106 is shown coupled via its data/control line 108 to each of the above-discussed modules.

As will be obvious to those skilled in the art, the coupling between the MSC and each of the above-discussed hardware and software modules represents a master/slave embodiment of the current invention. In alternate embodiments of the invention, peer-to-peer control methodology may be utilized instead. In still another embodiment of the invention, distributed control methodology may be implemented, e.g. each of the above-discussed modules may contain additional intelligence, sufficient to signal downstream/upstream modules as to the appropriate configuration to adopt, responsive to the datastream(s)/substreams being processed, the channel and access methodology to be utilized.

Datastream(s) 176 is delivered to mode detector 400. In this embodiment of the invention, a mode detection is utilized. As discussed above, this module provides the capability of distinguishing datastream(s). Datastream(s) might, as discussed, be categorized as traditional vs. spatial, or on the basis of QoS or bit rate requirement. In the embodiment shown, the detector 400 determines that the datastream(s) 176 is destined for spatial mode processing. Responsive to that determination, the parser

Exhibit 1002
Page 0505 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

404 is configured to parse the datastream(s) 176 into a plurality of the substreams. In the example shown, the two substreams 450-452 are generated by the parser. The substreams each contain a portion of the actual data from the original datastream(s). The function of the stretcher 408, to which the substreams are passed, is to effectively lower the baud rate at which the substreams are transmitted. Figuratively, this is accomplished by clocks 406 and 410 which are coupled to respectively the parser and the stretcher. Clock 410 operates at a rate which is a fraction of the rate of clock 406. The specific fraction is determined by the number of substreams generated by the parser 404. For example, if parser 404 generates from a single datastream(s) two substreams, then each of the substreams will be transmitted at a baud rate which is effectively 1/2 that of the original datastream(s). The stretched substreams are then passed to the router 420. In an alternate embodiment of the invention, the substreams need not be stretched, rather buffered and transmitted at the same baud rate in bursts, if the channel will support the resultant communication rate. The router operating, in the embodiment shown, under the control of the MSC 106 sends the selected substreams 454 and 456 to a single BTS 132 for single-base spatial transmission from each of the spatially separate antenna of that BTS. Those substreams passed through the selector 312 are injected on an appropriate channel within the multiple access protocol. The channel determination is made by the SM_MA processes/logic 104 that portion of which may be localized in a master/slave control implementation at the MSC. The substreams are then passed to the final transmission stage 316A for transmission to the subscriber unit 150 (see FIG. 6).

FIG. 4B shows hardware/software modules identical to those discussed above in connection with FIG. 4A. The router 420, responsive to a signal from, for example, the MSC 106 has re-routed one of the substreams to BTS 120. That substream 454 is passed to the selector 312B associated with BTS 120. The corresponding substream 456 is presented to selector 312A associated with BTS 132. Under the control of the MSC, each selector is directed to place the substreams on the same MA channel on each of the base stations. The final transmission stages 316A-B of each BTS places the substreams on one antenna of its spatially separate antenna array for transmission to the subscriber 150. The subscriber 150 is in a location in which the signals from base stations 120 and 132 overlap. The composite signals 180 and 178_M resulting from the transmission of spatially distinct subscriber substreams are received with

Exhibit 1002
Page 0506 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

spatially separable signatures by the subscriber unit 150 which, as discussed above, is equipped with spatially separate antennas.

The determination to move from a single-base spatial transmission (see FIG. 4A) to multi-base spatial transmission, as shown in FIG. 4B, may be made as a result of any one of the number of distinct determination methods. In the first of these methods, an evaluator portion of either the space/space-time processor 386 or the decoder 388 of the subscriber unit 138 determines that an incoming composite signal cannot be spatially separated into the required number of substreams. In response to this determination, the subscriber unit signals the BTS that a change of spatial configuration is required. This signal is processed by the BTS and may be passed to the MSC 106. In response, the MSC directs the router and selected BTSs, e.g. BTSs 120 and 132, to prepare for and transmit the substreams on an assigned channel. This transition from single-base to multi-base spatial transmission is handled transparently to the subscriber, in order to maintain a consistent QoS throughout the transmission by increasing the spatial separation of the transmitted substreams.

FIG. 4C shows an alternate embodiment of the invention that includes the capability of mode detecting between, for example, traditional and spatial mode datastreams. Datastream(s) 182 is presented to detector 400 via data/control line 108. The datastream(s) might, for example, be a traditional subscriber telephone call or a datastream which has both a low bit rate and QoS requirement. To minimize resources, it may be advantageous for the parser unit 402 to be configurable, so as not to subject all incoming datastream(s) to parsing or, if parsed, so as not to parse into a fixed number of substreams. In the embodiment shown, such capability is implemented. The detector determines that the datastream is traditional mode. That determination may result in the parser avoiding the parsing of the datastream 182. The datastream(s) 182 is passed unparsed to the router 420. The router 420 passes the datastream(s) 182 to the selector 312A of the associated BTS 132. Under the control of the MSC the selector and the final transmissions stage 316A inject the datastream(s) 182 on the appropriate channel of the appropriate multiple access protocol and transmit it via a selected one of the antennas, within the array from which it is received, by subscriber unit 144. That subscriber unit may be a traditional mobile phone lacking any spatial transmission characteristics. Alternately, the subscriber unit may be spatially configurable as well (see FIG. 2A). In this latter

Exhibit 1002
Page 0507 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

case, BTS 132 injects a control signal to the spatially configurable subscriber unit 144 and, in particular, to the configurable space/space-time processor thereof, indicating that the incoming composite signals are to be treated as a single datastream(s). As will be obvious to those skilled in the art, traditional mode datastreams including, for example, traditional voice telephone calls, may be subject to SM.

As will be obvious to those skilled in the art, each of the above-discussed datastream(s) 178, 176, 182 may include multiple subscriber sessions, time-division multiplexed for example. In this case, all the above-mentioned methodology may be practiced successively on each of the subscriber sessions of a single datastream.

FIG. 4D shows multiple subscriber datastream(s) presented to the detector 400. Specifically datastream(s) 176 and 182 are shown. The first of these datastream(s) is destined for spatial treatment and the second of these datastream(s) 182 is destined for non-spatial treatment. This determination is made by the mode detector 400 based on criteria including, but not limited to, those discussed above. The parsing unit 402 is, in this embodiment of the invention, configurable to concurrently handle multiple subscriber sessions. Upon receipt of control information received either directly from the detector 400 or indirectly from the MSC 106, the parsing module 402 performs the following concurrent operations. The traditional mode datastream(s) 182 is left unparsed and passed directly to the router 420. The spatial mode datastream(s) 176 is parsed by parser 404 into substreams 450-452. These substreams are stretched in stretcher 408, as discussed above, and passed to router 420. The router 420, operating under the control of the MSC, for example, directs each of the datastream(s) and substreams to a single BTS 132 and specifically the associated selector 312A of that BTS.

These substreams generated by the parser are labeled 450-452. The substreams passed by the router are labeled 454-456. This change in reference number is meant to indicate that the initial parsing operation may be accompanied by a lowering of the bit rate or stretching of the clock on which these substreams are transmitted. As will be obvious to those skilled in the art, an alternate methodology for implementing the invention would be to maintain the same the bit rate, provided it was compatible with the bandwidth of the wireless channel on which the transmission

Exhibit 1002
Page 0508 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

was to take place, and to buffer the data accordingly for transmission in bursts, along with other similarly processed datastream(s)/substreams.

Under the direction of the MSC, for example, the selector 312A and final transmission stage 316A of BTS 132 transmit the substreams 454-456 on a common channel and, depending on the access methodology, may transmit the datastream(s) 182 on the same or another channel. Signal 182 is transmitted from an antenna of BTS 132 to subscriber unit 144. The individual substreams and the associated signals 180, 178_S of the spatial mode datastream(s) 176 are transmitted to the subscriber unit 150.

FIG. 4E shows an embodiment of the invention identical to that described and discussed above in connection with FIG. 4D. Router 420 re-routes one of the substreams 454-456 of the spatially processed datastream(s) 176 to form a multi-base spatial transmission configuration. That determination to re-route, as discussed above, may originate either from signals received from the corresponding one of the subscriber units which is unable to spatially separate the substreams or alternately may result from a determination by the BTS initially implementing single-base transmission that the bit error rate (BER) is unacceptably high. In this example, subscriber unit 144 continues to receive composite datastream(s) 182 from an antenna on BTS 132. The composite signals received by subscriber 150 now, however, originate from a multi-base configuration. The substream 454 has been re-routed by router 420 to BTS 120, so the composite signals 180, 178_M originate from BTSs 132,120, respectively.

As will be obvious to those skilled in the art of the reference, in single or a multi-base spatial transmission, discussion to a substream been transmitted from a single antenna, should not be interpreted as a limitation on the teachings of this invention. A single substream in single or multi-base configuration may be transmitted from more than one antenna, if diversity or beam forming transmit processes are implemented in addition to spatial multiplexing.

FIGS. 4F-J show an alternate embodiment of the invention in which the router, as described and discussed above in connection with FIGS. 4A-E, is positioned upstream of the parsing unit rather than downstream of that unit. Consequently, each

Exhibit 1002
Page 0509 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

of the base stations has associated with it a corresponding parsing unit. FIGS. 4F-G and FIGS. 4I-J show a partial handoff.

FIG. 4F shows MSC 106, BTSs 120 and 132 and the upstream processes/logic 300. Each of the base stations 120 and 132 includes selectors and final transmission stages. Within the upstream processes/logic 300, the detector 400 communicates directly to the router 422. The router, in turn, communicates directly with the parsing units 402A-B associated with BTSs 132 and 120, respectively. Single-base spatial processing of subscriber datastream(s) 176 is shown. The subscriber datastream(s) 176 is received by the detector 400. The detector determines that the mode of the datastream(s) is spatial and that information is passed to the router 422. The router routes the datastream(s) 176 to the appropriate parsing unit 402A. The parsing module 404A of that unit parses the datastream(s) into substreams, e.g. substreams 450-452. Those substreams are passed to stretcher 408A which is coupled to selector 312A. The selector places both the stretched substreams 454-456 on the appropriate channel of the selected MA protocol. Those substreams are transmitted by the final transmit stage 316A of the BTS 132. The signals 178_S and 180 are transmitted to subscriber unit 150, along with the control information necessary for that subscriber unit to properly process the incoming communication.

FIG. 4G shows a multi-base implementation of the configuration described and discussed above in connection with FIG. 4F. The detector 400 determines that the datastream(s) 454-456 require spatial processing. Additionally, multi-base transmission is determined to be necessary based, for example, on a subscriber unit signal or on the BER detected by a BTS. The router 422, responsive to that determination, routes the datastream to parsing units 402A-B. Each of the parsing modules 404A-B is presented information, not only that the datastream(s) needs to be parsed, but also which substreams are to be discarded at each parsing unit in order to implement a multi-base spatial transmission. In an embodiment of the invention, those in control instructions are generated by the MSC 106. The parsing module 404A generates substream 452. The parsing module 404B generates substream 450. Collectively, substreams 450-452 contain all the information from the original datastream(s) 176 from which they were parsed. The selected substreams are passed to the corresponding stretching modules 408A-B. These stretching modules in turn pass the substreams with a reduced bit rate or in bursts as substreams 456-454 to the

Exhibit 1002
Page 0510 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

corresponding selectors 312A-B of the associated BTSs 132 and 120. The substreams are placed on the same channels of the multiple access protocol implemented by each BTS. These substreams are transmitted by the corresponding final transmissions stages 316A-B. Signal 180 corresponding to substream 456 is transmitted by at least an antenna on BTS 132 to subscriber unit 150. Signal 178_M corresponding to substream 454 is transmitted by at least an antenna of BTS 120 to subscriber unit 150. The inclusion of both single-base and multi-base spatial transmission capabilities in the system allows consistent QoS to be delivered to the subscribers.

FIG. 4H shows an implementation of the current invention in which the detector 400 includes the capability of distinguishing the mode of the datastream(s), e.g. traditional mode and spatial mode. The detector 400, upon determining that datastream(s) 182 can be processed in traditional mode, passes that information to the router 422. The router passes the datastream(s) 182 to the appropriate parsing unit 402. The parser unit 402A and specifically parser module 404A thereof avoids parsing the datastream(s) and passes it to the corresponding selector 312A associated with BTS 132. In the manner described and discussed above, the channel and antenna on which that datastream(s) is to be transmitted from BTS 132 is determined by the processes/logic 104, e.g. at the MSC. The associated signal 182 is passed from the BTS to the subscriber unit 144.

FIG. 4I shows the introduction of multiple subscriber datastream(s), i.e. datastream(s) 176 and 182 into the embodiment described and discussed above in connection with FIGS. 4F-H. The detector 400 determines that datastream(s) 182 may be processed in the traditional mode while datastream(s) 176 may be processed in the spatial mode. In this example, both the datastream(s) are routed by router 422 to a single BTS for, respectively, non-spatial and spatial transmission. Stretched datastream(s) 454-456 derived from substreams 450-452 of datastream(s) 176 are presented to the selector associated with BTS 132. Signals 178_S and 180 are transmitted to subscriber unit 150 on the same channel of the MA protocol implemented by the BTS. Traditional mode datastream(s) may be transmitted on the same or another channel.

FIG. 4J shows a multi-base spatial transmission of the datastream(s) 176 discussed above in connection with FIG. 4I. A change from single to multi-base

transmission is initiated by the processes/logic 104_ in response to, for example, a degradation in the bit error rate or to signals from subscriber unit 150 which indicate that a change in spatial configuration is required. This might include changing the antenna selection on the array of a single BTS. The selection might involve a reduction/increase in the number of transmitting antennas. Alternately, in the example shown, a partial handoff is implemented. To implement the partial handoff, router 422 routes the datastream(s) 176 to both parsing units 402A-B. Control information, indicating which of the substreams generated by the respective parsing unit is to be passed on to the associated BTS, may also be generated. Responsive to that information, the parsing modules 404A-B each generate only one of the substreams which can be generated from the datastream(s) 176. Each selected substream is stretched by the corresponding stretcher and passed to the corresponding BTS. BTS 132 continues to transmit the traditional mode datastream(s) 182 and the signal corresponding thereto to subscriber unit 144. BTS 132 transmits one of the stretched substreams 456 in the form of signal 180 to subscriber unit 150. The other of the substreams 454 is passed to the subscriber unit 150 as signal 178_M from the BTS 120.

As will be obvious to those skilled in the art, the above-mentioned arrangements of detector, router and parsing units represent only some of the possible configurations of these modules/logic which may be utilized to implement the current invention. In an embodiment of the invention, the wireless network may not support both traditional and spatial transmission together. In that embodiment, the detector may not be required, since all datastream(s) will be handled by spatially transmitting them. In still another embodiment of the invention, multi-base operation may not be implemented, allowing only for single-base SM. In still another embodiment of the invention, the routing may be accomplished by a single BTS which uses in/out of band channels to wirelessly relay one or more substreams to other BTSs for re-transmissions on the assigned channel.

FIGS. 5A-B show the upstream modules associated with the processing of datastream(s) and substreams received by the BTSs. That information may be destined for another subscriber unit or for the network 100 (see FIG. 1A).

Exhibit 1002
Page 0512 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 5A shows the base stations 120,132, the upstream processes/logic 300 and the MSC 106. In the example shown, single-base SM is implemented. The subscriber unit 150 is shown transmitting signals 178_S and 180. These are received by BTS 132 and processed by the associated modules of its configurable SM receiver 330 (see FIG. 3). From the decoder 340A, substreams 454-456 are passed to the upstream processes/logic 300. The upstream module includes a router 420 and a combiner 500. The combiner 500 operates in reverse of the manner described and discussed above in connection with the parsing unit 402. The router 420 passes the substreams 454-456 to the combiner 500. The output of the combiner is the subscriber datastream(s) 176.

FIG. 5B shows the modules discussed above in connection with FIG. 5A during the reception of multi-base spatial transmissions from the subscriber unit 150 as well as the single-base transmission from subscriber unit 144. BTS 132 and the associated receiver module 330, have their spatial processor configured to generate a single one of the substreams 456 that can be derived from the composite signals 178_M and 180 of subscriber unit 150. The other substream 454 is generated by corresponding modules associated with BTS 120. Additionally, on the same/different channel, BTS 132 with the receiver 330 is configured to generate a single datastream(s) 182 from the composite signal 182 transmitted by the subscriber unit 144. The datastream(s) 182 of the associated decoder of that BTS, i.e. decoder 340A is passed to the router 420. The combiner is configured to combine substreams 454-456 into datastream 176 and to pass datastream(s) 182 along without combining.

Thus, in an embodiment of the invention, the method and apparatus of the current invention may be used to implement SM_MA both on the down/up link. As will be obvious to those skilled in the art, SM may be asymmetrically implemented as well, on either the down/up link selectively, without departing from the scope of this invention.

FIG. 6 shows an antenna array of BTS transmitter 132 and the antenna array of the subscriber unit receiver 138 (see FIG. 3). The antenna array of the final transmissions stage 316 includes antennas 134T –136T. The antenna array of the first receiver stage 382 includes antennas 140R-142R. The first receiver stage passes the composite signals 640-642 to the space/space-time processor 386. The output of the

Exhibit 1002
Page 0513 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

processor is presented to the decoder 388 from which, as output, the substreams 454-456 are generated.

As will be obvious to those skilled in the art, the transmission of data through a wireless medium may involve modulation of an information signal derived from a datastream(s) or substream on a carrier signal. Information may, for example, be contained in the phase and/or amplitude relationship of the signal modulating the carrier. Each specific phase and/or amplitude relationship that is utilized is referred to as a "symbol". The set of all symbols is referred to as the "constellation". The greater the number of symbols in a constellation, the more binary bits of information may be encoded in each symbol in a given constellation. Current communication protocols allow for constellations with over 1024 symbols, each encoding for one of ten bit combinations. Antenna 134T is shown transmitting a symbol 600 within a signal constellation. This corresponds to an associated group of the bits corresponding to the data from a portion of substream 454. Antenna 136T is shown transmitting symbol 606 which corresponds to a different bit sequence derived directly from substream 456. The transmission of substream 454 by antenna 134 results in at least two signals 602-604. The transmission of the symbol 606 by antenna 136 generates at least two signals 608-610. Additional signals are likely in a multi-path environment with numerous scattering objects, such as buildings, etc. For the sake of simplicity, signals 602 and 610 transmitted from respectively antennas 134T-136T are both received by antenna 140R as a single composite signal. The corresponding signals 604 and 608 are received by antenna 142R as a single composite signal. In order for the spatial receiver of the subscriber unit to resolve the composite signals into the estimated subscriber datastream/substreams, the spatial processor 386 must include information about the spatial signatures 620-622 of the transmissions from each of the antennas 134-136. These spatial signatures may be determined using either blind and or non-blind training methods in the manner described and discussed above. By placing the decoder 388 downstream from the space/space-time processor 386, the appropriate symbols may then be derived from the substream and converted into a corresponding binary sequence from which the corresponding portions of the substreams 454-456 may be generated.

As will be obvious to those skilled in the art, any of a number of other modulation techniques may be used to implement the current invention including:

continuous phase modulation (CPM), continuous frequency modulation (CFM), phase shift keying (PSK), offset phase shift keying, amplitude shift keying (ASK), pulse position modulation (PPM), pulse width modulation (PWM), etc., without departing from the scope of this invention.

FIGS. 7A-B show an embodiment of the invention in which the spatial processor 386 is configured for both traditional and spatial mode signal reception. Additionally, in the spatial mode, the spatial processor is configurable to generate a variable number of substreams to correspond to the number transmitted. Spatial processor 386 and the decoder 388 are shown. The spatial processor 386 includes: first fabric switch 700, first configurable logic 702, second fabric switch 730, second configurable logic 732, an evaluator 740, and a controller 746.

The spatial processor 386 is coupled via the receive processes 384 to the receiver first stage 380 of the subscriber unit, as discussed above in connection with FIG. 3. Similar design applies to the spatial processor 338 in the BTS (see FIG. 3). The composite signal(s) detected by the first stage receiver is passed to the fabric switch 700 of the spatial processor. Responsive to signals generated by the control unit 746, the first fabric switch passes the composite signal/signals to one or more of the sub-modules within first logic unit 702. In the embodiment shown, a sub-module includes a multiplier 704 and a weight register 712. The multiplier generates an output signal which is a product of the weight stored in weight register 712 multiplied by the incoming composite signal. The weights in this register and the register of other sub-modules may be derived using non-blind or blind training methods as discussed above. In the example shown in FIG. 7A, a composite signal 750 is presented to fabric switch 700. This switch has been configured utilizing in/out of band control signals to process a single composite signal. The output of the multiplier is presented to the second fabric switch 730. This fabric switch also is configurable by means of the control unit 746. The fabric switch 730 presents the signals from the first logic module in variable configurations to one or more of the summers, e.g. summer 734 which is part of the second configurable logic in this embodiment of the invention. Because a single composite signal is being processed in the embodiment shown in FIG. 7A, only one summer is utilized. The input to that summer is the output of the multiplier 704 and the zero input provided by the control unit 746. The output of the summer 734 is passed to the evaluator 740 (optional). The evaluator

determines when signals that are spatially transmitted are not separable, and if separable, the quality of each link. The quality of each link may be evaluated using, for example, Signal to Interference Noise Ratio (SINR). The resultant traditional mode datastream(s) 182 is passed through the decoder. In the decoder the conversion from symbols to associated bit sequences is implemented. As shown above in FIG. 3, the output of the decoder is passed to an associated combiner. The configuration of the configurable spatial processor under the control of control unit 746 takes place as a result of in/out of band control signals. These signals may be generated during call setup or during an actual call session by SM_MA processes/logic 104.

In FIG. 7B, the configurable nature of the spatial processor is evident by comparison to FIG. 7A. Composite signals 640-642 are presented to the first fabric switch 700. Responsive to signals from the control unit 746, the first fabric switch generates output signals for each of the composite input signals. Composite signal 640 is passed to a first pair of logic sub-modules within the first logic unit 702. Composite signal 642 is passed to a second pair of logic sub-modules within the first logic unit 702. The first pair of logic sub-modules include: multiplier 704 together with associated weight register 712, and multiplier 706 together with associated weight register 714. The second pair of logic sub-modules include: multiplier 708 together with associated weight register 716, and multiplier 710 together with associated weight register 718. Multipliers 704-706 receive as inputs the composite signal 640. Multipliers 708-710 receive as inputs the composite signal 642. The weight registers may contain weights obtained during transmission of a training sequence which allow training sequences to be separated. These are multiplied by the corresponding composite signal inputs and the four products are cross-coupled to summers 734-736 of the second logic unit 732 by the second fabric switch. The output of summers 734-736 is, respectively, the estimated substreams 454-456. In the embodiment shown, these are passed through an evaluator 740 to the decoder 388. Subsequently, the estimated substreams are combined into the original datastream 176 (not shown). The decoder 388 performs the above-mentioned function of mapping the summer output into symbols and from the symbols, into the appropriate binary sequences. In an alternate embodiment of the invention, the evaluator may be placed downstream of the decoder and perform a similar function at that location.

Exhibit 1002
Page 0516 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

The evaluator monitors the estimated substreams to determine if they are appropriately separated, and if separable, the quality of the link(s). This determination might, for example, be made during the transmission of a training sequence. When the evaluator determines it is no longer possible to spatially separate the corresponding substreams, that determination may be passed to the upstream processes/logic 104, e.g. the MSC 106 (see FIG. 1). This results in an alteration of the spatial configuration of the transmission. A change in spatial transmission may be implemented in any number of ways. These include: a change in the antenna selection and/or number at a single base, a change from traditional to spatial mode broadcasting at a single base, a change from single-base to multi-base transmission. Similarly, when the evaluator determines that the substreams are separable, it may pass on the link quality parameters to the upstream processes/logic 104, e.g. the MSC 106. This can help the BTS/MSC/CO side of the processes/logic 104_ choose the modulation rate (bits per symbol) of each substream, and carry out parsing accordingly.

FIGS. 7C-D show an embodiment of space-time processor. To the capabilities of the above-discussed spatial processor is added the ability to remove the interference in the composite signal caused by the delayed versions of the composite signal over time. To account for these perturbations, one or more delay elements may be introduced into the signal paths in the first logic unit to account for these effects. An exploded view of an embodiment of a time logic sub-module is shown in FIG. 7D. In the embodiment shown, each time sub-module is coupled to the output of a corresponding multiplier in the first logic unit. Time sub-modules 720-726 are coupled to the outputs of multipliers 704-710, respectively. Each time module may consist of a plurality of delay elements. In the exploded view, a sub-module includes delay modules 760-762; multipliers 770-772 together with associated weight registers 780-782, as well as a summer 790. The output of multiplier 704 is an input both to delay module 760 and summer 790. The output of delay module 760 is an input both to delay module 762 and to multiplier 770. The output of delay module 762 is an input to multiplier 772. The outputs of the multipliers provide additional inputs to the summer 790. The output of the summer is presented to the second fabric switch 730. Each time module may include additional multipliers with associative delay units and weight registers. As was the case in FIGS. 7A-B, the space-time processor in FIGS. 7C-D is configurable. FIG. 7C shows the processor configured for a single input

Exhibit 1002
Page 0517 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

composite signal 750. FIG. 7D shows the space-time processor configured for two composite input signals 640-642.

The spatial/space-time processor of FIGS. 7A-D is configurable; e.g. capable of processing a variable number of composite signals and outputting a corresponding number of estimated subscriber substreams. In another embodiment of the invention, the spatial/space-time processor is not configurable; accepting instead a fixed number of substreams and outputting a corresponding fixed number of estimated subscriber substreams.

As will be obvious to those skilled in the art, any of a number of other processing techniques may be used to implement the current invention, including: space-time, space- frequency, space- code, etc. In turn, these may further utilize any, or a combination of techniques including, but not limited to: linear or non-linear processing, Maximum Likelihood (ML) techniques, Iterative decoding/interference canceling, Multi-user detection (MUD) techniques, etc., without departing from the scope of this invention.

FIG. 8 shows a datastream interspersed with the training sequences consistent with a non-blind embodiment of the current invention. Training sequences 800-802 and data sequences 850-852 are shown. Suitable training sequences include orthogonal Walsh codes transmitted by the spatially separate antennas. The spatial/space-time processor of the receiver attempts to generate weights which separate the known Walsh code sequences. Those weights are then used in processing the subsequent datastream(s)/substreams. In an embodiment of the invention, the training sequences are inserted into the datastream at frequency/duty cycle, which depend on the mobility of the subscriber unit. In another embodiment of the invention, the training sequences vary in duration and are constant in frequency. The training sequences may be transmitted in/out of band. As the mobility of a subscriber increases, the frequency/duty cycle of the training sequences may be increased. The mobility of the subscriber unit can, as discussed above, be detected by Doppler shift/spread detected by the mobility detector 334 (see FIG. 3) on the receive side of the base station, for example. When the subscriber unit is fixed, training may only be performed at, or before, call setup or at a relatively low frequency/duty cycle during a call/data session. In still other embodiments of the invention, no training sequences

Exhibit 1002
Page 0518 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

would be inserted into the datastream(s)/substreams, instead relying on blind training techniques discussed above.

FIGS. 9A-B to 12A-B show various access methodologies utilized to provide multiple-access spatial multiplexing in accordance with the current invention. The figures labeled with "A" show the transmit portion of each access method while the figures labeled with "B" show the receive side. FIGS. 9A-B show SM time-division multiple access (TDMA). FIGS. 10A-B show SM frequency-division multiple access (FDMA). FIGS. 11A-B show SM code-division multiple access (CDMA). FIGS. 12 A-B show SM space-division multiple access (SDMA). The modules disclosed herein on the upstream side, as well as the subscriber side, may be implemented in hardware/software. They may be implemented on a single chip, e.g. DSP or ASIC. The modules disclosed on the upstream side may be located in the BTS or further upstream, e.g. the MSC/CO. On the subscriber side the modules may be implemented in a single unit.

FIG. 9A shows a slot selector 900, a transmit processor module 314A (optional), and a final transmit stage 316A. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. The mobility detector is, in an embodiment of the invention shown in FIG. 3, part of the receive side of the BTS. It is shown in FIG. 9A for purposes of clarity, since it interacts with the training module 328 and CPU 324 to detect and generate training sequences responsive to the mobility of the subscriber unit. Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the slot selector 900. In TDMA each subscriber session is allocated a specific time segment in which to be transmitted. Time segments are assigned in round-robin fashion. In the traditional public switched telephone network (PSTN), there are twenty-four time slots (a.k.a. channels/D0). The slot selector 900, under the direct/indirect control of processes/logic 104 and implemented at, e.g. the MSC 106, assigns the related substreams 454-456 to identical channels (TDMA slots) within the separate TDMA datastream(s) 902-904, which are output by the slot selector. The traditional mode datastream 182 is assigned to a separate channel/slot within TDMA datastream 904.

Exhibit 1002
Page 0519 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Each of the TDMA datastream(s) 902-904 is, in an embodiment of the invention, provided as an input to an optional transmit processing module 314A. That module may implement any one of a number of well known prior art techniques for improving signal quality in a wireless network including: diversity, space coding, space-time coding, space-frequency coding, beam forming, interference canceling, etc.

The transmit processor 314A (optional) includes, in the embodiment shown, diversity processing, space-time coding and beam-forming. Beam-forming exploits channel knowledge to direct transmissions to the location of the corresponding subscriber. Diversity may be implemented in: frequency, time, space, polarization, space/space-time, etc. The outputs of the optional transmit processor 314A are provided as inputs to the final transmit stage 316A. That stage includes encoder modulators 924-926, operating off a common carrier 914 for processing each of the TDMA datastream(s) 902-904. These modulated datastream(s) are passed to respective RF stages 934-936 and associated antennas 134T-136T for spatially separate transmission of the individual substreams that they contain, e.g. 454-456. Additional antenna arrays 940-942, RF stages 930-932, encoder/modulator stages 920-922 are used to implement any of the optional transmit processes.

FIG. 9B shows the receive side of a subscriber unit 150 enabled for spatial multiplexing utilizing TDMA access. That unit includes: first receiver stage 382A, receive processor 384A (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, TDMA slot selector 978, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R which are coupled via, respectively, RF stages 952-950 to demodulator/sampling modules 962-960. The demodulator/sampling units operate off a common carrier 970. An additional antenna array 946, RF stage 954, demodulator/sampling module 964, and carrier generator 972 are utilized by the receive processor 384A to implement: diversity processing, space-time decoding, beam-forming, etc.

In operation, the carrier recovery module 376 synchronizes the carriers 970-972 to the carrier frequency of the incoming composite signals 990-992. The TDM slot selector 978 accepts a channel assignment from the BTS(s) and synchronizes the

Exhibit 1002
Page 0520 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

receive processes accordingly. The composite signals from each antenna are demodulated and sampled by the corresponding one of the demodulator/sampling modules 964-960. The outputs of these modules provide inputs to the receive processor 384A. The receive processor implements signal processing techniques which may complement one or more of the optional processes discussed above for the transmit side (see FIG. 9A). Each composite signal output by the receive processes/logic 384A provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived from the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams, e.g. 996-998. In configurable embodiments of the spatial/space-time processor, information received from the BTS(s) at the start of, or during, a call session configures the processor to generate a number of substreams that correspond to the actual number of substreams transmitted. Next, the estimated subscriber substreams are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as for example, an audio signal, a video signal, a data file, etc.

FIGS. 10A-B show a BTS implementing SM frequency-division multiple access (FDMA). In FDMA, each subscriber session, whether traditional or spatially processed, is provided with a single frequency slot within the total bandwidth available for transmission. The BTS includes: a frequency slot selector 1000, a transmit processor module 314B (optional), and a final transmit stage 316B. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the frequency slot selector 900. The selector 1000, under the direct or indirect control of the MSC 106, selects the appropriate frequency slot for

the datastream(s)/substreams. This is represented in FIG. 10A by a final transmit stage which includes encoder/modulator clusters (1020-1022), (1024-1026), and (1028-1030), each of which modulates about a unique center frequency as determined by respective associated carriers 1010-1014. Intermediate the frequency selector 1000 and the final transmit stage 316B, is an optional transmit processing unit 314B which may impose on the datastream(s)/substreams additional signal processing utilizing antenna arrays 1040-1042 in conjunction with antennas 134T-136T, as discussed above in connection with FIG. 9A.

Within the final transmit stage two spatially separate antennas 134T-136T are shown. These are coupled via, respectively, RF stages 1034-1036 and summers (1002-1004),(1006-1008), to separate outputs of each of three encoder/modulator clusters. Each encoder/modulator cluster operates about a distinct center frequency. Each cluster contains a number of encoder/modulator outputs at least equivalent to the number of spatially separate antennas in the final transmit stage. Since there are two antennas in the example shown, each cluster contains at least encoding/modulating capability for processing two distinct substreams and for outputting each separately onto a corresponding one of the antennas for spatially separate transmission. The traditional mode datastream 182 is assigned to the first cluster with a center frequency determined by carrier 1010. That datastream is output via summer 1006 on antenna 136T. Each of the substreams 454-456, parsed from a common datastream 176 (see FIGS. 4A-J) is passed to a single cluster for spatially separate transmission on a single center frequency corresponding, in the example shown, to the center frequency determined by carrier 1012. The modules disclosed herein may be implemented in the BTS or further upstream, e.g. the mobile switching center. They may be implemented as hardware or software. They may be implemented on a single chip, e.g. DSP or ASIC.

FIG. 10B shows a subscriber unit 150 enabled for spatial multiplexing utilizing FDMA access methodology. That unit includes: first receiver stage 382B, receive processor 384B (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, frequency selector 1078, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are coupled via RF stages 1052-1050, respectively, to demodulator/sampling modules 1062-1060. The

demodulator/sampling units operate off a common frequency synthesizer 1070. Additional antenna array 1046, RF unit 1054, demodulator/sampling unit 1064, and frequency synthesizer 1072 are shown. Optionally, these may be utilized by receive processing unit 384B to implement any of the receive processes discussed above in connection with FIG. 9B.

In operation, the carrier recovery module 376 synchronizes the carriers 1070-1072 to the carrier frequency assigned by the BTS for the subscriber session, i.e. the carrier frequency at which the composite signals 1090-1092 are transmitted. The composite signals from each antenna are demodulated and sampled by the corresponding one of the demodulator/sampling modules 1064-1060. The outputs of these modules provide inputs to the receive processor/logic 384B. The receive processor implements signal processing techniques which may complement one or more of those discussed on the transmit side (see FIG. 10A). Each composite signal output by the receive processor/logic 384B provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1096-1098. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during a call session, configures the processor to generate a number of substreams/datastream(s) which correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams in their binary equivalent 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIGS. 11A-B show a BTS implementing SM code-division multiple access (CDMA). In CDMA, each subscriber session, whether traditional (unparsed) or spatially processed (parsed), is provided with a distinct code sequence. The datastream/substreams are modulated (spread) onto the distinct code sequence/key code (Kn), and the spread signal is, in turn, modulated onto a common carrier. This has the effect of spreading each session across the entire transmission bandwidth. The BTS includes a key/code selector 1100, a transmit processor module 314C (optional), and a final transmit stage 316C. In the embodiment shown, these are part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Shown here for ease of explanation, the mobility detector, as discussed above, is actually implemented on the receive side of the BTS and interacts with the training module 328 to inject training sequences into the SM_CDMA transmissions.

Subscriber datastream 182 and substreams 454-456 derived from subscriber datastream 176 (see FIGS. 4A-J) are shown as inputs to the key/code selector 1100. The selector 1100, under the direct or indirect control of the MSC 106, selects the appropriate key/code sequence for the datastream(s)/substreams. This is represented in FIG. 11A by a final transmit stage which includes spreader and encoder/modulator clusters, (1110-1111,1120-1121), (1112-1113,1122-1123), and (1114-1115,1124-1125) each of which modulates over a unique key code, respectively 1116-1118, and all of which modulate on a common carrier 1126. Intermediate the code/key selector 1100 and the final transmit stage 316C is the optional transmit processing unit 314C, which may impose on the datastream(s)/substreams additional signal processing, such as that described and discussed above in connection with FIG. 9A.

Within the final transmit stage, two spatially separate antennas 134T-136T are shown, along with an optional antenna array 1140-1142 associated with transmit processing. These are coupled via, respectively, RF stages 1134-1136 and summers (1102-1104),(1106-1108) to separate outputs of each of three spreader encoder/modulator clusters. Each spreader encoder/modulator cluster operates about a distinct key code. Each cluster contains a number of encoder/modulator outputs at least equivalent to the number of spatially separate antennas in the final transmit

stage. Since there are two antennas in the example shown, each cluster contains at least encoding/modulating capability for processing two distinct substreams and for outputting each separately onto a corresponding one of the antennas for spatially separate transmission. The traditional mode datastream 182 is assigned to the second cluster with the key code 1117. That datastream is output via summer 1104 on antenna 134T. Each of the substreams 454-456, parsed from a common datastream 176 (see FIGS. 4A-J), is passed to a single cluster for spatially separate transmission with a single key code 1116.

FIG. 11B shows a subscriber unit 150 enabled for spatial multiplexing utilizing CDMA access methodology. That unit includes: first receiver stage 382C, receive processor 384C (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, key/code selector 1182, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are coupled via, respectively, RF stages 1152-1150 to demodulator/sampling modules 1168-1166. Demodulator/sampling modules 1168-1166 operate off a carrier 1172. The output of these is passed to de-spreaders 1162-1160, respectively, which operate off of key code 1176, assigned by the key/code selector 1182 on the basis of control information passed between subscriber unit and base station. Carrier recovery and synchronization may be handled by carrier recovery module 376, operating in conjunction with carrier generator 1172. Additionally, first receiver stage 382C includes optional antenna array 1146, RF stage 1154, demodulator/sampling unit 1170, carrier generator 1174, de-spreader 1164, and key/code generator 1178. These may be utilized in conjunction with the optional receive processor 384C in the manner discussed above in FIGS. 9B and 10B.

In operation, the carrier recovery module 376 synchronizes the carriers 1172-1174 to the carrier assigned by the BTS for the subscriber session, i.e. the carrier at which the composite signals 1190-1192 were transmitted. The composite signals from each antenna are then demodulated and sampled by the corresponding one of the demodulator/sampling modules 1168-1166. Respectively, the outputs of these modules provide inputs to de-spreaders 1162-1160, where they are de-spread using the key code 1176 assigned for the session. The outputs of the de-spreaders provide inputs to the optional receive processor 384C. The receive processor may implement signal processing techniques which complement one or more of those discussed on

the transmit side (see FIG. 11A). Each composite signal output by the receive processes/logic 384C provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1196-1198. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during, a call session configures the processor to generate a number of substreams/datastream(s) which correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams 454-456 in their binary equivalent to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as, for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

FIGS. 12A-B show a BTS implementing space-division multiple access (SDMA). In SDMA, each subscriber session, whether traditional (unparsed) or spatially processed (parsed), is transmitted as a shaped beam; a high gain portion of which is electronically directed using beam forming toward a known subscriber, at a known location, within a cell. This has the effect of allowing channel re-use within a single cell by beam forming each subscriber session to a separate segment of a cell.

The BTS includes a beam steering selector 1200, a transmit processor module 314D (optional), and a final transmit stage 316D. In the embodiment shown, these are a part of the above-discussed BTS 132 (see FIG. 1A). Each of these modules is coupled to the control elements shown in FIG. 3, i.e. training module 328, mobility detector 334, memory 322, processor 324, and clock 326. These are coupled via signal/control line 108 to the MSC 106. Subscriber datastream 182 and substreams 454-456, derived from subscriber datastream 176 (See FIGS. 4A-J), are shown as inputs to the beam steering selector 1200. The selector 1200, under the direct/indirect

Exhibit 1002
Page 0526 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

control of the MSC 106, selects the appropriate direction in which beam steering is to be carried out for each subscriber session and its associated datastream/substreams. Intermediate the beam steering selector 1200 and the final transmit stage 316D is the optional transmit processing unit 314D, which may impose on the datastream(s)/substreams additional signal processing, such as that described and discussed above in connection with FIG. 9A, with the exception of beam forming.

Within the final transmit stage, two pairs of spatially separate antennas 134TA/B-136TA/B are shown. Additionally, antenna array 1240 associated with transmit processes 314D is shown. The two pairs of antennas are coupled via, respectively, RF stages 1234,1230,1236,1232 to beam steering module 1202. The beam steering module accepts as inputs the separately encoded and modulated outputs from encoder modulators 1220-1226, each of which operated on a common carrier 1210, and each of which handles a different substream/datastream. The steering of datastream 182 to subscriber 144 (see FIG. 1B), and of substreams 454-456 to subscriber 150, is accomplished by beam steering unit 1202. That unit, operating with a known location/channel for each subscriber, steers the output beams from the antennas so that they interfere in a manner which maximizes the gain appropriately. At the location of subscriber 144, beam steering results in the composite signal corresponding to datastream 182 reaching a relative maximum, while the gain of the composite signals corresponding to the substreams 454-456 at that location is minimized. Beam steering also accomplishes the opposite effect at the location of subscriber unit 150.

FIG. 12B shows a subscriber unit 150 enabled for spatial multiplexing utilizing SDMA access methodology. That unit includes: first receiver stage 382D, receive processor 384D (optional), spatial/space-time processor 386, decoder 388, combiner 390, I/0 module 392, processor 374, carrier recovery module 376, memory 372, and training module 378. The first receiver stage includes antennas 140R-142R, which are respectively coupled via RF stages 1252-1250 to demodulator/sampling modules 1262-1260. Demodulator/sampling modules 1262-1260 operate off of a common carrier 1270. Carrier recovery and synchronization may be handled by carrier recovery module 376 operating in conjunction with carrier generator 1270. Additionally, the first receiver stage may also include: an antenna array 1246, coupled via RF stage 1254 to a demodulator/sampler 1264, and associated carrier module

Exhibit 1002
Page 0527 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

1272. These operate under the control of receive processes 384D to implement any of the receive processes discussed above in connection with FIG. 9B, 10B and 11B.

In operation, the carrier recovery module 376 synchronizes the carriers 1270-1272 to the carrier at which beam forming is conducted by the BTS(s). The composite signals from each antenna are then demodulated and sampled by the corresponding one of the demodulator/sampling modules 1268-1266. The outputs of these modules provide inputs to the receive processor 384D. Each composite signal output by the receive processes/logic 384B provides inputs to the spatial/space-time processor 386 (see FIGS. 7A-D). That processor, using parameters/weights derived using the above-discussed blind/non-blind training techniques, separates the composite signals into the appropriate number of estimated subscriber substreams/datastream(s), e.g. 1296-1298. In configurable embodiments of the spatial/space-time processor, information received from the base stations at the start of, or during, a call session configures the processor to generate a number of substreams/datastream(s) that correspond to the actual number of substreams/datastream(s) transmitted. Next, the estimated subscriber substreams/datastream(s) are provided as inputs to a similarly configured decoder 388. The decoder maps symbols utilized during the transmission of the substreams/datastream(s) into their binary equivalent. The decoder outputs the estimated subscriber substreams in their binary equivalent 454-456 to the combiner 390. The combiner reverses the operation performed on the transmit side by the parser, generating thereby an estimated subscriber datastream 176. This datastream is provided to the I/O module 392 for subsequent presentment to the subscriber as, for example, an audio signal, a video signal, a data file, etc. As will be obvious to those skilled in the art, the subscriber unit may be configured to receive more than one channel concurrently.

Although FIGS. 9-12 show four distinct multiple access methods, it will be obvious to those skilled in the art that each of these may be combined with one or more of the others without departing from the scope of this invention, as well as with such multiple access methods as: orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access, or any other orthogonal division multiple access/quasi-orthogonal division multiple access (ODMA) techniques.

FIGS. 13A-B show the process flow for transmit and receive processing/logic 104_ associated with an embodiment of the current invention. These processes/logic may be carried out across multiple datastreams, either in parallel, serially, or both. Processing begins at process block 1300 in which the next datastream is detected. Control then passes to decision process 1302. In decision process 1302 a determination is made as to the mode of the datastream. As discussed above, the mode determination may distinguish traditional/spatial, quality of service, bit rate, etc. as well as various combinations thereof. If a determination is made that the mode is traditional, control passes to process 1304. In process 1304 a routing determination is made for the datastream. The routing decision may involve the MSC directing the datastream to an appropriate one of the base stations for transmission. Control then passes to process 1306. In process 1306, the datastream is placed on the appropriate channel within the access protocol implemented on the wireless network. Channel assignment may also be made by the MSC. Control then passes to process 1308 in which the subscriber datastream is transmitted. Next, in decision process 1310, a determination is made as to whether any handoff from one BTS to another is appropriate. If this determination is in the affirmative, control returns to process 1304 for re-routing of the datastream. Alternately, if a negative determination is made in process 1310 that the subscriber is fixed, or still within the cell associated with the transmitting BTS, then control returns to process 1300 for the processing of the next datastream.

If, alternately, in decision process 1302 the mode of the next datastream is determined to be spatial, control passes to process 1320. In process 1320 the datastream is split into a configurable number of substreams. Control is then passed to process 1322. In process 1322 the individual substreams are routed and to one or more base stations for transmission to the subscriber. Control then passes to process 1324. In process 1324, under the direct or indirect control the MSC (see FIG. 1A), the access channel on which to transmit the substreams is selected. That information is communicated to the BTS(s) which are involved in the transmission of the substreams. Control then passes to decision process 1326. In decision process 1326 a determination is made as to whether the intended subscriber is mobile or fixed. If a negative determination is reached, i.e. that the subscriber is fixed, control passes to process 1328. In process 1328, a training sequence either at set-up or during a call

session is generated provided non-blind training protocols are being utilized. The receipt of these training sequences by the subscriber unit allows that unit to derive appropriate weight parameters in the first logic unit of the spatial/space-time processor for separating the composite signals into individual estimated substreams (see FIGS. 7A-D). Alternately, if in decision process 1326 an affirmative determination is reached, i.e. that the subscriber is mobile, then control is passed to process 1330. In process 1330, the frequency or duration of the training sequences inserted into the datastream is increased appropriately. This allows the subscriber unit to continually re-train its spatial/space-time parameters to account for possible changes in the spatial environment brought about by its motion. Control is then passed to process 1332. In process 1332 a determination is made as to the number of substreams that are to be transmitted. The subscriber unit is then signaled as to the number of substreams for which it should configure its spatial/space-time processor and other modules. Control is then passed to process 1334. In process 1334 the selected BTS(s) transmit the selected substreams to the corresponding subscriber unit. Control is then passed to decision process 1336.

In decision process 1336, a decision is made as to whether signal separation at the subscriber unit is adequate. As discussed above, this determination may, for example, be based on feedback from the subscriber unit by monitoring the received signal stream from the subscriber unit, or by monitoring bit error rate (BER) at the transmitting BTS(s). Numerous other methods will be evident to those skilled in the art for making this determination. If this decision is in the negative, i.e. that the subscriber unit is unable to separate the substreams, control returns to process 1320. The process 1320 may now parse the data stream into lesser number of substreams than before, or may do parsing as before, then pass the control to process 1322 for re-routing of the datastream's substreams. Re-routing might, for example, include a change of spatial configuration on a single BTS, or a changeover from single-base to multi-base transmission, as discussed above in connection with FIGS. 4A-J. Alternately, if in decision process 1336 an affirmative determination is reached that the subscriber unit is able to separate the substreams, control passes to decision process 1338. In decision process 1338 a determination is made as to whether a handoff is required. This may result in a partial or full handoff. If that determination is in the negative, e.g. the subscriber unit is fixed, or still within the cell and is capable

of separating the substreams, then control returns to process 1300 for the interception of the next datastream. Alternately, if that decision is in the affirmative, control returns to process 1320. The process 1320 parses the datastreams as before, and passes the control to process 1322 for re-routing of the substreams to one or more base stations.

FIG. 13B shows the receive processes/logic of a subscriber unit associated with an embodiment of the invention. Processing begins at process 1350, in which the next datastream in his detected. Control is then passed to decision process 1352. In decision process 1352, a control signal from the BTS is received indicating the mode of the transmitted signal, e.g. traditional/spatial, and in the latter case, the number of substreams to be generated from the composite signals received. If the composite signals are to be treated as carrying a traditional datastream, control is passed to process 1354. In process 1354 the appropriate channel on which to receive the composite signal is assigned. Channel assignment may occur: during call setup, during a change in spatial configuration, or during a change from single-base to multi-base transmission, for example. Control is then passed to process 1356. In process 1356 the composite signals are received and appropriately processed by the associated modules of the subscriber unit (see FIG. 3). Control is then passed to decision process 1358. In decision process 1358, any training sequences and update of signal processing parameters that may be required are performed. Control is then passed to decision process 1360 for a determination as to whether signal quality and/or strength is adequate. If an affirmative determination is reached, e.g. that quality and/or strength is adequate, then control returns to process 1350 for the processing of the next datastream. Alternately, if a negative determination is reached, then control is passed to process 1362. In process 1362 signaling of the BTS(s) that signal strength or quality is not acceptable is accomplished. In an embodiment of the invention, the subscriber unit signals the BTS that signal strength is no longer suitable for reception, or that signal separation, in the case of spatial transmissions, is no longer adequate. Control then returns to process 1350 for the processing of the next datastream.

If, alternately, in decision process 1352 the control signal from the BTS indicates that the mode of the incoming composite signals is spatial, control is passed to process 1370. In process 1370, control information received by the subscriber unit indicates the number of substreams for which the spatial processor, and other modules

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

of the receive portion of the subscriber unit, are to be configured. Control is then passed to process 1372. In process 1372 access parameters, e.g. channel, for the transmission from the BTS(s) to the subscriber unit are passed to the subscriber unit. Control then passes to process 1374. In process 1374 the composite signals are received and processed into corresponding estimated subscriber substreams. Control then passes to decision process 1376. In decision process 1376 a determination is made as to whether any training sequence is present in the datastream. This embodiment of the invention therefore implements non-blind training. Other embodiments of the invention implementing blind training methods need not implement this particular act. If, in decision process 1376 a negative determination is reached, i.e. that no training sequences are present, control returns to process 1350. Alternately, if in decision process 1376 an affirmative determination is reached, i.e. that a training sequence is present, then control is passed to process 1378. In process 1378, evaluation of the training sequence is performed and new weights registered within the spatial/space-time processor for separating the training sequences. Control is then passed to decision process 1380 for evaluation of the training sequences, then passed to decision process 1382 for a determination of whether the training sequences can be separated adequately. If an affirmative decision is reached, then control returns to decision process 1350. Alternately, if the separation is not adequate, then control passes to process 1384. In process 1384, a control signal is sent to the BTS indicating that a change in spatial configuration is required. The BTS(s) might respond by changing spatial configuration from single to multi-base, by changing the number or spatial configuration of the antennas utilized at a single base, by changing a channel, etc. Control then returns to process 1350 for processing of the next datastream.

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

It should also be apparent that the described subscriber units may be used in a wide variety of other applications without departing from the scope of the present

Exhibit 1002
Page 0532 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

invention. One such application contemplates the use of the described subscriber units in network access units that are used provision extend or otherwise supplement the range of existing high speed telephone or cable networks. By way of example, a hybrid DSL/wireless link is diagrammatically illustrated in Fig. 14. As is well known in the telecommunications art, in conventional high speed xDSL networks, high speed communications are made between a head end DSL modem (typically located at a central office (CO) or optical network unit (ONU)) and a remote DSL modem located on a customer's premises. The link between the central and remote modems is made on ordinary twisted pair wires. Thus xDSL system have the strong advantage of allowing high speed communications using existing wiring infrastructure. However, twisted pair wiring has significant signal attenuation and therefore, it is typically difficult or impossible to provide DSL service to customers who are located too far (e.g. more than 2 or 3 miles) from the central office/ONU. Further, even among customers within the coverage area, the loading coils and the bridge taps which are used around the binders of twisted pair wires that connect the modems, as well as other potential obstacles may make DSL technology difficult to implement in many circumstances.

In the embodiment illustrated in Figure 14, the range and/or accessibility of the DSL network is extended by placing a head end DSL modem 1430 in proximity to the remote DSL modem 1425. A suitable xDSL protocol (such as ADSL, VDSL, etc.) and modulation technique (such as DMT, DWMT, CAPs, etc.) is used to communicate between the remote DSL modem 1425 located at the customer premises and the head end DSL modem 1430 located at an appropriate location that is within range of the customer premises. By way of example, the head end DSL modem 1430 may be located at the terminal server 1410 on a nearby telephone pole 1432 from which the twisted pair drop 1435 originates that serves the customer premises. The head end DSL modem 1430 then provides the raw input data stream to the network access unit (subscriber unit) 1440 that communicates with appropriate BTSs 1445 as described above. Of course, in embodiments where a plurality of different remote DSL modems within the same neighborhood are being serviced, the head end DSL modem may multiplex the data streams from the various xDSL connections.

It is noted that the location of the described network access units may be widely varied based on the needs of a particular system. One advantage to placing the

network access units at the terminal servers is that it provides a readily accessible location where installation is relatively easy. Also, terminal servers are often located on a telephone pole as illustrated in Figure 14. This may be advantageous in that top telephone poles are relatively higher as compared to many other potential deployment locations, which may provide a clearer path between the network access unit 1440 and the BTS transceiver. This, of course may result in increased data speeds. It should be appreciated that the described arrangements can bring DSL service to a wide variety of locations using the POTS (plain old telephone service) infrastructure.

Referring next to Fig. 15 another embodiment of the present invention is illustrated. In this embodiment, the network access unit 1440 is connected to a plurality of cable modems 1460 via an appropriate cable 1470. Any suitable cable including hybrid fiber co-axial (HFC) cables, co-axial cables or fiber cables may be used as cable 1470. Like the previously described hybrid DSL link, the illustrated hybrid cable link provides the possibility of expanding the range of high speed data communications using existing infrastructure.

As suggested above, the described subscriber unit can be used as a node in virtually any network to facilitate communications between that network and other devices and/or networks. For example, with the growing popularity of home networks, a subscriber unit can be used as a node in a home network. Alternatively, a subscriber can be used in office networks and/or any other type of local area, wide area, or other networks.

Another networking concept that has attracted some attention lately is vehicle based networking. For example, people have contemplated wiring carriers such as buses, airplanes, ships and other vehicles with networks that provide multiple nodes within the vehicle for use by passengers. The described spatial multiplexing based subscriber units which take advantage of a wireless link are particularly well adapted to providing high speed access for any vehicle based network.

Referring next to Fig. 16, yet another deployment possibility for the subscriber units will be described. In the embodiment illustrated in Fig. 16, the subscriber unit 1601 is utilized as a wireless interface for a repeater BTS 1610 in a cellular network. Various parties have proposed and implemented the concept of using repeater BTSs in cellular networks. Generally, a repeater BTS 1610 is designed to extend the coverage

area of a master BTS 1620 and/or cover dead spots in the master BTS's coverage area. The repeater BTS simply repeats the signals being transmitted by the master BTS. The link between the master BTS and the repeater link can be either a wireless link or a wired link. Given the high data rates that are possible using the spatial multiplexing based subscriber units, it should be apparent that the described subscriber units are particularly well suited for use in repeater BTSs.

Although a few specific deployments have been described, it should be appreciated that the described spatial multiplexing based subscriber units may be deployed in a wide variety of other situations as well.

Exhibit 1002
Page 0535 of 1285

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

CLAIMS

1. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

base stations each including spatially separate transmitters for transmitting in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for assigning an available channel on which to transmit each subscriber datastream, for routing at least a substream of each datastream to at least a selected one of the base stations and for generating control signals to configure the at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel.

2. The wireless cellular network of Claim 1 wherein the logic is arranged for changing a spatial transmission configuration from a first transmitting base station to at least the first base station together with a second transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

3. The wireless cellular network of either of claims 1 and 2 wherein the logic is arranged for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

4. The wireless cellular network of any of the preceding claims wherein the logic further comprises a parser for parsing each datastream into substreams.

Exhibit 1002
Page 0536 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

5. The wireless cellular network of Claim 4, wherein:

the parser includes responsiveness to a mode signal to parse each datastream into a variable number of substreams and to avoid parsing of each datastream; and

the parser is responsive to a modulation rate of each substream.

6. The wireless cellular network of Claim 4, wherein the logic further comprises a router for routing the substreams to at least a selected one of the base stations and each of the base stations further comprises a selector responsive to the control signals generated by the logic to inject a routed one of the substreams onto the channel assigned by the logic.

7. The wireless cellular network of Claim 6, wherein each of the base stations further comprises a selector responsive to the control signals generated by the logic to inject routed ones of the substreams onto both the channel assigned by the logic as well as onto selected ones of the spatially separate transmitters.

8. The wireless cellular network of any of the preceding claims wherein the logic further comprises:

a detector to detect modes of the subscriber datastreams from the first network and to generate a mode signal corresponding to the mode of each of the subscriber datastreams;

a parser responsive to the mode signal to parse the datastream into a variable number of substreams and to avoid parsing of the datastream; and

a router for routing both an unparsed datastream as well as a variable number of substreams to at least a selected one of the base stations.

9. The wireless cellular network of Claim 8, wherein the modes of the datastreams include voice mode and data mode and wherein further the parser is

Exhibit 1002
Page 0537 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

responsive to a voice mode signal avoids parsing of the datastream, and responsive to a data mode signal parses the datastream into a variable number of substreams.

10. The wireless cellular network of Claim 8, wherein the modes of the datastreams include high bit rate and low bit rate and wherein further the parser avoids parsing of a low bit rate datastream, and parses a high bit rate datastream into a variable number of substreams.

11. The wireless cellular network of Claim 8, wherein the modes of the datastreams include low QoS requirement and high QoS requirement and wherein further the parser avoids parsing a datastream with a low QoS requirement, and parses a datastream with a high QoS requirement into a variable number of substreams.

12. The wireless cellular network of any of Claims 8-11, wherein each of the base stations further comprises:

a selector responsive to the control signals generated by the logic to inject routed ones of the substreams as well as the unparsed datastream onto both the channel assigned by the logic as well as a selected one of the spatially separate transmitters.

13. The wireless cellular network of any of the preceding claims wherein each of the base stations further comprises a training module for injecting a training sequence into the transmissions of the spatially separable transmitters.

14. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprises:

spatially separate receivers for receiving composite signals resulting from the spatially separate transmission of spatially separate source signals corresponding to

Exhibit 1002
Page 0538 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

selected substreams of an uplink subscriber datastream from selected ones of the subscriber units, on an assigned channel of the multiple access protocol;

a spatial processor configurable in response to the control signal to separate the composite signals into estimated source signals based on information obtained during the transmission of known data patterns from the selected ones of the subscriber units; and

a combiner for combining the estimated source signals into a corresponding uplink subscriber datastream.

15. The wireless cellular network of Claim 14, wherein the spatial processor further comprises:

a configurable logic responsive to the control signal to vary both a number of the composite signals separated as well as the number of the estimated source signals.

16. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprise:

mobility detectors for determining a mobility of each of the subscriber units and generating a mobility signal; and

a training module responsive to the mobility signal for varying at least one of: an injection interval and duration of a training sequence into the transmissions of the spatially separable transmitters.

17. The wireless cellular network of any of the preceding claims, wherein each of the base stations further comprises transmit processes selected from at least one of a group of transmit processes consisting of: diversity, space coding, space time coding and beam forming.

18. A subscriber unit for use in a cellular system with base stations each including spatially separate transmitters for transmitting selected substreams of at least one of a

Exhibit 1002
Page 0539 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

plurality of subscriber downlink datastreams on an assigned channel of a multiple access protocol, and the subscriber unit comprising:

spatially separate receivers for receiving on the assigned channel of the multiple access protocol composite signals resulting from the spatially separate transmission the selected substreams;

a spatial processor to separate the composite signals into estimated subscriber substreams, and to signal the base stations when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams; and

a combiner for combining the estimated substreams into a corresponding subscriber datastream.

19. The arrangement of Claim 18, wherein the spatial processor further comprises responsiveness to a control signal from the base station to vary a number of estimated subscriber substreams.

20. The arrangement of Claim 18 or 19, wherein the spatially separate receivers further comprise:

a first selector responsive to the control signal to assign a channel on which to operate said spatially separate receivers; and

a second selector responsive to the control signal to enable selected ones of the spatially separate receivers on the assigned channel to receive the composite signals.

21. The arrangement of any of Claims 18-20, wherein the spatial processor further comprises a configurable logic responsive to the control signal to vary both a number of the composite signals separated as well as the number of the estimated source signals and to evaluate the composite signals over time.

Exhibit 1002
Page 0540 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

22. The arrangement of any of Claims 18-21, wherein the spatial processor further comprises an evaluator to evaluate the estimated source signals during a transmission interval in which at least one of the base stations transmits the known data patterns and to initiate the signal to the at least one of the base stations when a change of the spatial transmission configuration is required.

23. The arrangement of any of Claims 18-22, wherein the combiner includes responsiveness to the control signal to vary a number of estimated source signals combined into a corresponding subscriber datastream.

24. The arrangement of any of Claims 18-23, further comprising:

a parser for parsing an uplink subscriber datastream into substreams; and

spatially separate transmitters for transmitting the substreams of the uplink subscriber datastream on an assigned channel of a multiple access protocol.

25. The arrangement of any of Claims 18-24, wherein the subscriber unit further comprises receive processors from at least one of a group of receive processes consisting of diversity, space decoding, space-time decoding, beam forming and interference canceling.

26. A wireless cellular network for transmitting subscriber downlink datastreams from a first network to subscribers located within the wireless cellular network, and said wireless cellular network comprising:

base stations each configured for spatially separate transmission of selected substreams of each subscriber downlink datastream on an assigned channel of a multiple access protocol;

subscriber units each configured for spatially separate reception on the assigned channel of the selected substreams and for combining the substreams into the corresponding subscriber datastream; and

a logic communicating with each of the base stations and to the first network and the logic configured to route at least a substream of each subscriber downlink datastream to at least a selected one of the base stations and further configured to vary the routing between a single base station and multiple base stations to vary a spatial transmission configuration of the selected substreams.

27. A wireless cellular network for receiving subscriber datastreams at corresponding ones among a plurality of base stations located within the cellular network, and said wireless cellular network comprising:

a plurality of subscriber units each including spatially separate transmitters for transmitting, in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for generating control signals to configure selected ones of the base stations to receive composite signals resulting from the spatially separate transmission of the selected substreams from a corresponding one among the plurality of subscriber units on the assigned channel, for converting the composite signals into estimate substreams and for combining the estimated substreams of each subscriber datastream into each subscriber datastream.

28. The logic of Claim 27, further for changing the spatial reception configuration from a first receiving base station to at least the first base station together with a second base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the composite signals into estimated substreams.

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Exhibit 1002
Page 0542 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

29. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

base stations each including at least one transmitter for transmitting, in response to control signals, selected substreams of each subscriber datastream on an assigned channel of a multiple access protocol; and

logic communicating with each of the base stations and the logic for assigning an available channel on which to transmit each subscriber datastream, for routing at least a substream of each datastream to at least a selected one of the base stations and for generating control signals to configure the at least a selected one of the base stations to transmit the selected substreams to a corresponding one among the plurality of subscriber units on the assigned channel.

30. The arrangement of Claim 29, wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station to at least the first base station together with a second transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

31. The arrangement of Claim 29 or 30, wherein the logic is further arranged for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

32. The arrangement of any one of Claims 29-31 wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station together with a second transmitting base station to at least the first

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

transmitting base station together with a third transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

33. The arrangement of any one of Claims 29-32, wherein the logic is further arranged for changing a spatial transmission configuration from a first transmitting base station together with a second transmitting base station to at least the third transmitting base station together with a fourth transmitting base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the selected substreams at the corresponding one among the plurality of subscriber units.

34. A method for transmitting subscriber downlink datastreams from base stations to corresponding ones among a plurality of subscriber units, and said method for transmitting comprising the acts of:

routing at least a substream of each subscriber downlink datastream to selected ones of the base stations;

transmitting the at least a substream of each subscriber downlink datastream from the selected ones of the base stations on an assigned channel of a multiple access protocol; and

re-routing at least a substream of each subscriber downlink datastream between a single base station and multiple base stations responsive to a determination that a change of a spatial transmission configuration of the at least a substream of each subscriber downlink datastream signal is required.

35. The method of Claim 34, wherein the at least a substream comprises at least one of: a whole subscriber downlink datastream and substreams of the subscriber downlink datastream.

Exhibit 1002
Page 0544 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

36. The method of Claim 34 or 35, wherein the routing act and re-routing acts further comprise the acts of:

parsing each of the subscriber downlink datastreams into a configurable number of substreams; and

configuring the at least a selected one of the base stations to transmit selected substreams of each subscriber downlink datastream to a corresponding one among the plurality of subscriber units on the assigned channel.

37. The method of Claim 36, wherein the parsing act further comprises the acts of:

determining a mode for each of the subscriber downlink datastreams;

parsing the subscriber downlink datastream into a plurality of substreams responsive to a first mode determination in said act of determining; and

avoiding the parsing of the subscriber downlink datastream responsive to a second mode determination in said act of determining.

38. The method of Claim 37, wherein the first mode and the second mode correspond to at least one of: a transmission rate of each of the subscriber downlink datastreams, and a data type of each of the subscriber downlink datastreams.

39. The method as recited in any of Claims 34-38, wherein the determination that a change of a spatial transmission configuration is required corresponds to a signal generated by a corresponding one of the subscriber units.

40. The method as recited in any of Claims 34-39, further comprising the acts of:

receiving at a corresponding one among the plurality of subscriber units signals generated in said transmitting act;

determining a number of substreams to be derived from the signals;

separating the signals into the number of substreams determined in said act of determining; and

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

combining the substreams into a corresponding subscriber downlink datastream.

41. A method of receiving subscriber downlink datastreams transmitted from a plurality of spatially separate transmitters, comprising the acts of:

receiving signals generated from at least one of the plurality of spatially separate transmitters;

determining a number of substreams to be derived from the signals;

separating the signals into the number of substreams determined in said act of determining; and

combining the substreams into a corresponding subscriber downlink datastream.

42. The method Claim 41, wherein said separating act further comprises the acts of:

determining that a change of a spatial transmission configuration is required in order to separate the number of substreams; and

changing the spatial transmission configuration responsive to said act of determining.

43. A wireless cellular network for transmitting subscriber datastreams to corresponding ones among a plurality of subscriber units located within the cellular network, and said wireless cellular network comprising:

means for routing at least a substream of each subscriber downlink datastream to selected ones of the base stations;

means for transmitting the at least a substream of each subscriber downlink datastream from the selected ones of the base stations on an assigned channel of a multiple access protocol; and

Exhibit 1002
Page 0546 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

means for re-routing the at least a substream of each subscriber downlink datastream between a single base station and multiple base stations responsive to a signal from a corresponding one of the subscriber units requesting a change of spatial transmission configuration.

44. A subscriber unit for use in a cellular system with base stations each including spatially separate transmitters for transmitting selected substreams of at least one of a plurality of subscriber downlink datastreams on an assigned channel of a multiple access protocol, and the subscriber unit comprising:

means for receiving signals generated from at least one of the plurality of spatially separate transmitters;

means for determining a number of substreams to be derived from the signals;

means for separating the signals into the number of substreams determined in said act of determining;

means for combining the substreams into a corresponding subscriber downlink datastream; and

means for signaling the base when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams.

45. A wireless cellular remote unit for transmitting a datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas, the transmitter further being responsive to a control signal from the base station to vary the number of applied substreams.

Exhibit 1002
Page 0547 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

46. The unit of Claim 45, wherein the remote unit communicates with a first network to provide the first network with access to the cellular network.

47. The unit of Claim 46 wherein the first network is one selected from the group consisting of a home network, a vehicle based network and a local area network.

48. A unit as recited in any one of claims 45-47 wherein the subscriber unit is incorporated into a bridge or router to provide a wireless bridge or router.

49. The unit of any one of claims 45-48, wherein the remote unit is one of a fixed unit and a mobile unit.

50. The unit of any one of claims 45-49, wherein the remote unit further comprises transmit processes from at least one of a group of transmit processes consisting of diversity, space coding, space-time coding, space frequency coding, beam forming and interference canceling.

51. The unit of any one of claims 45-50, wherein the transmitter includes a parser for parsing the datastream into the substreams.

52. The wireless cellular remote unit of Claim 51, wherein the parser is responsive to at least one of:

a mode signal to parse the datastream into a variable number of substreams and to avoid parsing of each datastream; and

a modulation rate of each substream.

53. The unit of any one of claims 45-52 further comprising a selector arranged to inject a routed one of the substreams onto the assigned channel.

Exhibit 1002
Page 0548 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

54. A wireless cellular remote unit for transmitting a datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas;

a detector to detect a mode of the datastream and to generate a corresponding mode signal; and

a parser responsive to the mode signal to parse the datastream into a variable number of substreams and to avoid parsing of the datastream.

55. The wireless cellular remote unit of Claim 54, wherein the modes of the datastream includes at least one of:

voice mode and data mode and wherein further the parser responsive to a voice mode signal avoids parsing of the datastream, and responsive to a data mode signal parses the datastream into a variable number of substreams;

high bit rate and low bit rate and wherein further the parser avoids parsing of a low bit rate datastream, and parses a high bit rate datastream into a variable number of substreams; and

low QoS requirement and high QoS requirement and wherein further the parser avoids parsing a datastream with a low QoS requirement, and parses a datastream with a high QoS requirement into a variable number of substreams.

56. A wireless cellular remote unit for receiving a downlink datastream from and transmitting an uplink datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

Exhibit 1002
Page 0549 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a transmitter for transmitting a plurality of uplink substreams of the uplink datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each uplink substream to an associated one of the spatially separate antennas;

a receiver including a spatial processor arranged to separate a composite downlink signal received by the spatially separate antennas into estimated substreams, and a combiner for combining the estimated substreams into a corresponding subscriber datastream, the receiver being arranged to signal the base stations when a change of a spatial transmission configuration is required in order to resolve the composite signals into estimated substreams.

57. A wireless cellular remote unit as recited in claim 56 wherein the remote unit takes the form of a network access unit that is a node in a network that facilitates communication outside of the network.

58. A method of transmitting a datastream from a remote unit to at least one cellular base station in a cellular network, the method comprising:

forming a plurality of substreams from the datastream, wherein the number of substreams formed is determined in response to a control signal received from one of the base stations; and

transmitting the substreams in parallel from spatially separate antennas on an assigned channel or slot using a multiple access protocol.

59. A method of communicating between a remote location and one or more base stations in a cellular network, the method comprising:

transmitting a datastream from the remote location to a wireless access unit over a wired connection using a communications protocol selected from the group consisting of an xDSL protocol, a cable modem protocol and a networking protocol;

forming a plurality of substreams from the datastream; and

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

transmitting the substreams to the one or more base stations in parallel from spatially separate antennas on an assigned channel or slot using a multiple access protocol.

60. A wireless cellular remote unit for receiving a downlink datastream from and transmitting an uplink datastream to at least one base station that is part of a cellular network, the wireless cellular remote unit comprising:

a plurality of spatially separate antennas;

transmission means for transmitting a plurality of uplink substreams of the uplink datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each uplink substream to an associated one of the spatially separate antennas; and

receiver means arranged to separate a composite downlink signal received by the spatially separate antennas into estimated substreams, and combine the estimated substreams into a corresponding subscriber datastream.

61. A wireless cellular remote unit as recited in claim 60 wherein:

the remote unit is arranged to signal the base stations when a change of a spatial transmission configuration is required by the receiver in order to resolve the composite signals into estimated substreams; and

the transmitter is responsive to a control signal from the base station to vary the number of applied substreams.

62. A repeater base station suitable for use in conjunction with a master base station that is part of a cellular network, the repeater base station including:

a slave base station; and

a wireless interface unit comprising,

a plurality of spatially separate antennas; and

Exhibit 1002
Page 0551 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a transmitter for transmitting a plurality of substreams of a datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas, the transmitter further being responsive to a control signal from the master base station to vary the number of applied substreams.

63. A communications network comprising:

a master station controller;

at least one base station controller that communicates with the master station controller;

a plurality of base station, each base station being arranged to communicate with an associated one of the base station controllers, wherein at least one of the base stations is designated as a master base station; and

a repeater base station as recited in claim 62.

64. A unit for use in a communications network that delivers DSL service to customers, the unit comprising:

a head end DSL modem arranged to communicate with a remotely located DSL modem using a DSL protocol; and

a wireless access unit comprising arranged to receive a datastream from the head end DSL modem, the wireless access unit including, a plurality of spatially separate antennas and a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas.

65. A unit for use in a communications network that delivers DSL service to customers, the unit comprising:

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a head end DSL modem arranged to communicate with a remotely located DSL modem using a DSL protocol; and

a wireless access unit comprising,

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a base station in the communications network;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the head end DSL modem for transmission to a remotely located DSL modem using a DSL protocol.

66. A unit for use in a communications network that delivers high speed data delivery service to customers, the unit comprising:

a head end cable modem unit arranged to communicate with a remotely located cable modem over a cable;

a wireless access unit comprising arranged to receive a datastream from the head end cable modem, the wireless access unit including, a plurality of spatially separate antennas and a transmitter for transmitting a plurality of substreams of the datastream on an assigned channel or slot of a multiple access protocol, the transmitter being arranged to apply each substream to an associated one of the spatially separate antennas.

67. A unit for use in a communications network that delivers high speed data delivery service to customers, the unit comprising:

a head end cable modem unit arranged to communicate with a remotely located cable modem over a cable;

a wireless access unit comprising,

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a base station in the communications network;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the head end cable modem for transmission to a remotely located cable modem.

68. A unit as recited in claim 66 or 67 wherein the cable is one selected from the group consisting of a hybrid fiber co-axial cable, a co-axial cable and a fiber cable.

69. A repeater base station suitable for use in conjuction with a master base station that is part of a cellular network, the repeater base station including:

a slave base station; and

a wireless interface unit comprising,

spatially separate receivers for receiving on an assigned channel of a multiple access protocol composite signals resulting from spatially separate transmission selected substreams communicated from a master base station;

a spatial processor to separate the composite signals into estimated slave substreams; and

a combiner for combining the estimated substreams into a corresponding slave datastream, wherein the slave datastream is passed to the slave base station for transmission by the slave base station.

70. A communications network comprising:

a master station controller;

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

at least one base station controller that communicates with the master station controller;

a plurality of base station, each base station being arranged to communicate with an associated one of the base station controllers, wherein at least one of the base stations is designated as a master base station; and

a repeater base station as recited in claim 69.

71. A unit as recited in claim 64 or 65 wherein the unit is coupled to a terminal server in a POTS communications network such that a first link between the remotely located DSL modem and the head end DSL modem takes the form of twisted pair wiring and a second link between the wireless access unit and a base station takes the form of a wireless link.

72. An arrangement as recited in any of the preceding claims, wherein the multiple access protocol is selected from at least one of a group of multiple access protocols consisting of: code-division multiple access, frequency-division multiple access, time-division multiple access, space-division multiple access, orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access, orthogonal division multiple access (ODMA) and quasi-orthogonal division multiple access (ODMA) techniques.

73. An arrangement as recited in any of the preceding claims, wherein the assigned channel comprises, within a transmission bandwidth, at least one of: a frequency-division, a time-division, a spatial-division, a code-division, orthogonal frequency division multiple access (OFDMA), wavelength division multiple access (WDMA), wavelet division multiple access or any other orthogonal division multiple access (ODMA)/quasi-orthogonal division multiple access techniques.

74. The arrangement of any of the preceding claims wherein the base stations receive the plurality of subscriber downlink datastreams from at least one of a group of networks consisting of: a public switched telephone network, a local area network, a wide area network, a satellite network, an adhoc network, a virtual private network, an intranet and an internet.

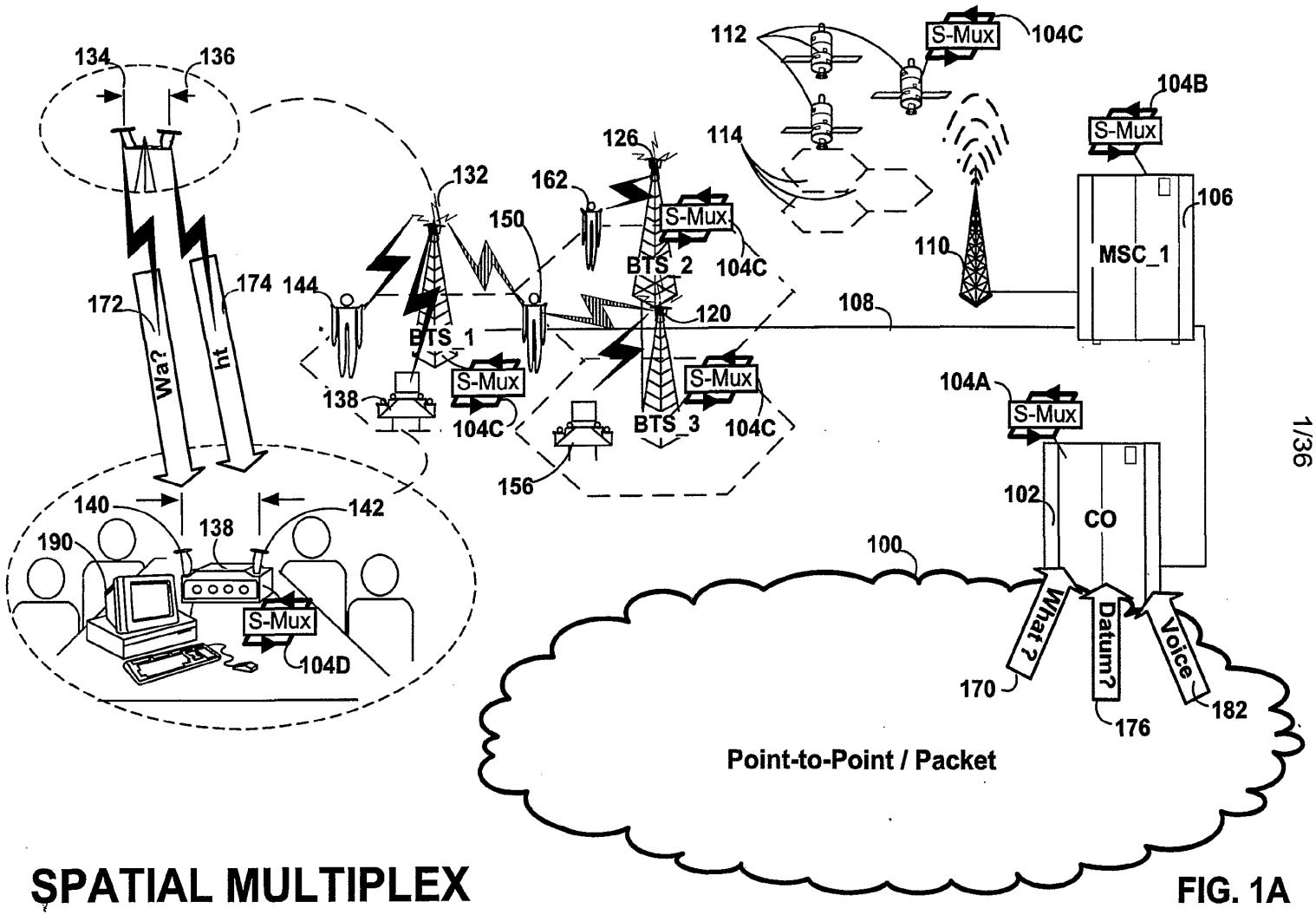
75. The arrangement of any of the preceding claims, wherein the base stations include satellites.

76. An arrangement as recited in any of the preceding claims wherein the subscriber unit is incorporated into a bridge or router to provide a wireless bridge or router.

77. The logic of Claim 27 or 28 , further for changing the spatial reception configuration from a first receiving base station to at least a second base station together with a third base station responsive to a determination that a change of a spatial reception configuration is required in order to resolve the composite signals into estimated substreams.

RECTIFIED SHEET (RULE 91) ISA/EP

Exhibit 1002
Page 0556 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148



SPATIAL MULTIPLEX

FIG. 1A

SUBSTITUTE SHEET (RULE 26)

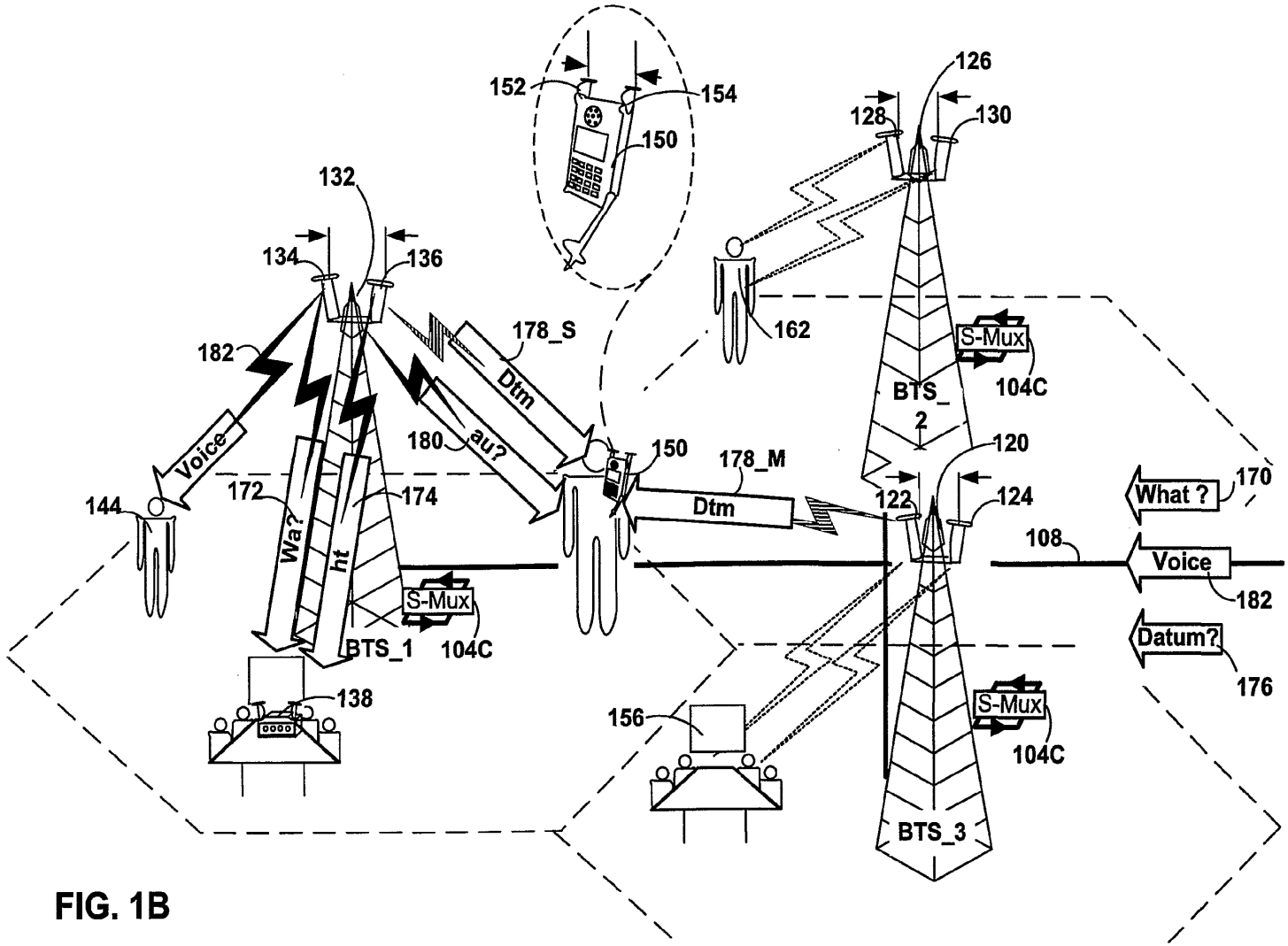


FIG. 1B

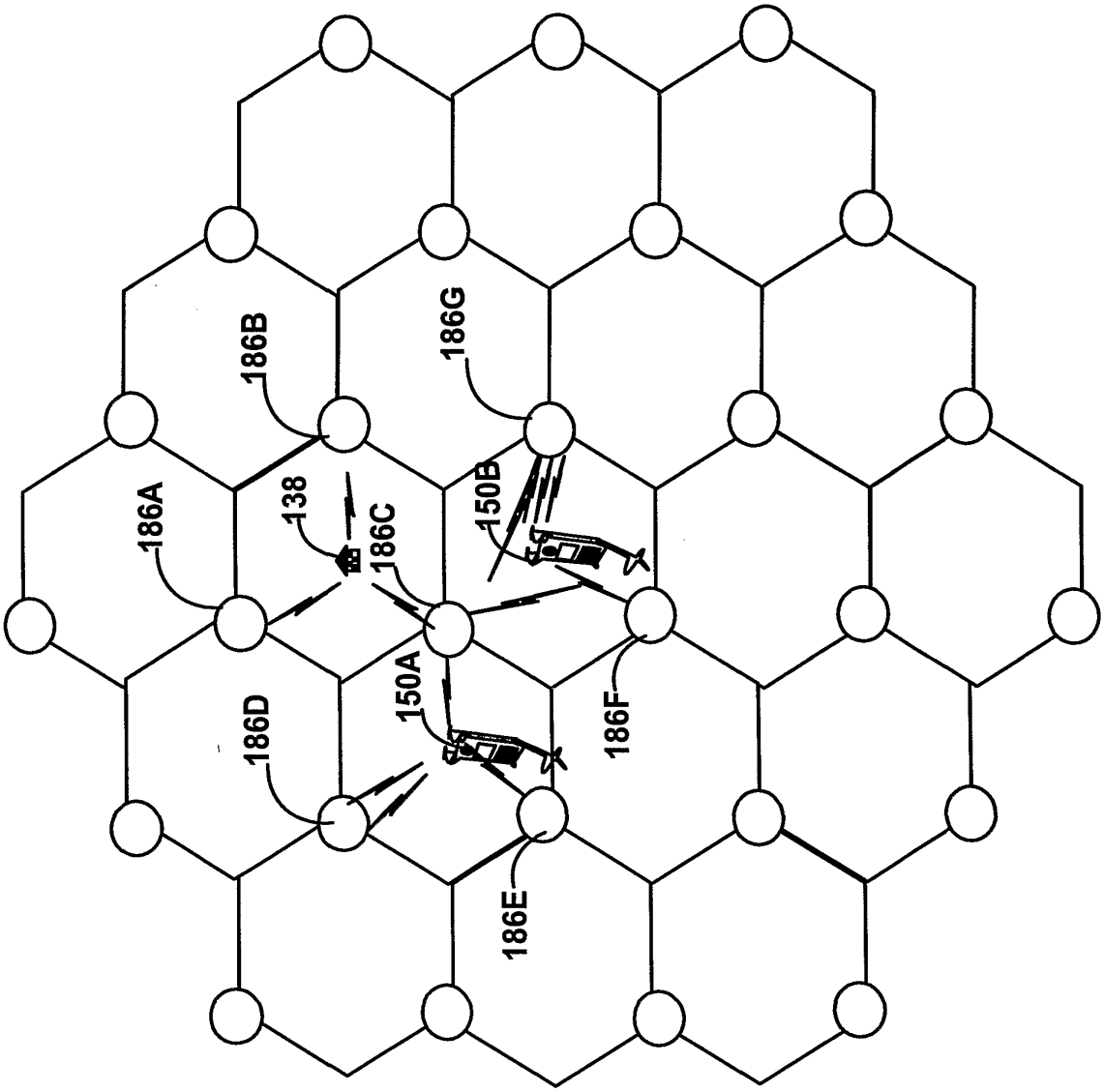


FIG.1C

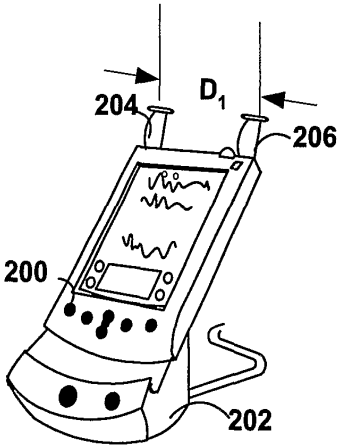


FIG. 2D

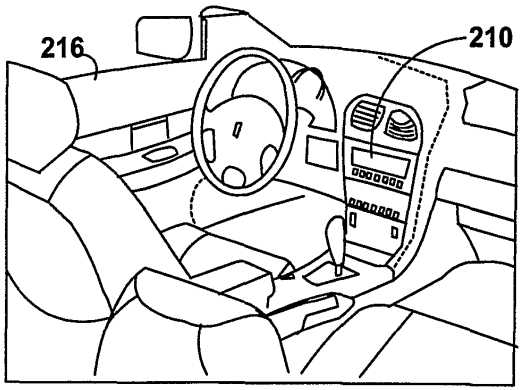


FIG. 2E

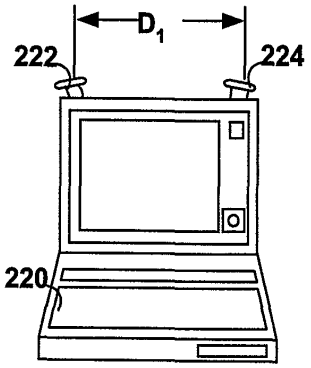


FIG. 2F

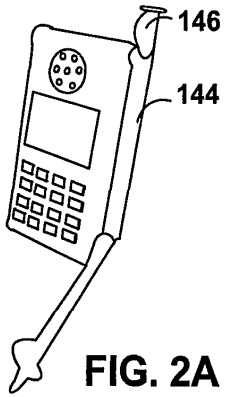


FIG. 2A

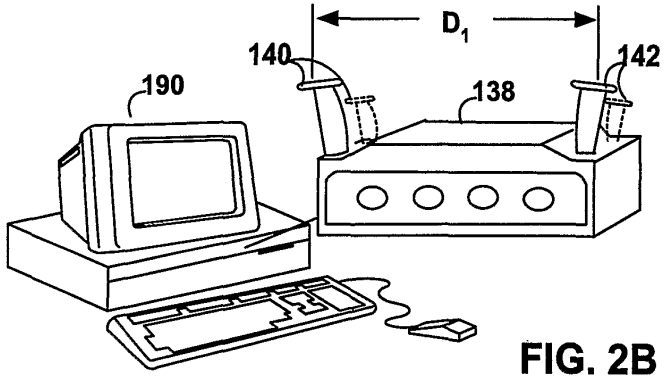


FIG. 2B

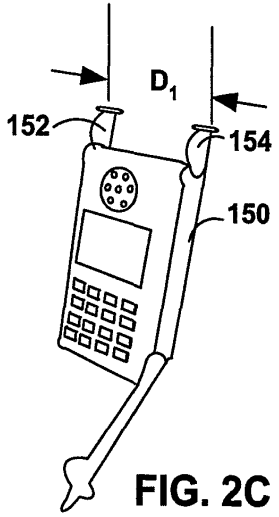


FIG. 2C

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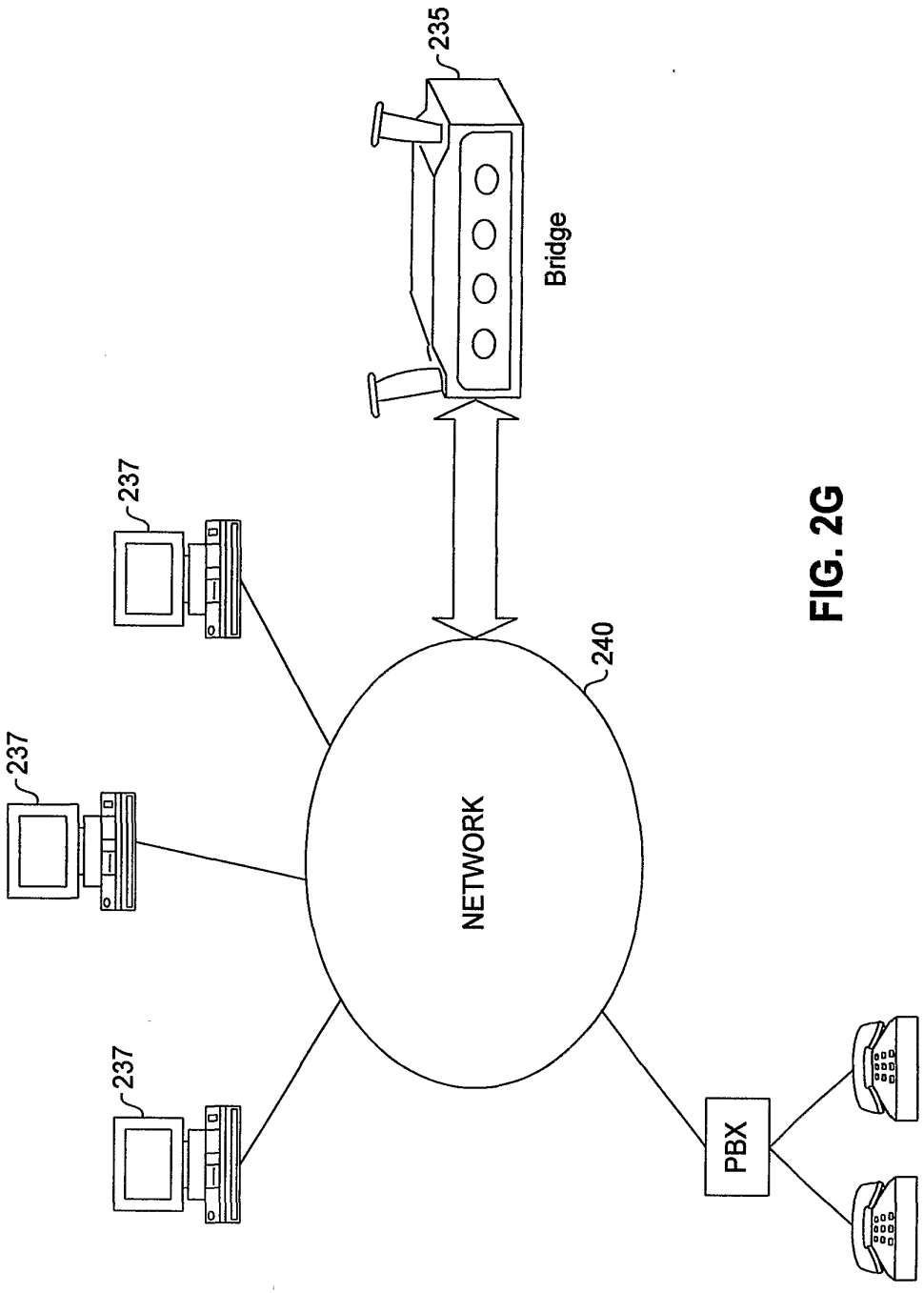


FIG. 2G

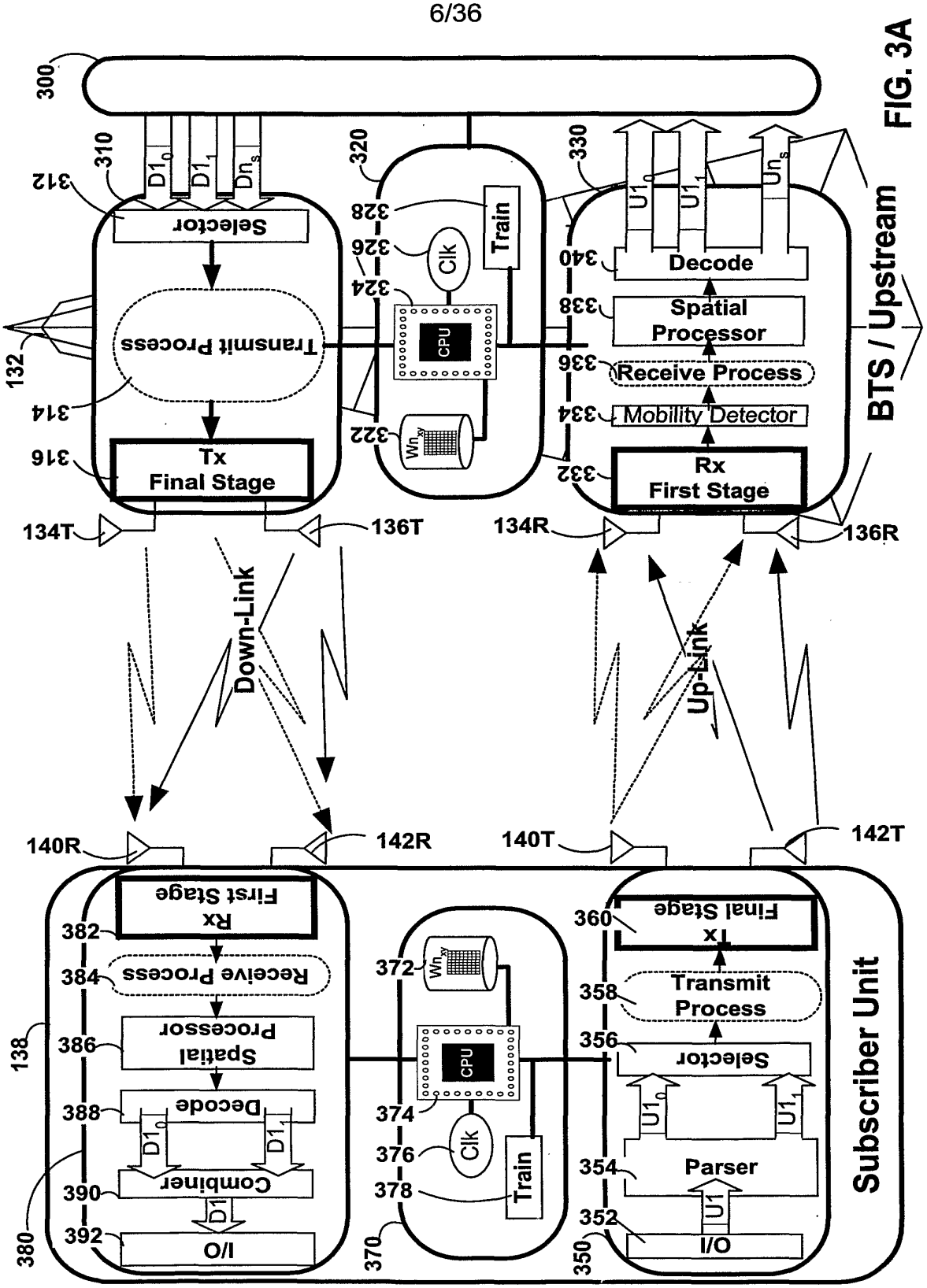
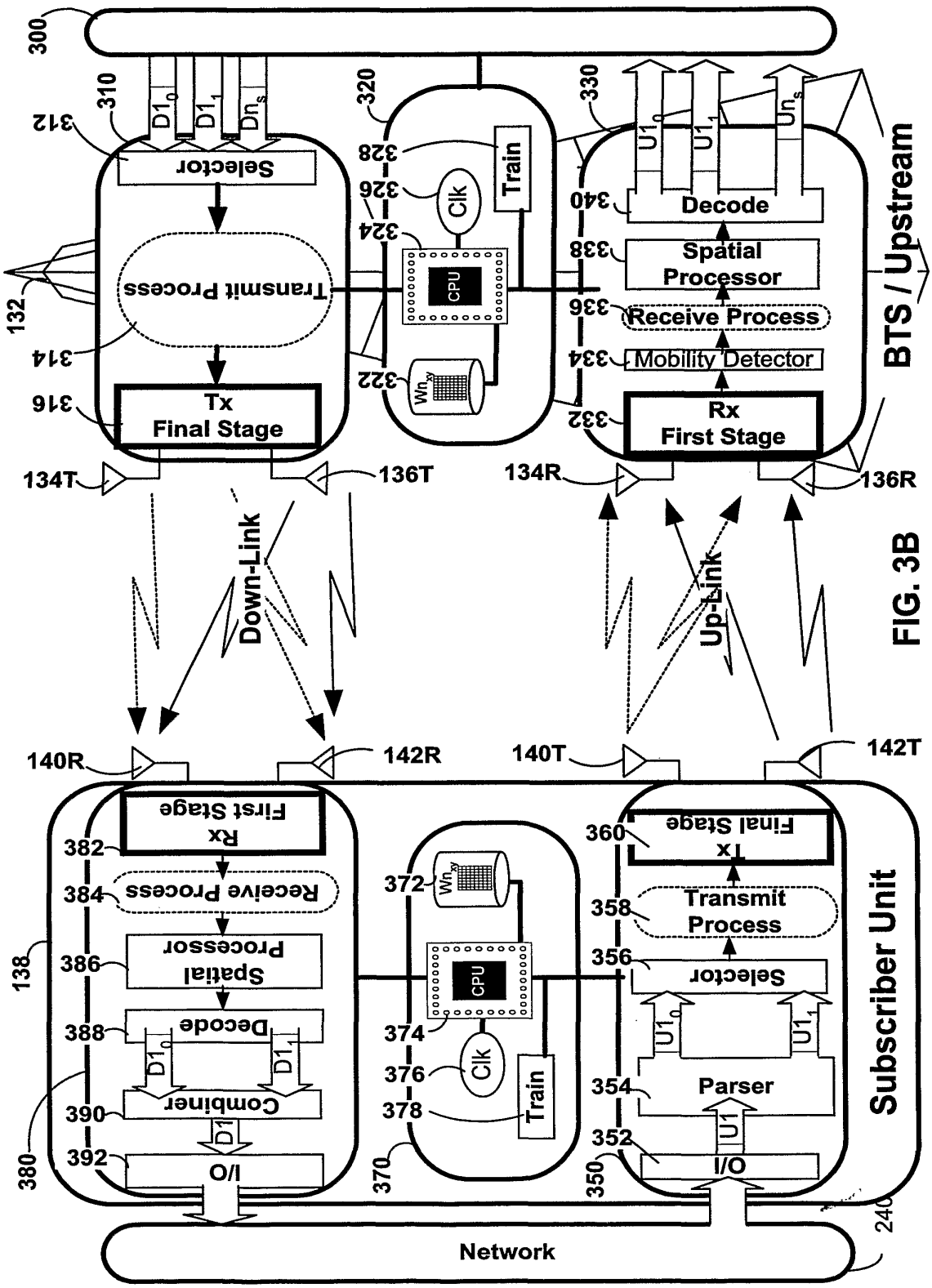


FIG. 3A

SUBSTITUTE SHEET (RULE 26)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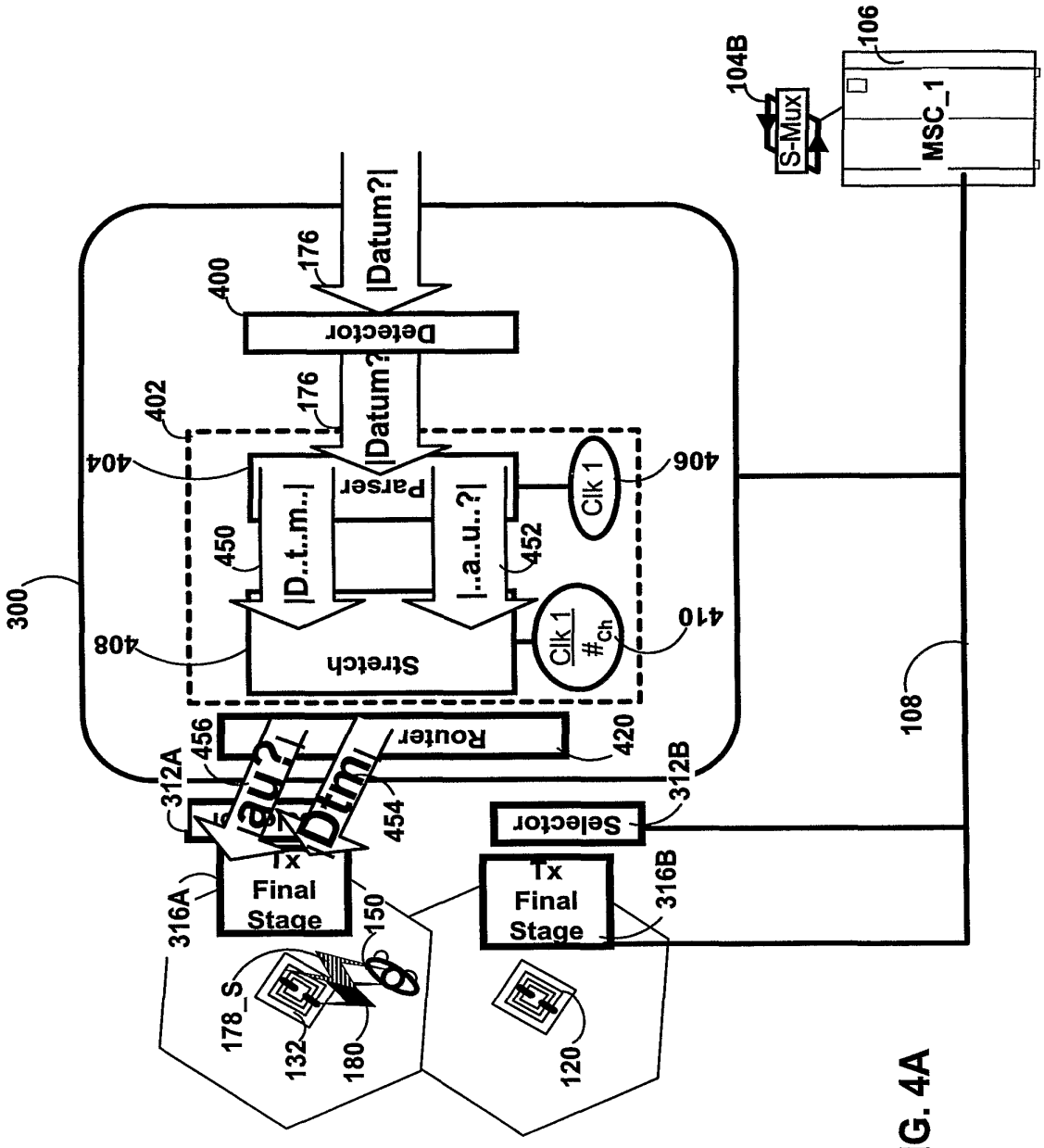
310
312
Selector
Transmit Process
314
316
Tx
Final Stage
132
320
328
326
324
322
Clk
Train
CPU
330
340
338
336
334
332
Decode
Spatial
Processor
Receive Process
Mobility Detector
Rx
First Stage
BTS / Upstream
134T
136T
134R
136R
Down-Link
Up-Link
140R
142R
140T
142T
138
382
384
386
388
390
392
380
Rx
First Stage
Receive Process
Spatial
Processor
Decode
Combiner
I/O
372
374
376
378
370
360
358
356
354
352
350
Tx
Final Stage
Transmit
Process
Selector
Parser
I/O
Subscriber Unit
240
Network

FIG. 3B



300
400
Detector
176
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402
404
Parser
|D..t..m..|
|..a..u..?|
450
452
406
Clk 1
408
Stretch
410
Clk 1
#Ch
Router
420
456
312A
|au?|
|Dtm|
454
312B
Selector
Tx
Final
Stage
316A
316B
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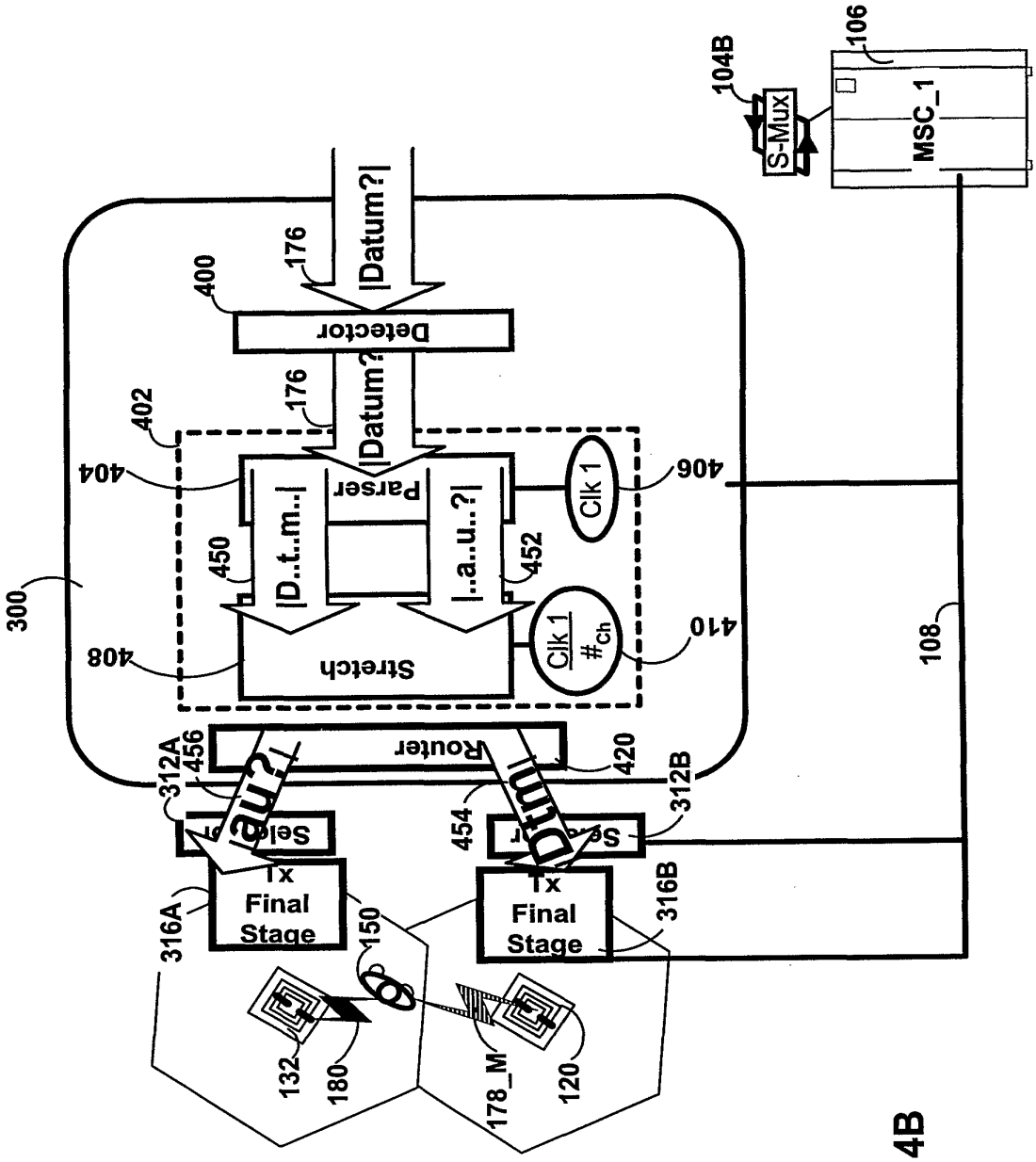
178_S
132
180
120
108
104B
S-Mux
106
MSC_1

FIG. 4A



106
104B
S-Mux
MSC_1
|Datum?|
176
400
Detector
402
404
Parser
|D..t..m..|
|..a..u..?|
450
452
Clk 1
406
300
408
Stretch
Clk 1
#Ch
410
108
Router
420
312A
456
312B
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Tx
Final
Stage
316A
316B
150
132
180
178_M
120

FIG. 4B

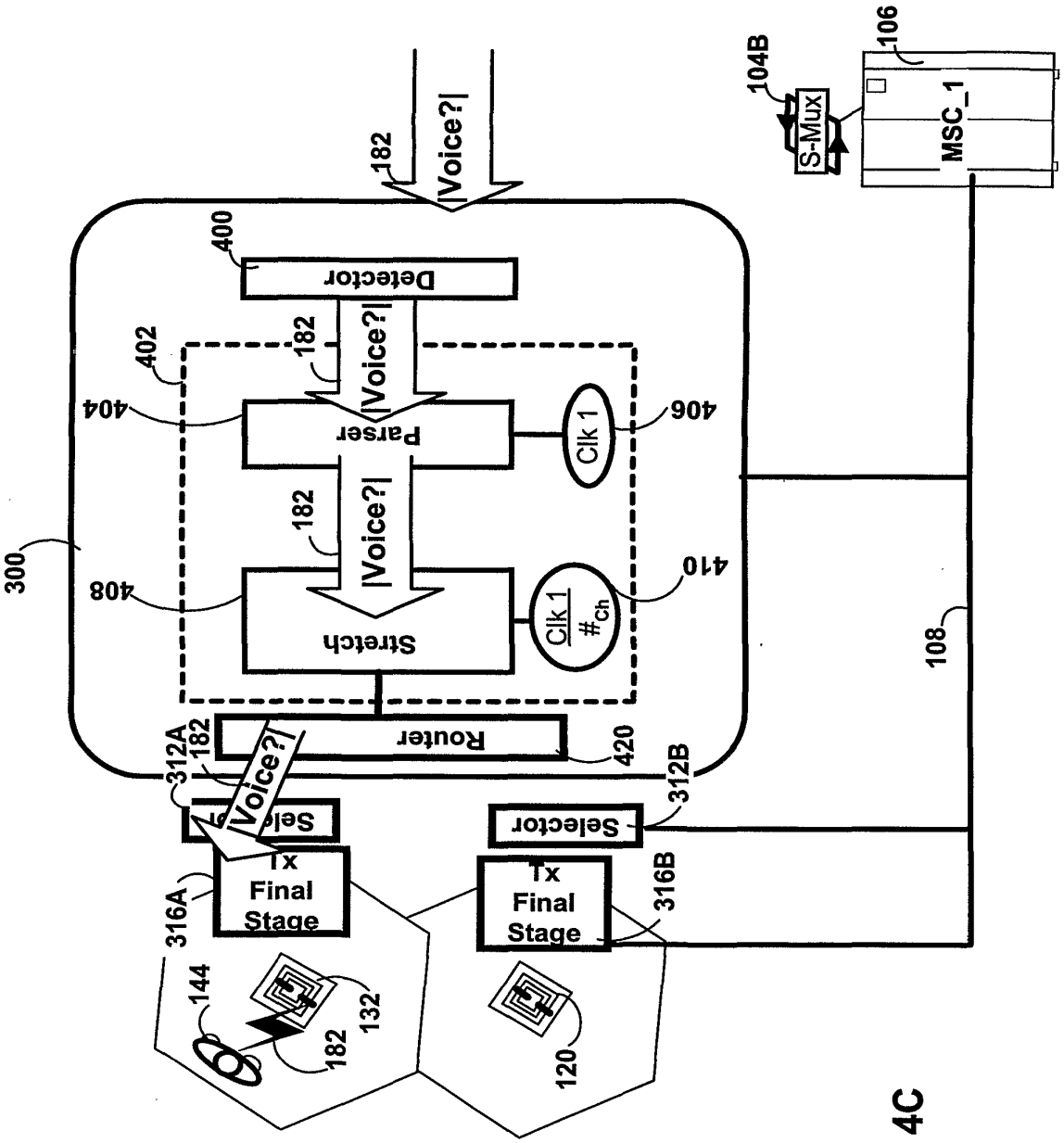
104B
106
S-Mux
MSC_1
182
Voice?
400
Detector
402
182
Voice?
404
Parser
406
Clk 1
182
Voice?
300
408
Stretch
410
Clk 1
#ch
108
Router
420
312A
182
Voice?
312B
Selector
Selector
Tx
Final
Stage
316A
Tx
Final
Stage
316B
144
132
182
120

FIG. 4C

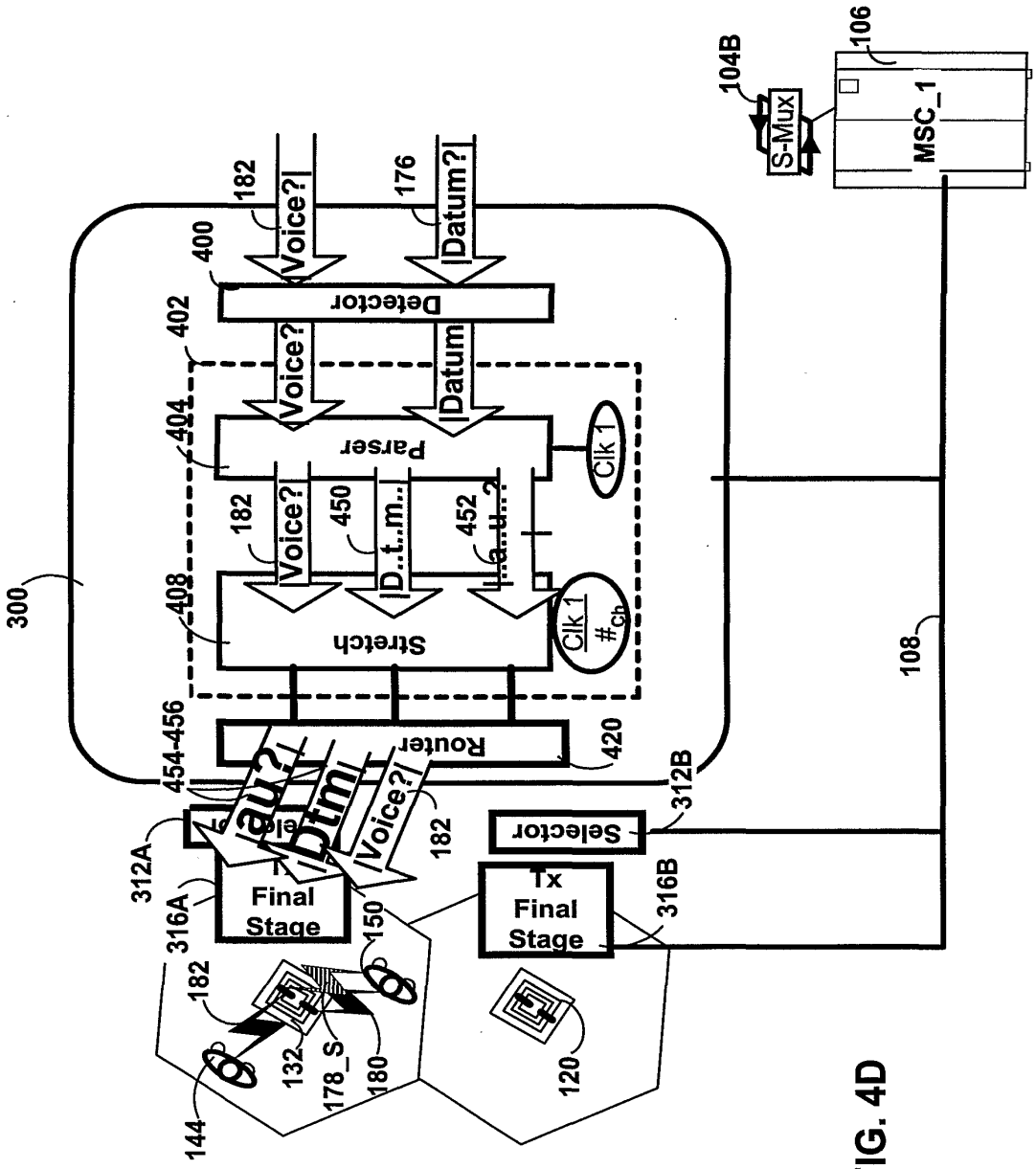

FIG. 4D

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0567 of 1285

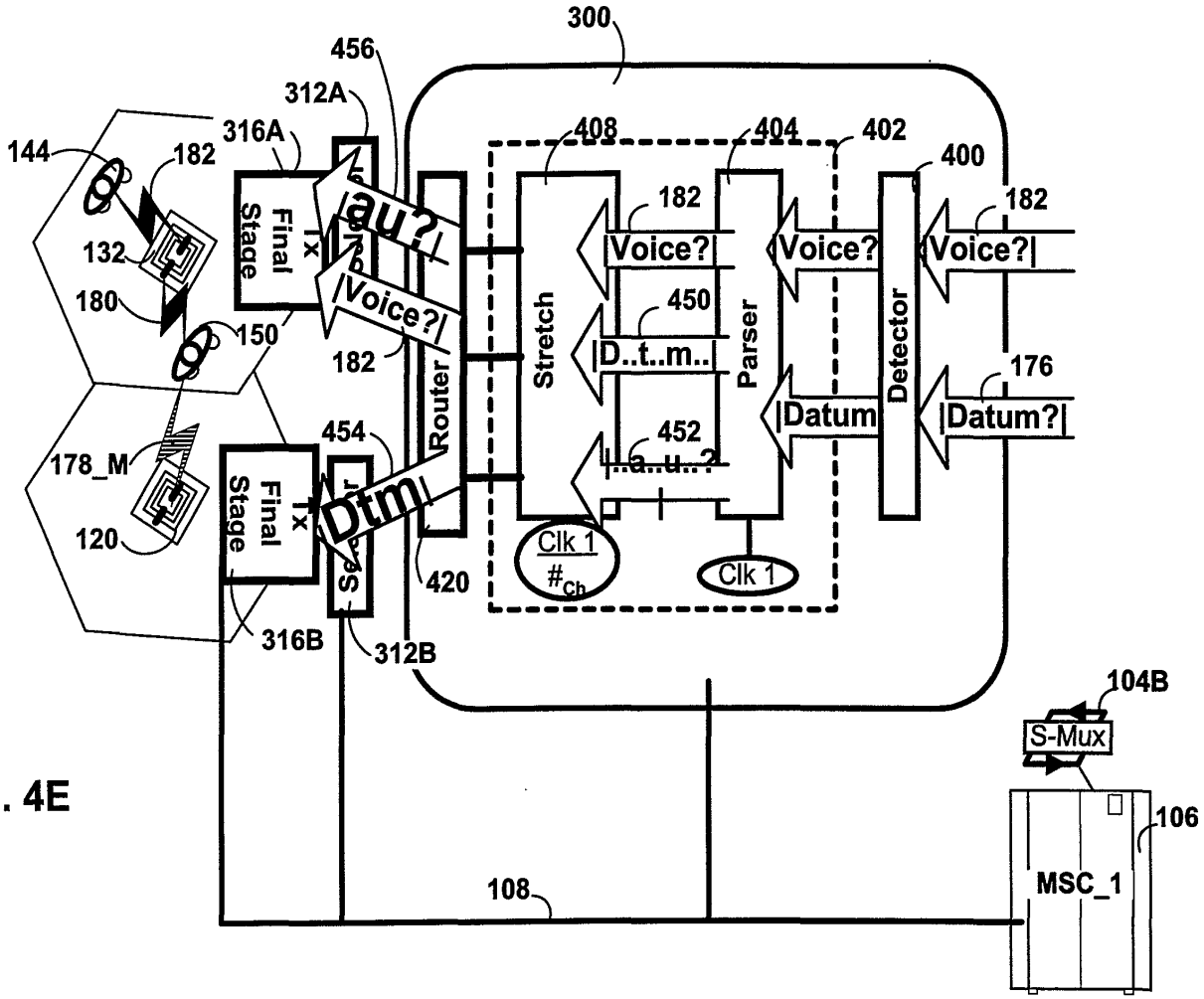

FIG. 4E

SUBSTITUTE SHEET (RULE 26)

SUBSTITUTE SHEET (RULE 26)

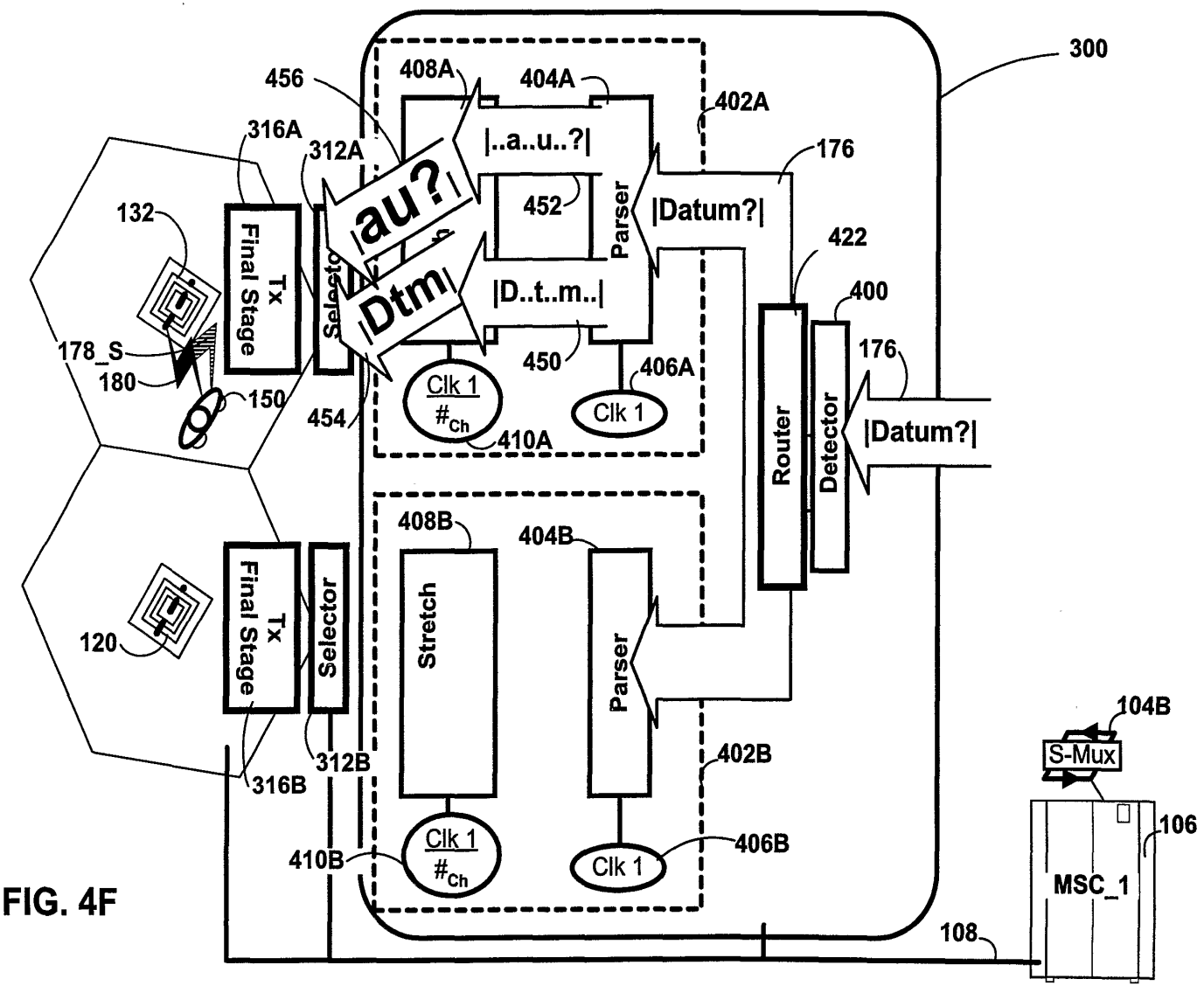

FIG. 4F

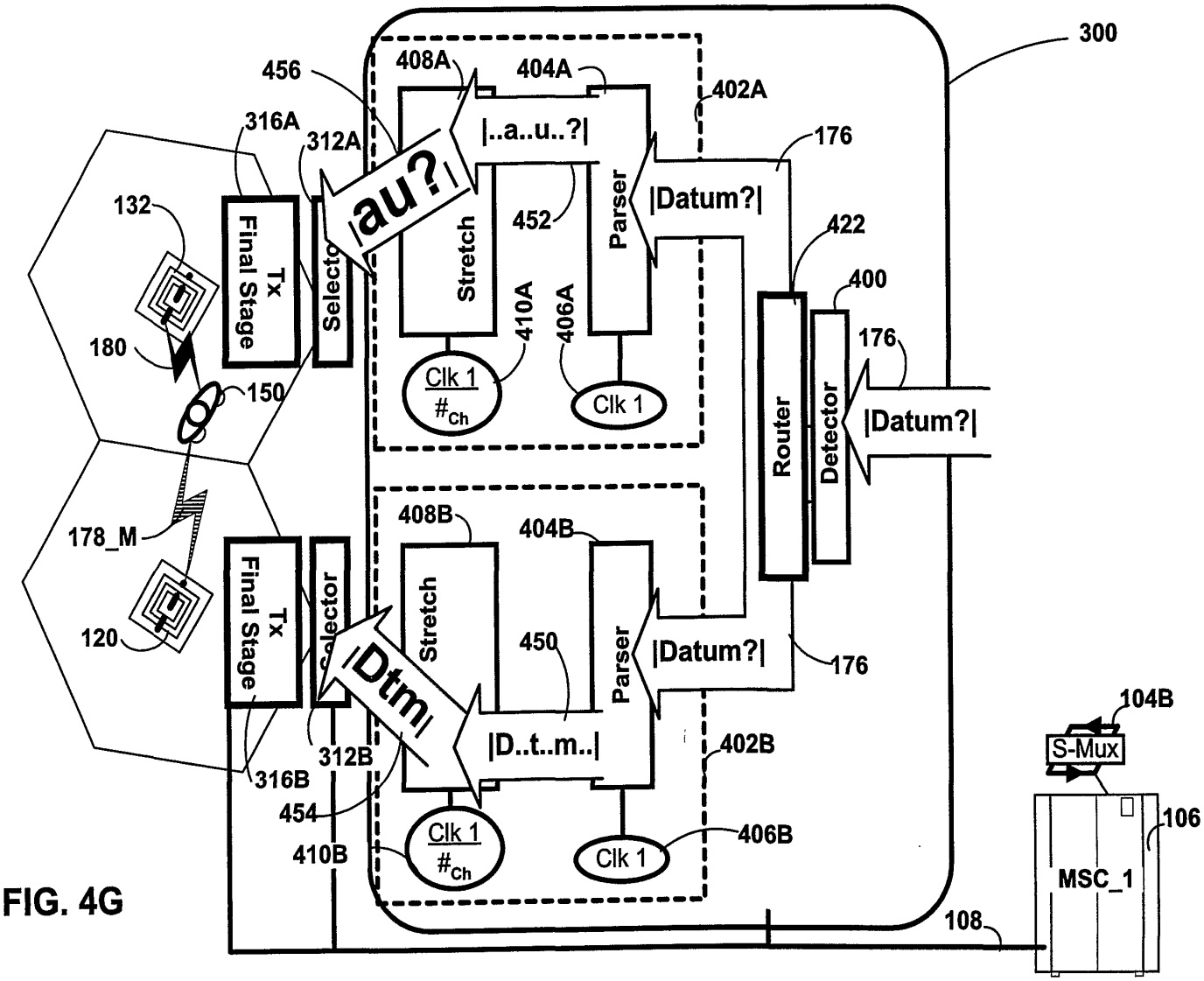

FIG. 4G

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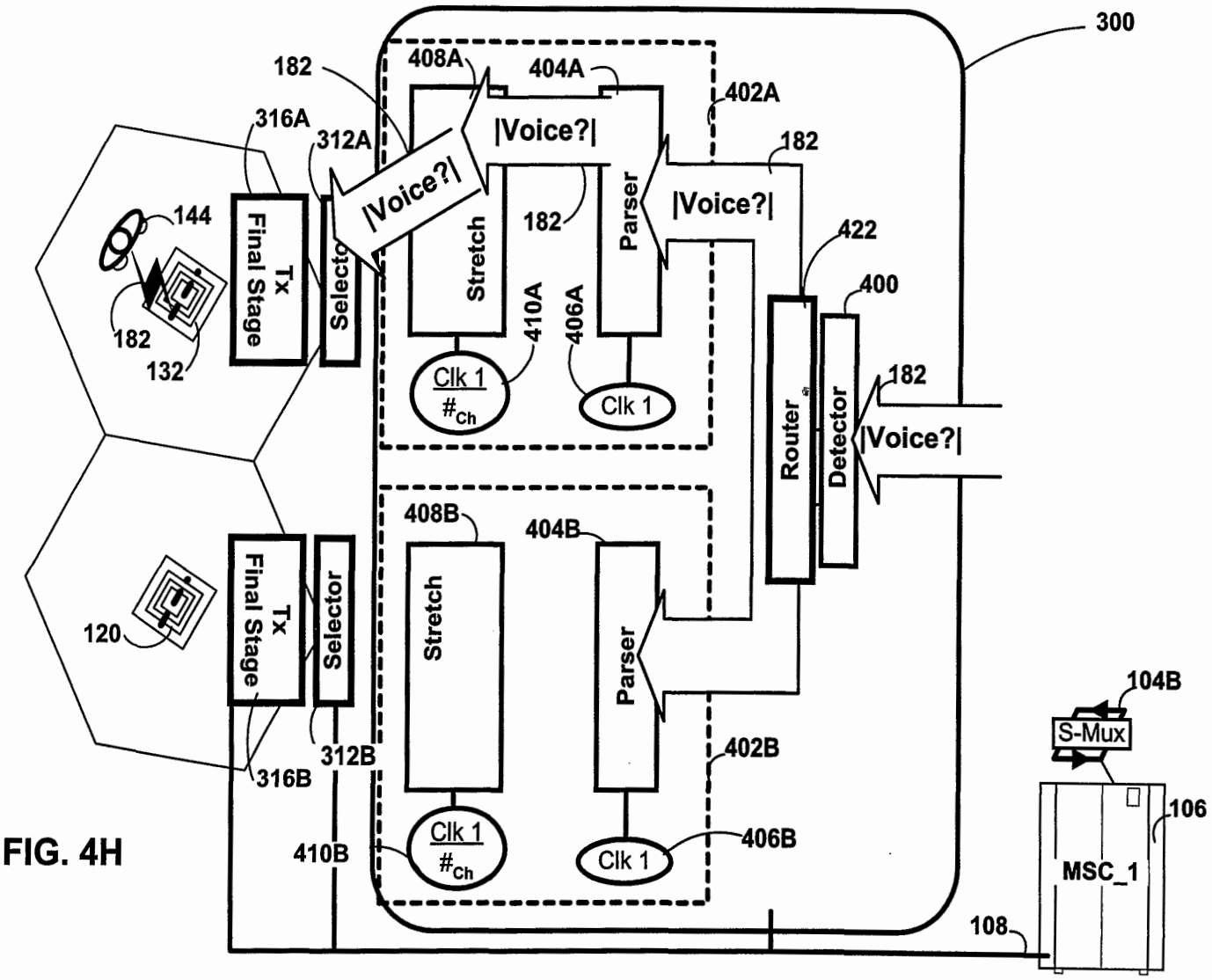
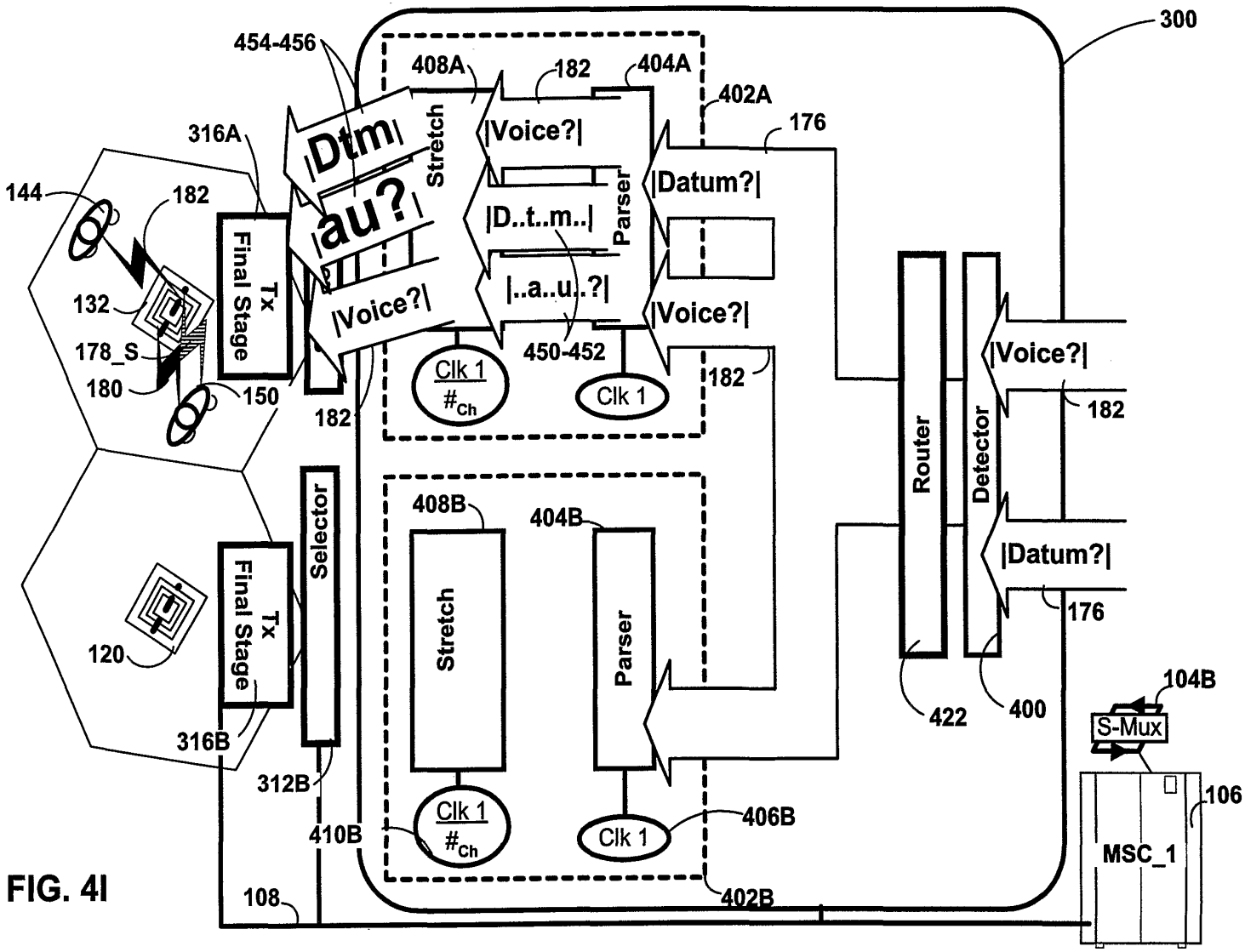


FIG. 4H

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148


300
454-456
408A
182
404A
402A
176
316A
144
182
Dtm
au?
Stretch
|Voice?|
|Datum?|
|D..t..m..|
Parser
|..a..u..?|
|Voice?|
|Voice?|
132
178_S
180
150
Tx Final Stage
182
450-452
Clk 1
#Ch
Clk 1
182
Router
Detector
|Voice?|
182
|Datum?|
176
Selector
408B
404B
Stretch
Parser
120
Tx Final Stage
316B
312B
410B
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Clk 1
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402B
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400
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S-Mux
106
MSC_1
108

FIG. 4I

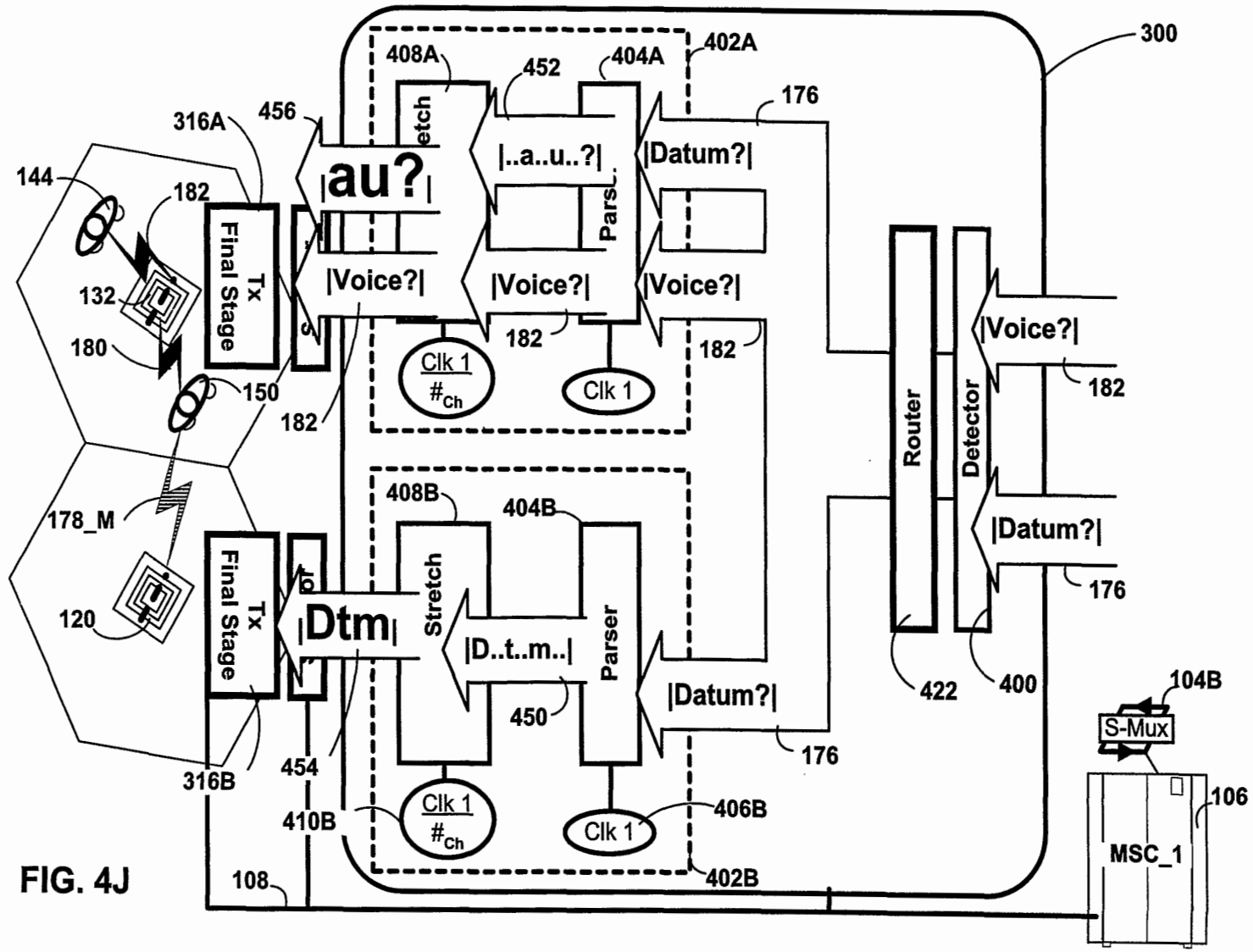

FIG. 4J

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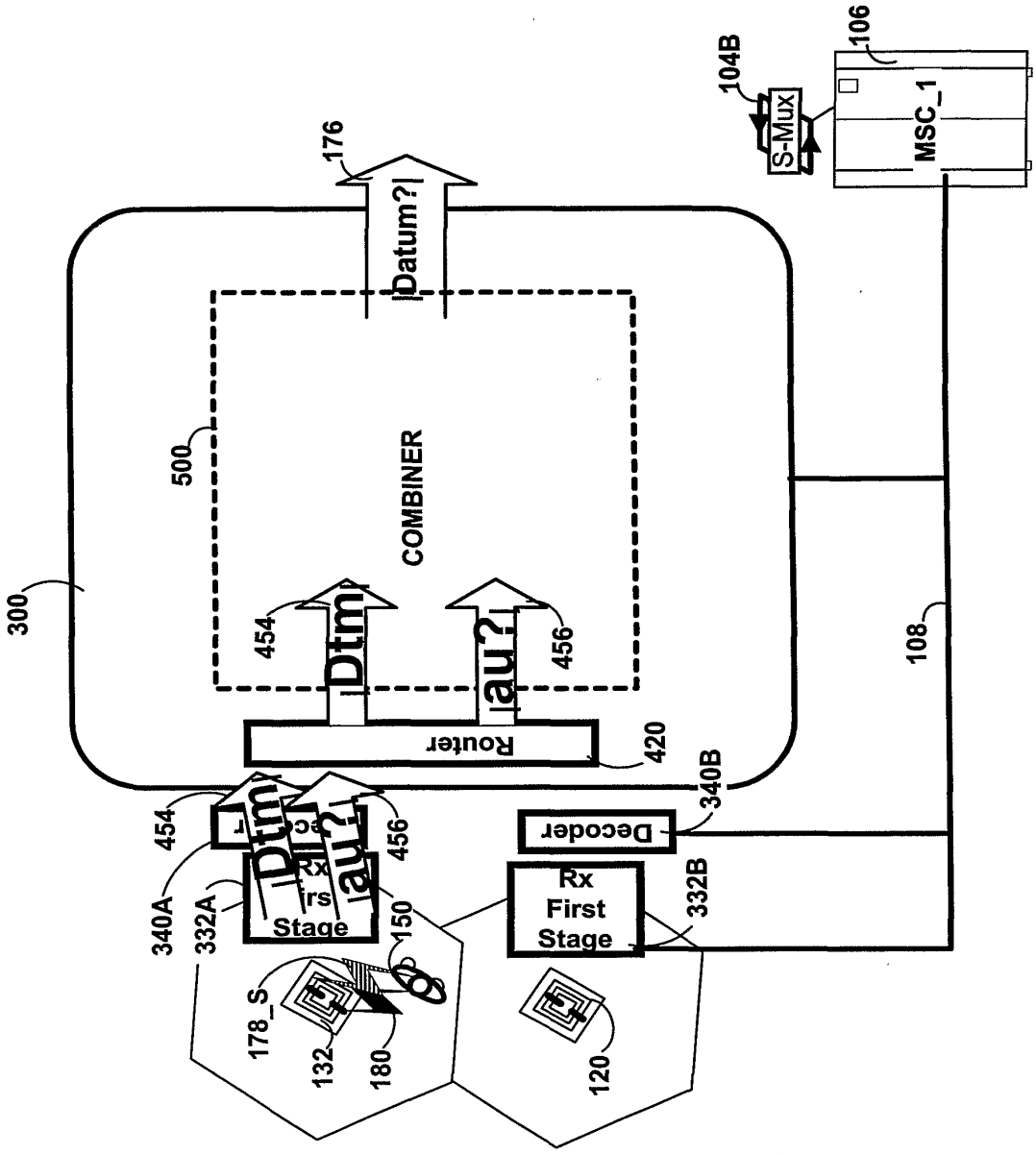
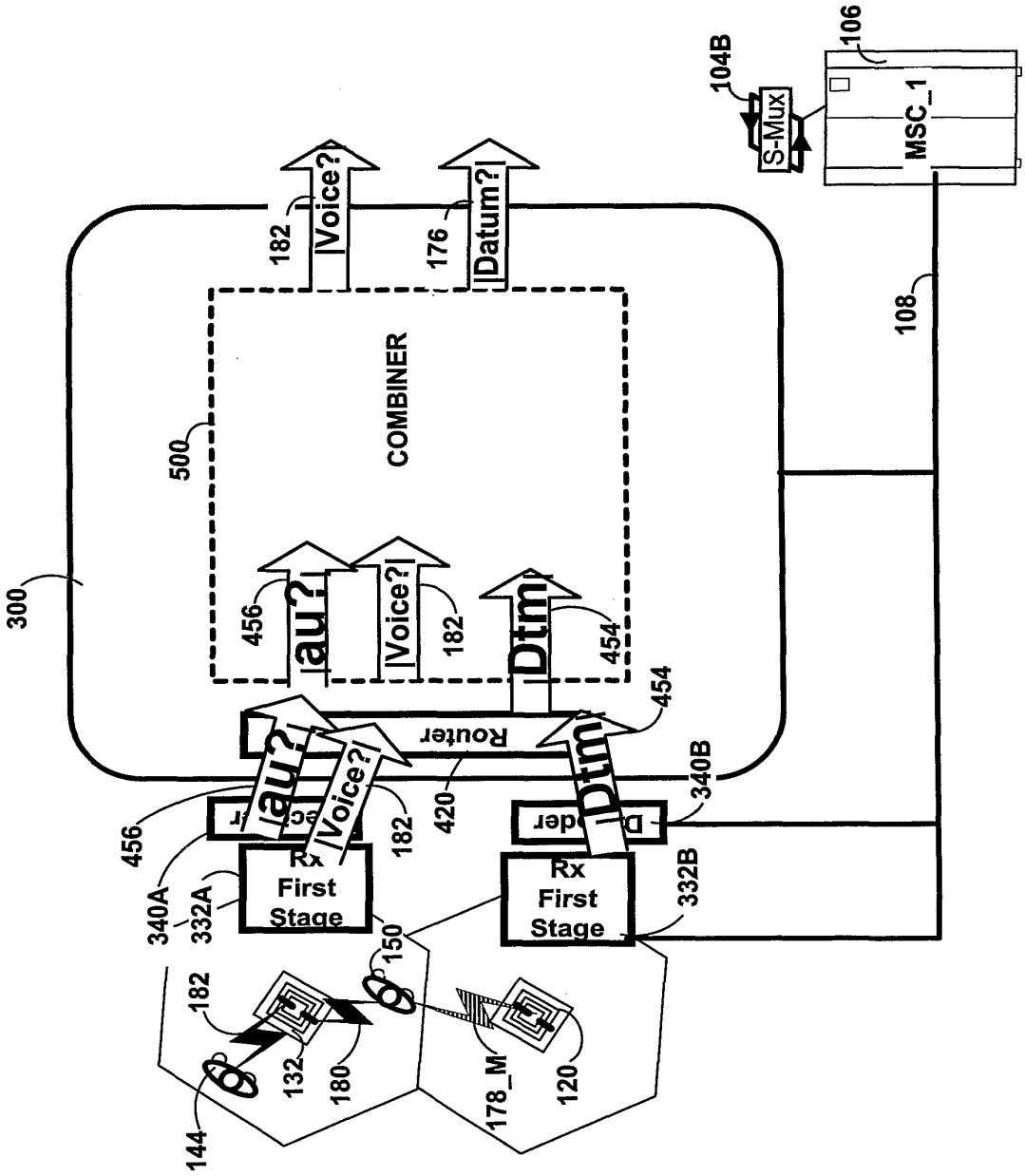


FIG. 5A

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0574 of 1285

FIG. 5B



Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0575 of 1285

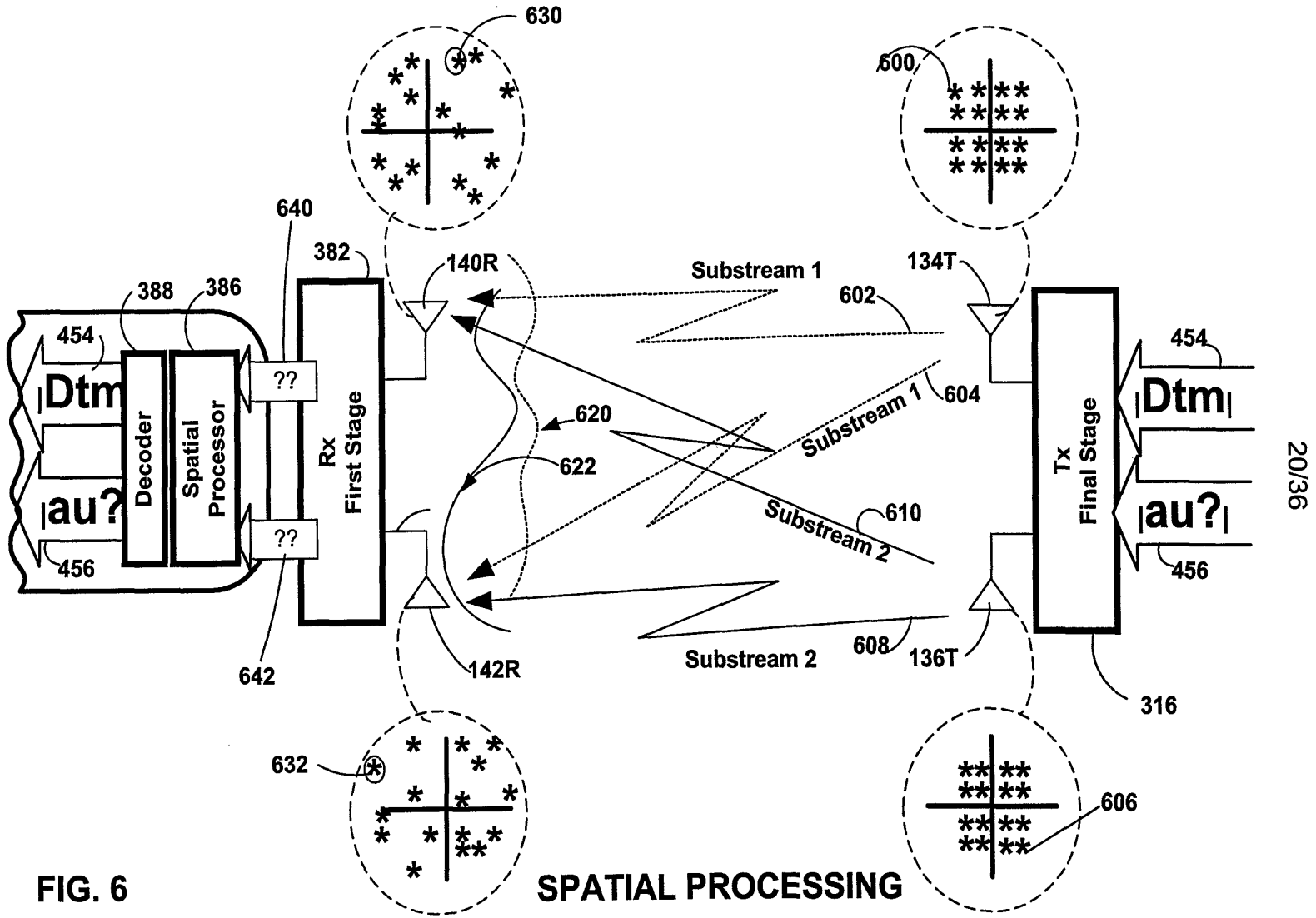


FIG. 6 SPATIAL PROCESSING

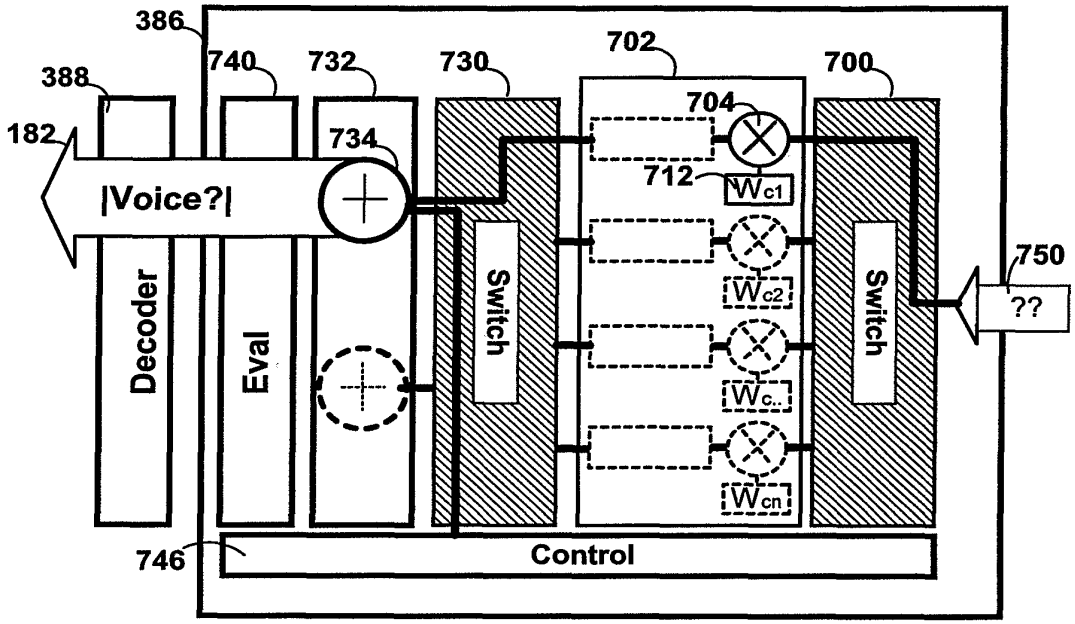
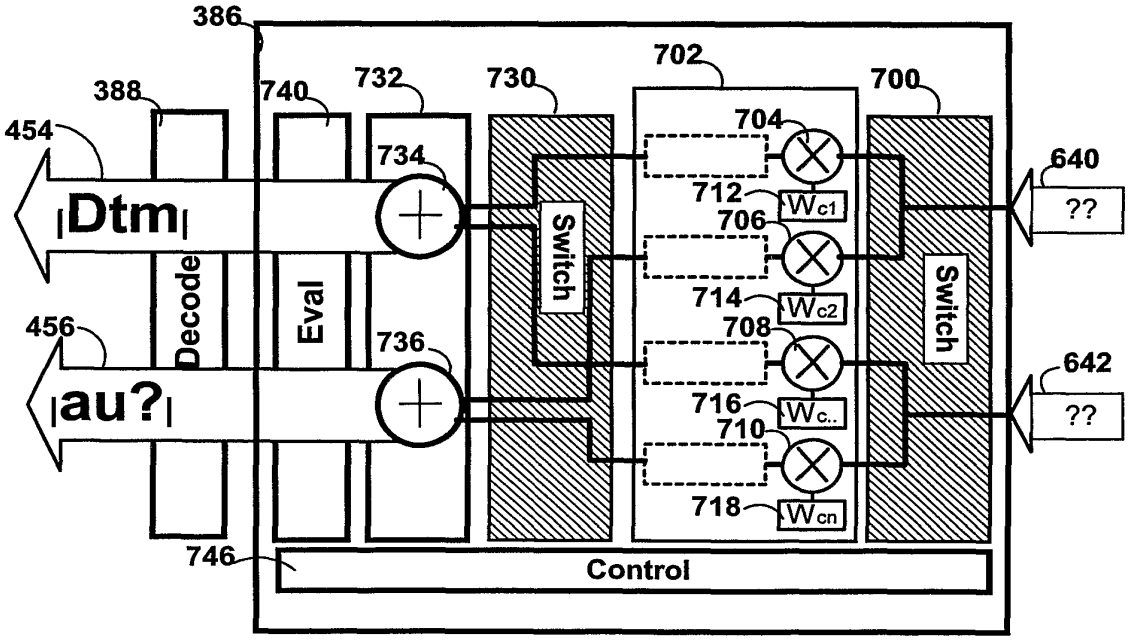

386
388
740
732
730
702
700
704
182
734
712
Wc1
|Voice?|
Wc2
Wc..
Wcn
Decoder
Eval
Switch
Switch
750
??
746
Control
Spatial Processor

FIG. 7A


386
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730
702
700
704
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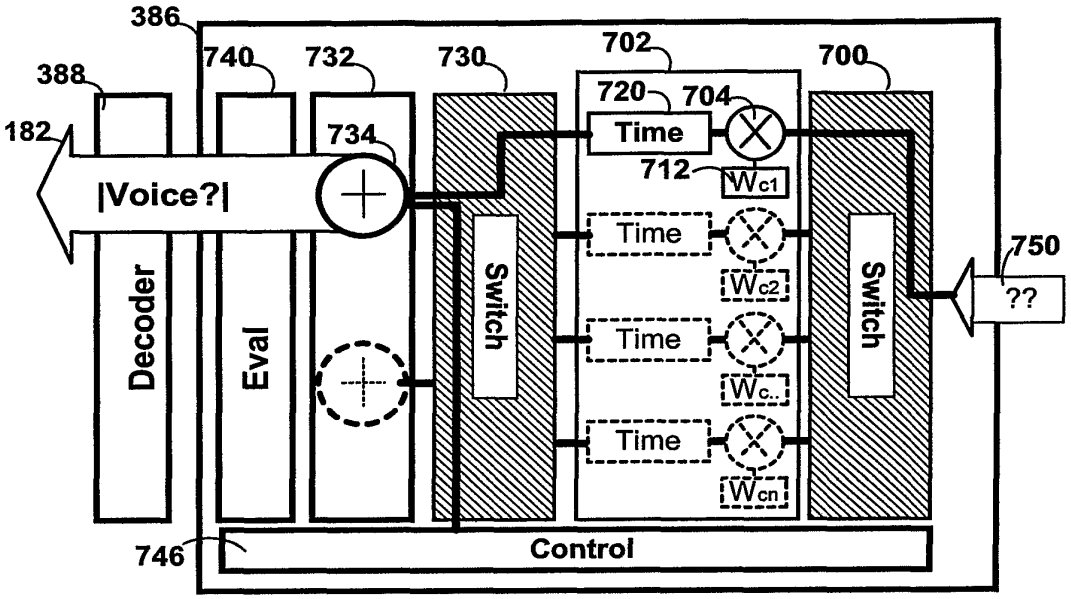
734
640
712
Wc1
??
|Dtm|
706
Switch
Switch
Decode
Eval
714
Wc2
456
708
736
642
|au?|
716
Wc..
??
710
718
Wcn
746
Control
Spatial Processor

FIG. 7B



Space-Time Processor FIG. 7C

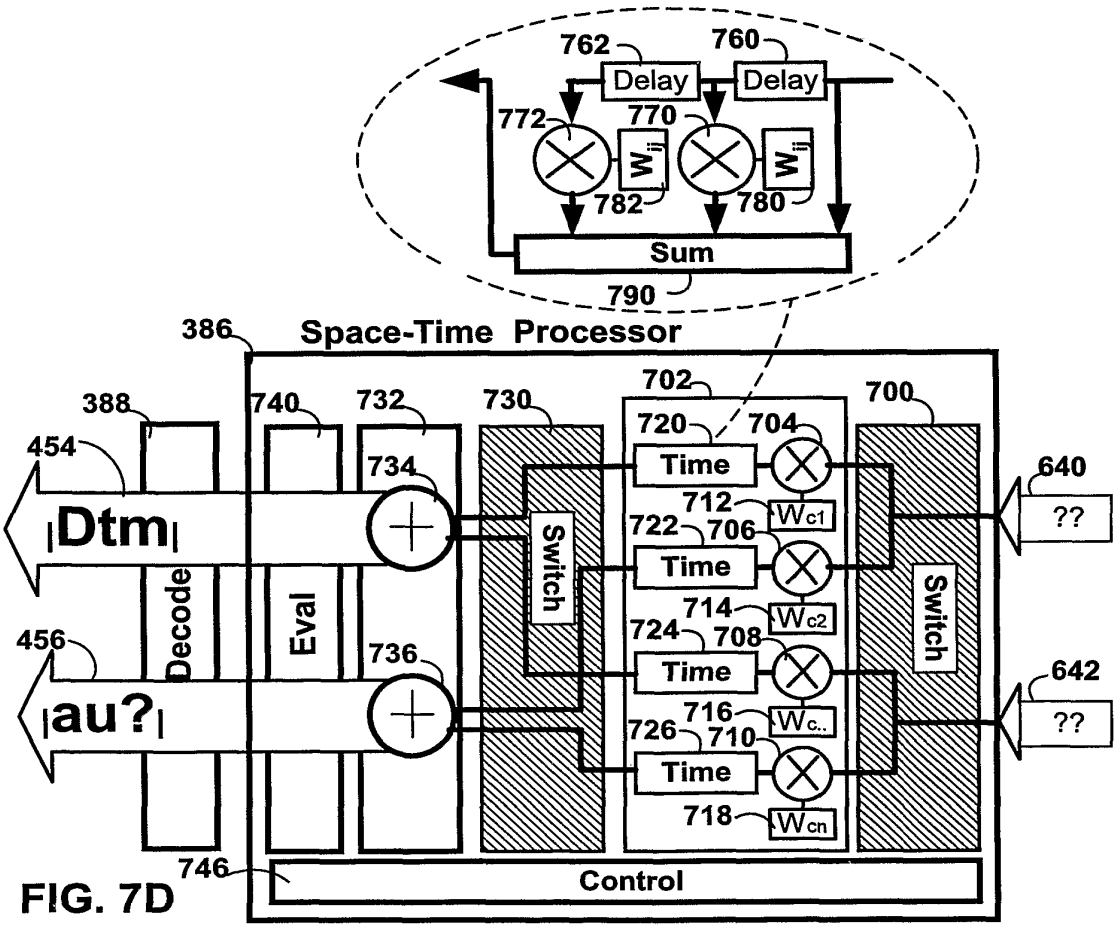


FIG. 7D

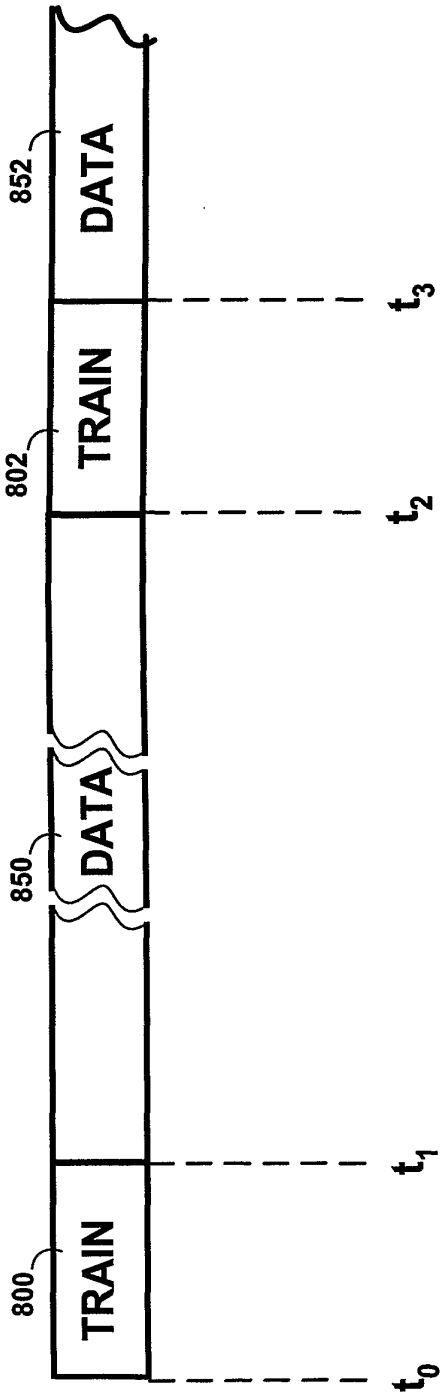


FIG. 8

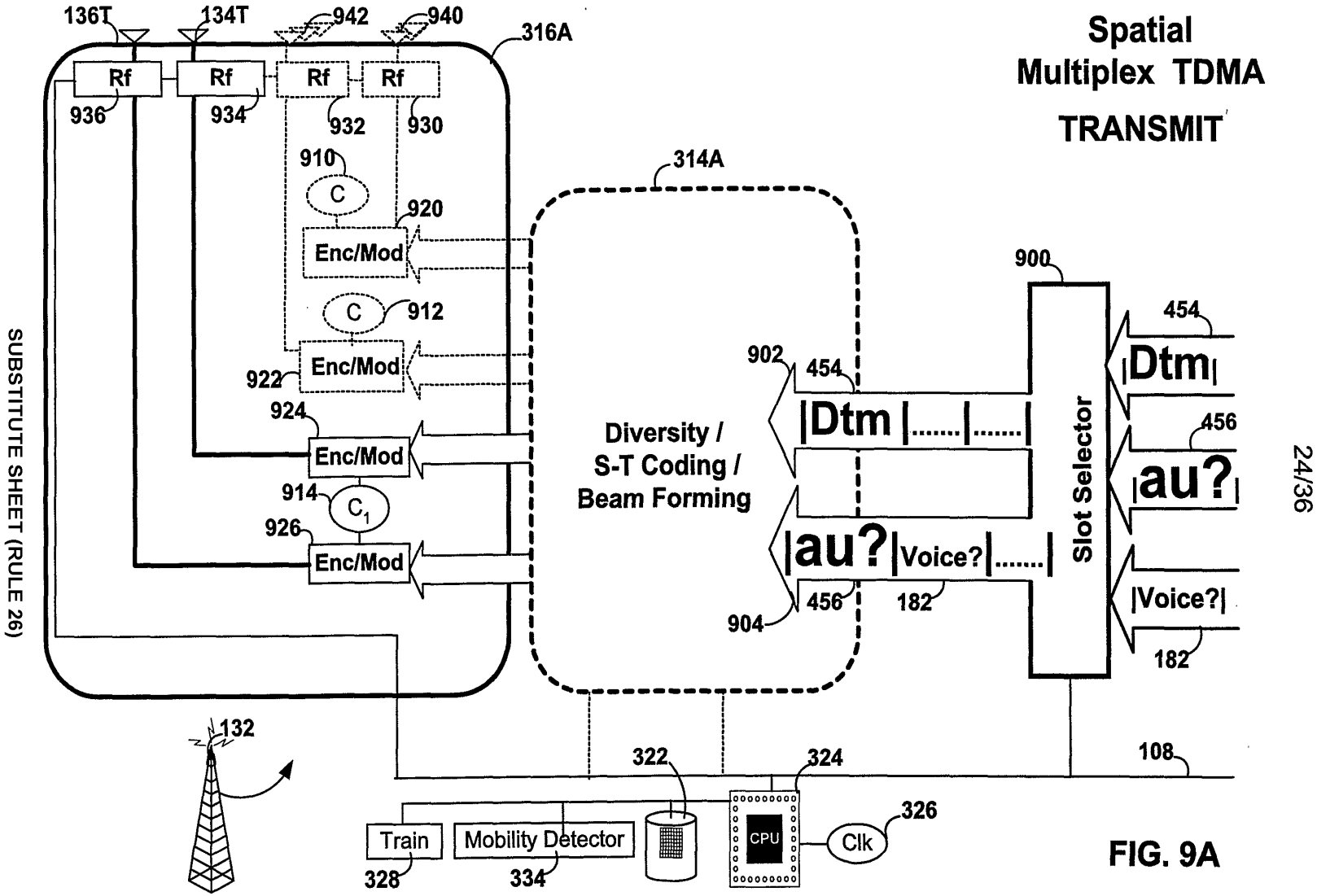

Spatial
Multiplex TDMA
TRANSMIT
136T
134T
942
940
316A
Rf
936
934
932
930
910
C
920
Enc/Mod
912
922
924
914
C_1
926
314A
Diversity /
S-T Coding /
Beam Forming
900
902
454
456
182
904
Slot Selector
|Dtm|
|au?|
|Voice?|
132
322
324
108
Train
328
Mobility Detector
334
CPU
Clk
326

FIG. 9A

SUBSTITUTE SHEET (RULE 26)

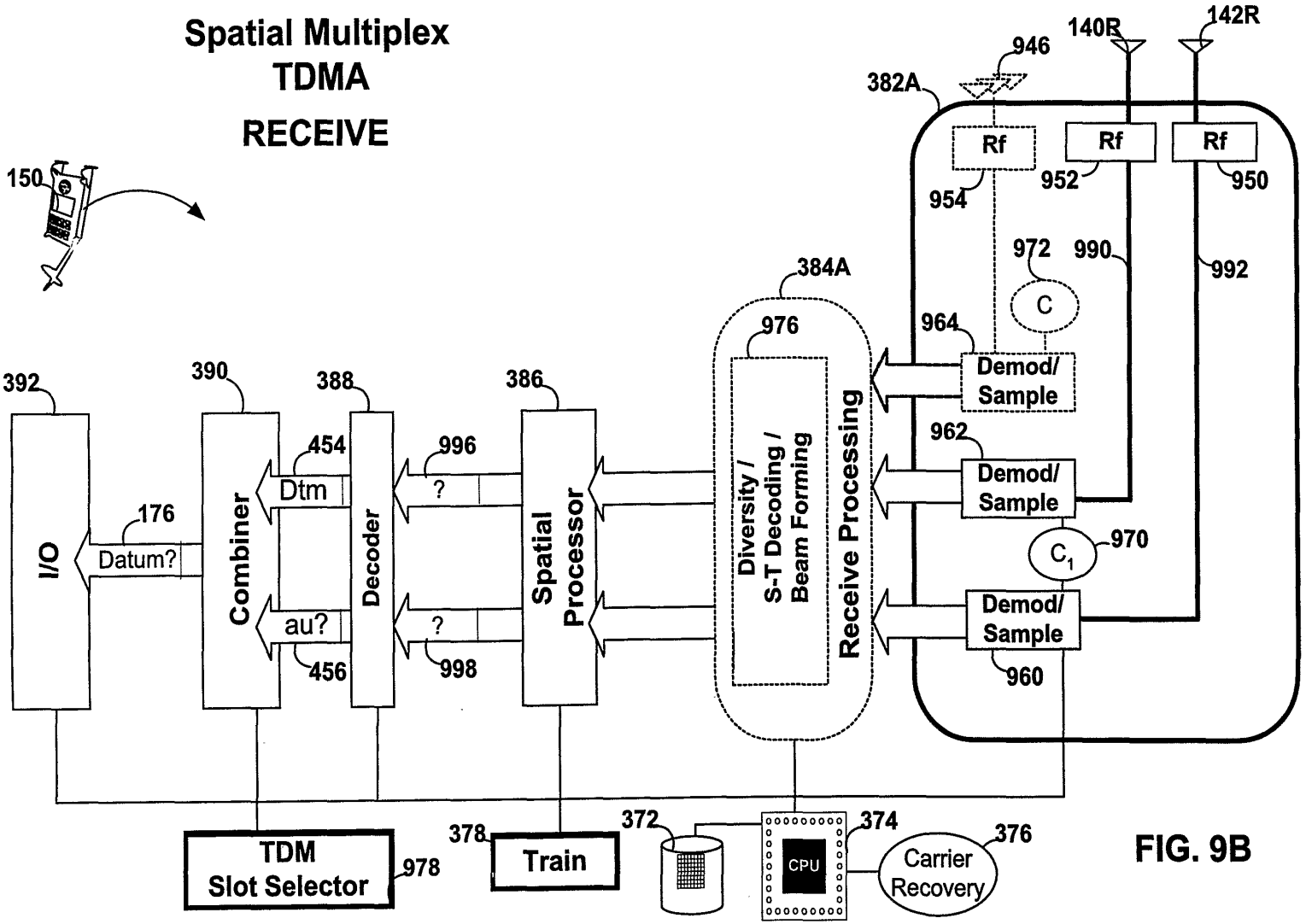


FIG. 9B

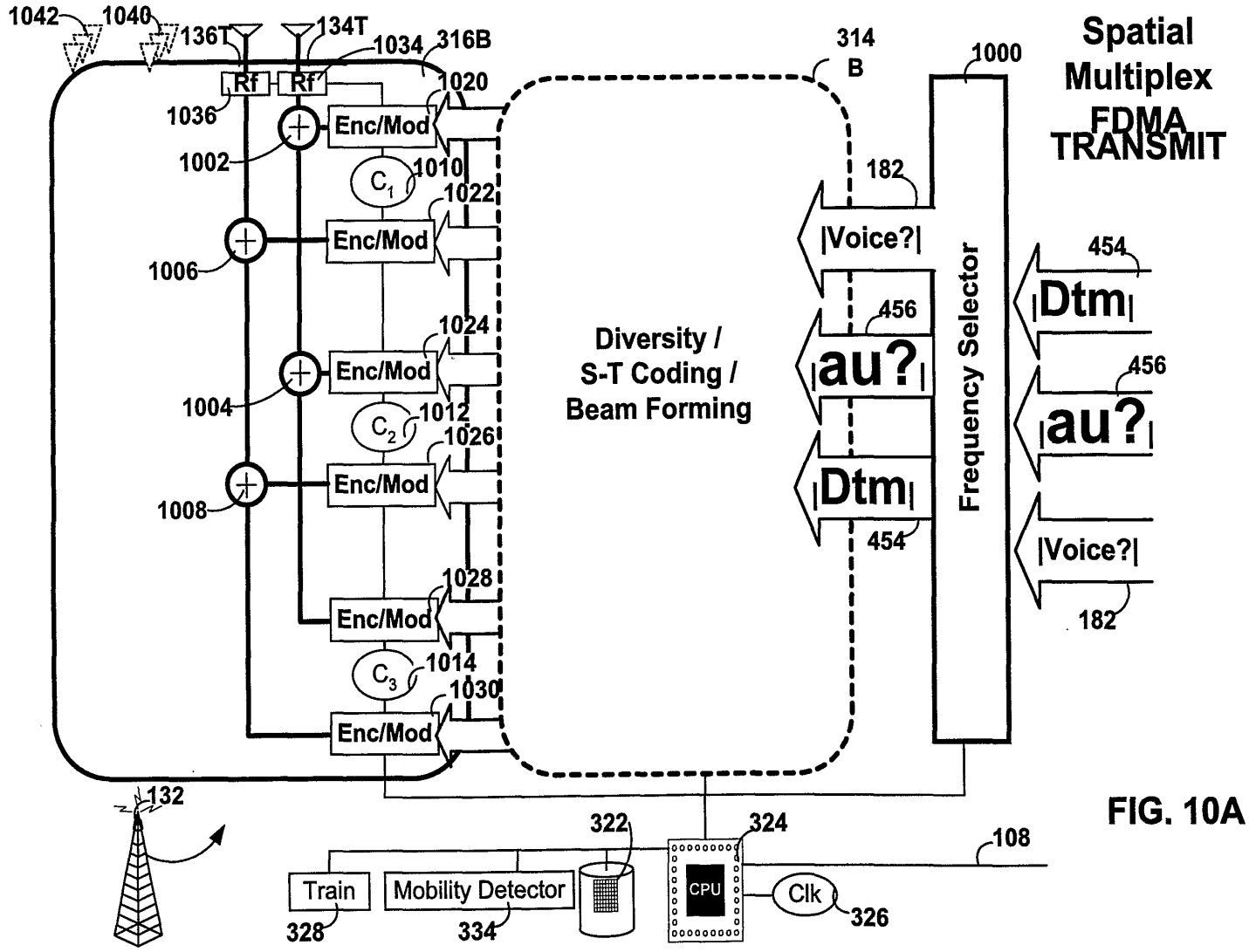


FIG. 10A

SUBSTITUTE SHEET (RULE 26)

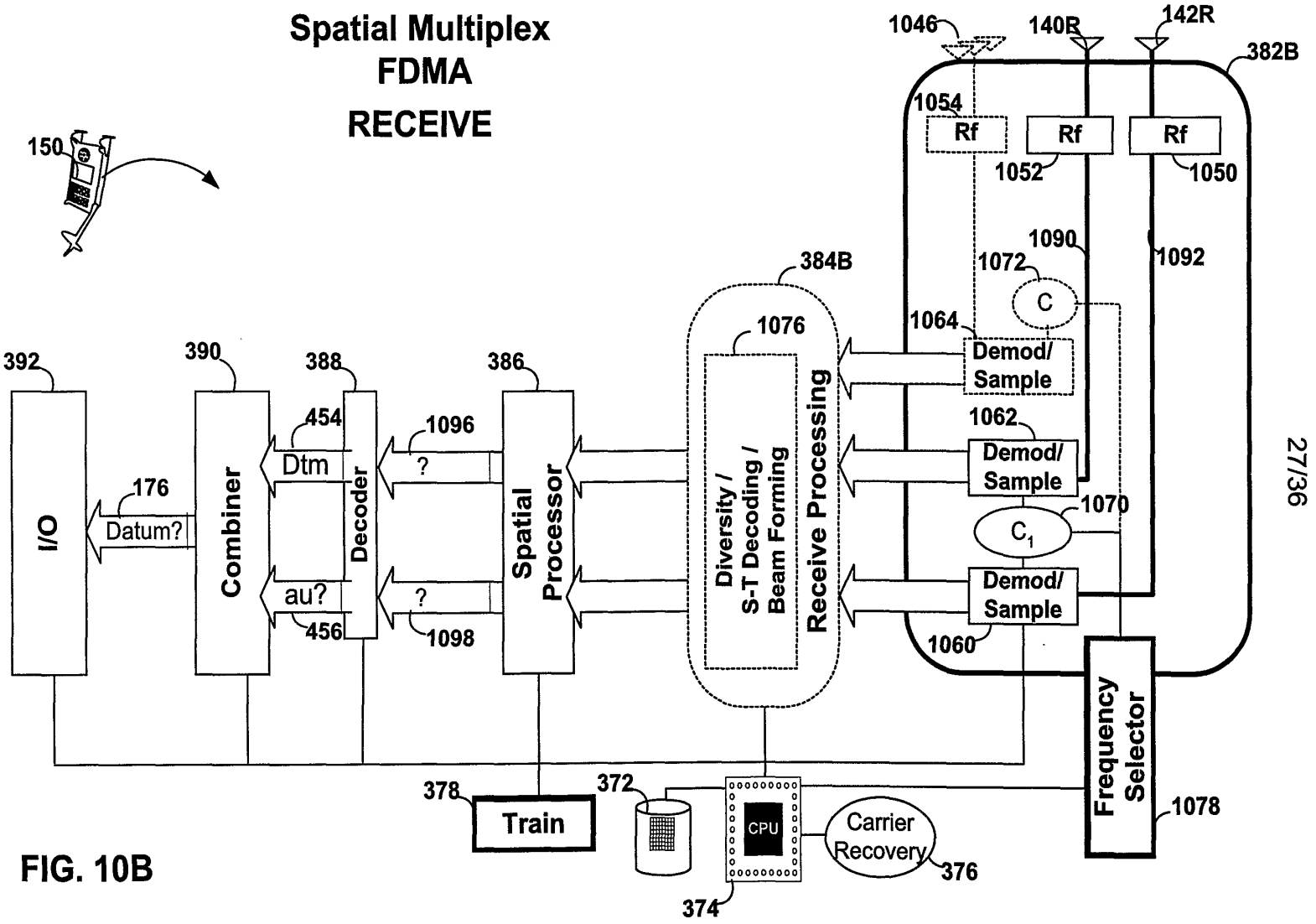

Spatial Multiplex
FDMA
RECEIVE
150
1046
140R
142R
382B
1054
Rf
Rf
Rf
1052
1050
1090
1092
1072
C
384B
1076
1064
Demod/
Sample
1062
Demod/
Sample
1070
C1
Demod/
Sample
1060
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
392
390
388
386
I/O
176
Datum?
Combiner
454
Dtm
au?
456
Decoder
1096
?
?
1098
Spatial
Processor
Frequency
Selector
1078
378
Train
372
CPU
Carrier
Recovery
376
374

FIG. 10B

SUBSTITUTE SHEET (RULE 26)

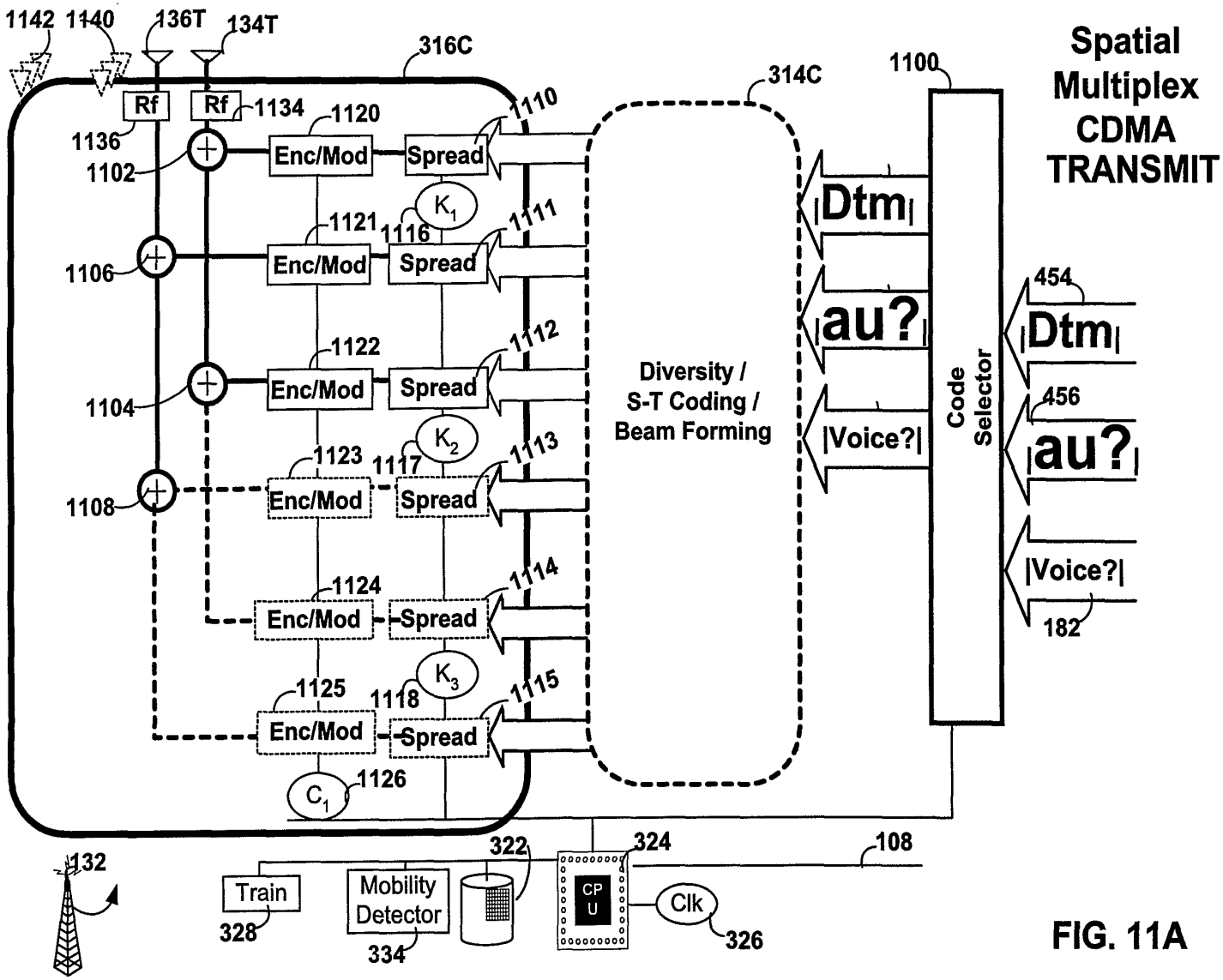
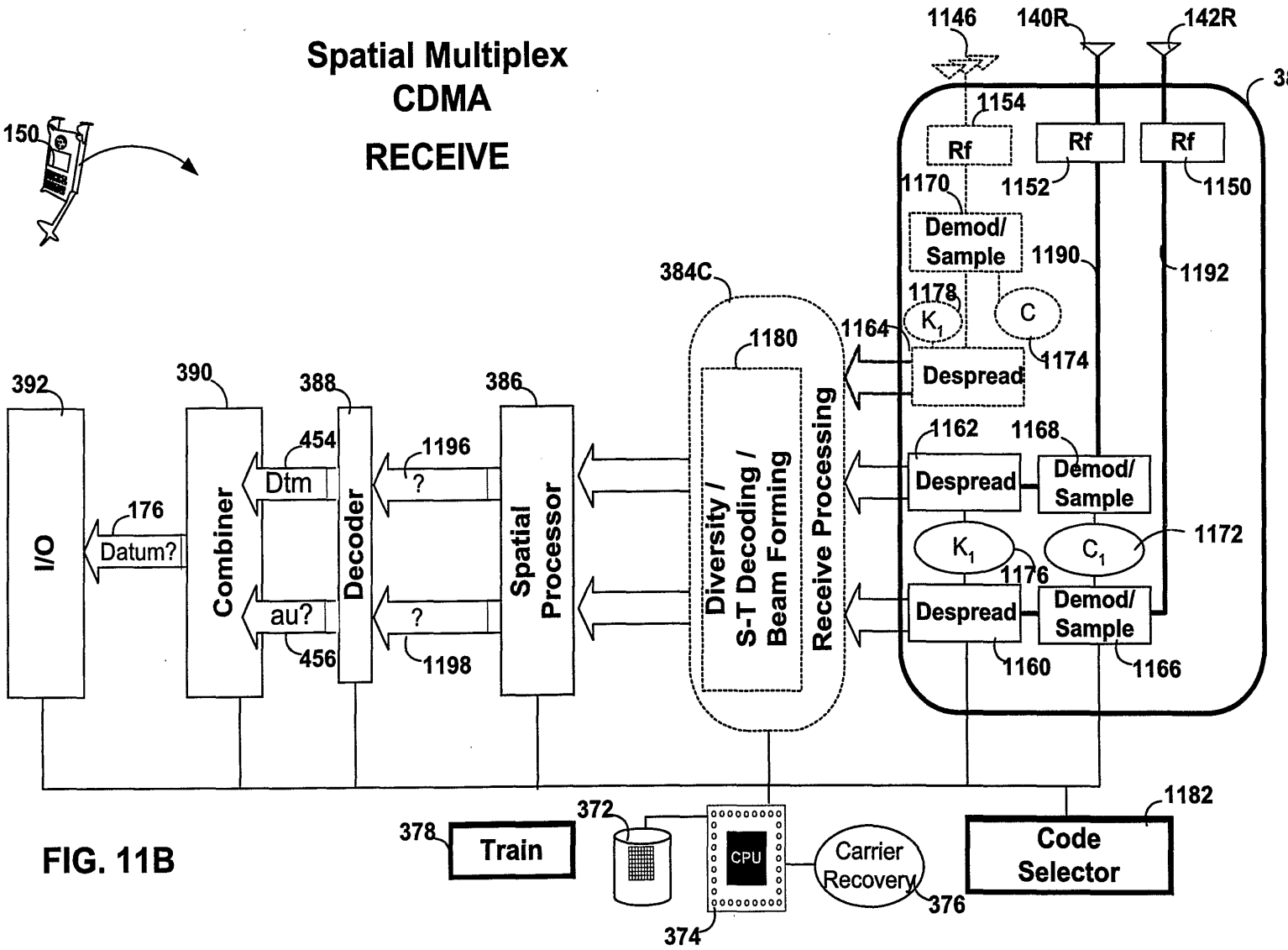


FIG. 11A


Spatial Multiplex
CDMA
RECEIVE
150
1146
140R
142R
382C
1154
Rf
Rf
Rf
1170
1152
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Demod/
Sample
1190
1192
384C
1178
K_1
C
1164
1180
1174
Despread
392
390
388
386
454
1196
1162
1168
Despread
Demod/
Sample
I/O
Combiner
Decoder
Spatial
Processor
Diversity /
S-T Decoding /
Beam Forming
Receive Processing
Dtm
?
176
K_1
C_1
1172
Datum?
1176
au?
?
Despread
Demod/
Sample
456
1198
1160
1166
1182
372
378
Train
CPU
Carrier
Recovery
Code
Selector
376
374

FIG. 11B

SUBSTITUTE SHEET (RULE 26)

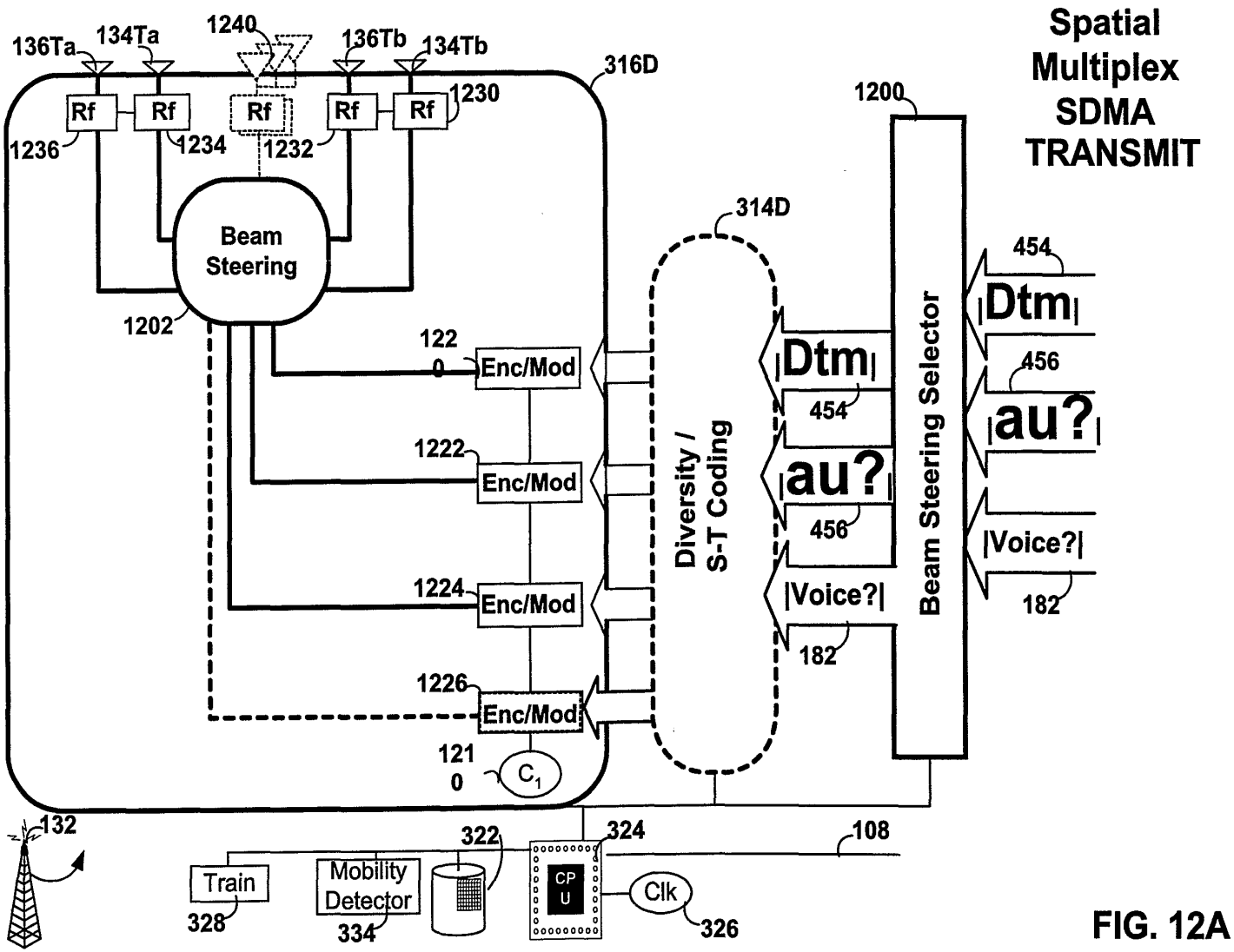


FIG. 12A

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

SUBSTITUTE SHEET (RULE 26)

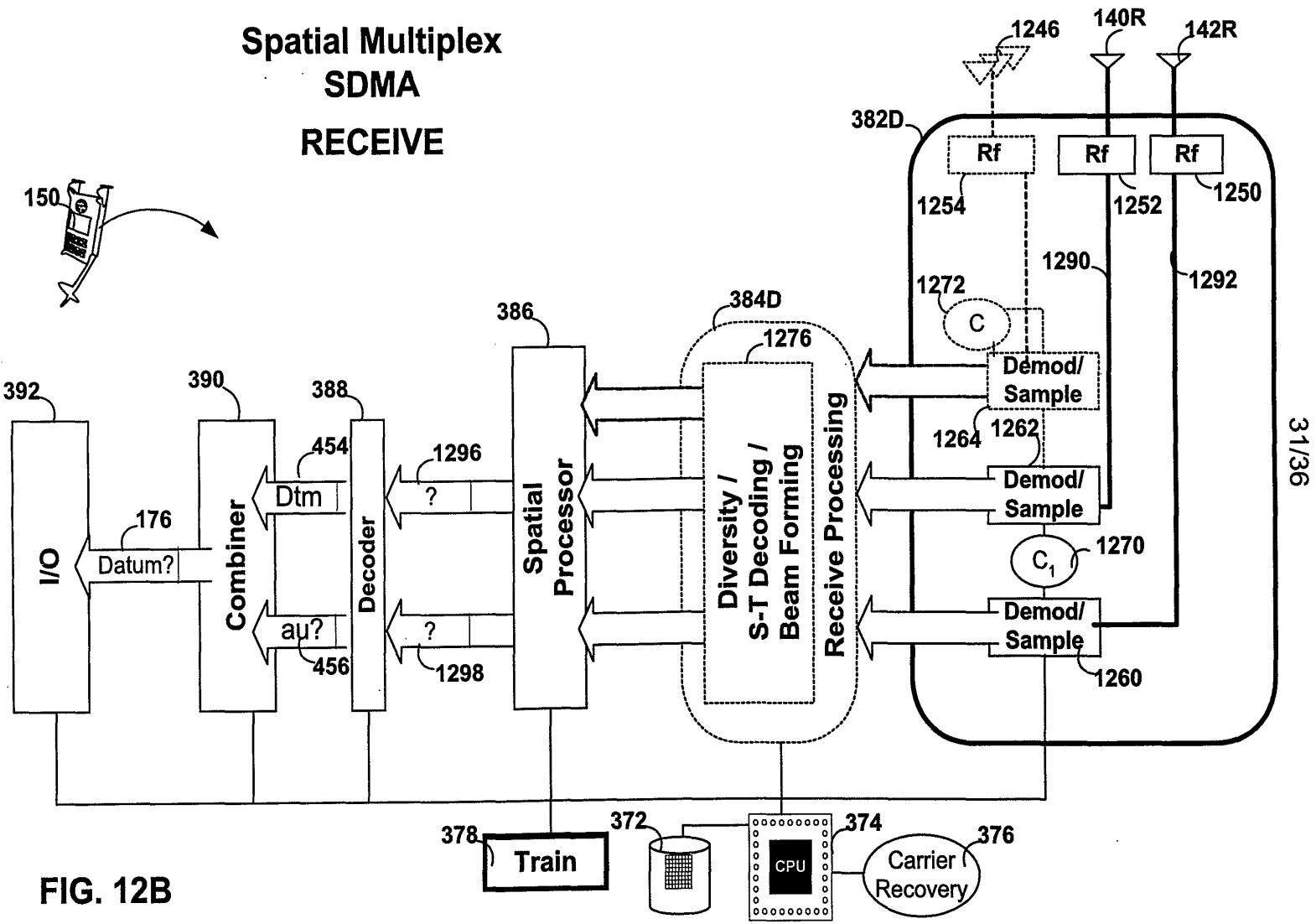


FIG. 12B

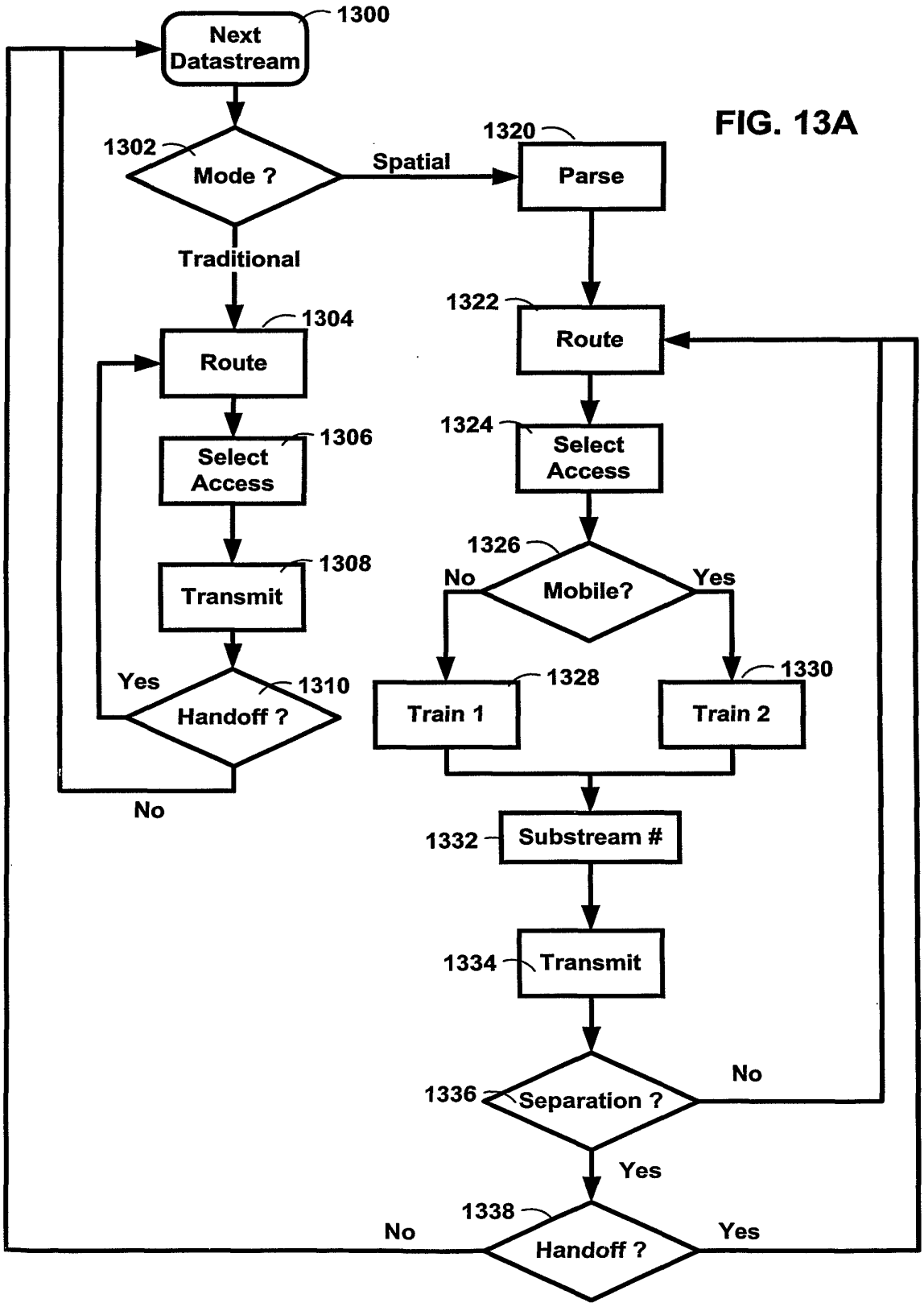
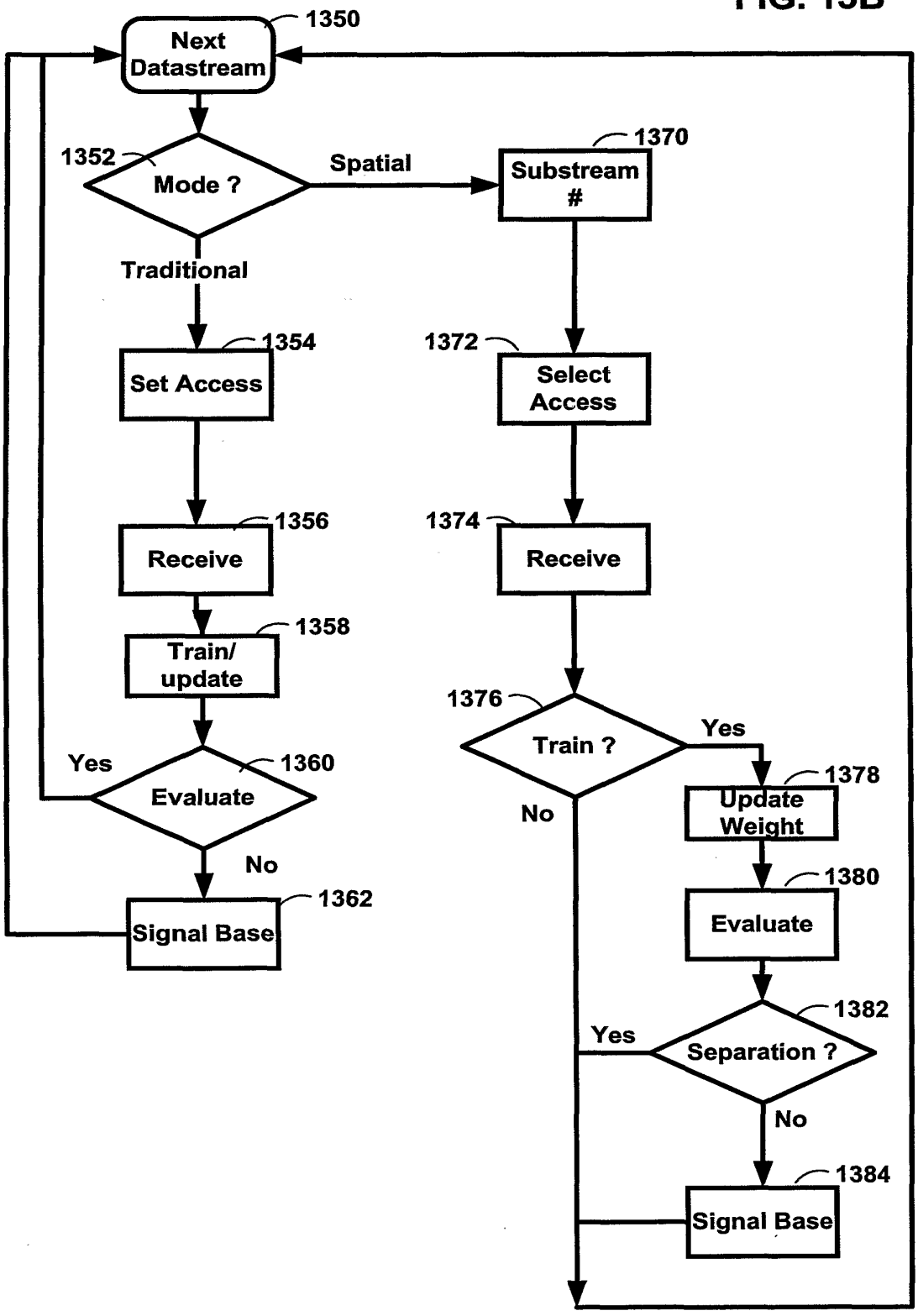


FIG. 13A

Exhibit 1002
Page 0588 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 13B


1350
Next Datastream
1352
Mode ?
Spatial
1370
Substream #
Traditional
1354
Set Access
1372
Select Access
1356
Receive
1374
Receive
1358
Train/ update
1376
Train ?
Yes
1378
Update Weight
Yes
1360
Evaluate
No
1362
Signal Base
No
1380
Evaluate
1382
Separation ?
Yes
No
1384
Signal Base

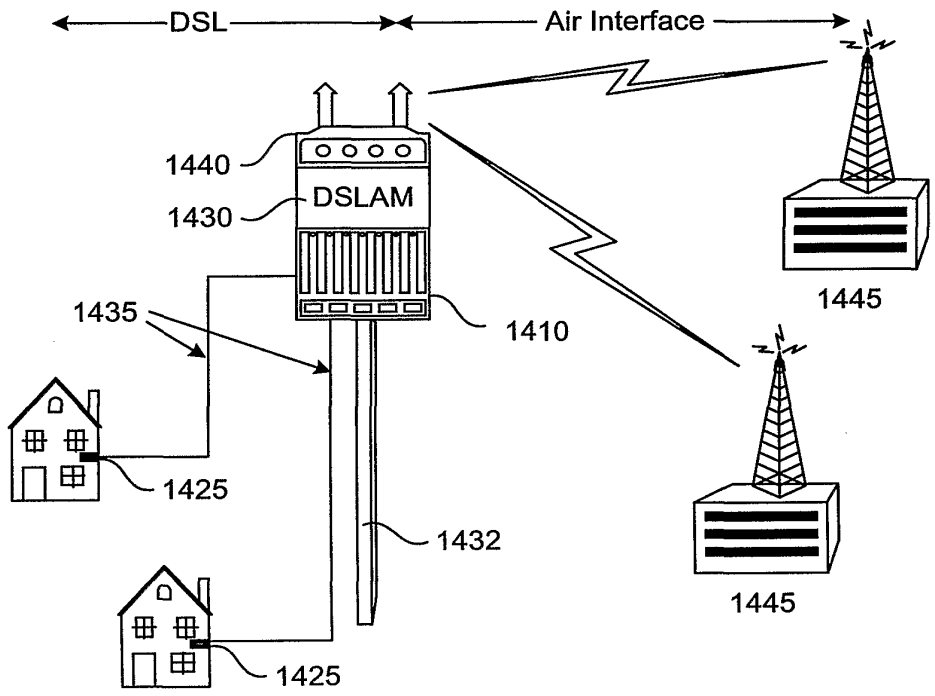

DSL
Air Interface
1440
DSLAM
1430
1435
1410
1445
1425
1432
1445
1425

FIG. 14

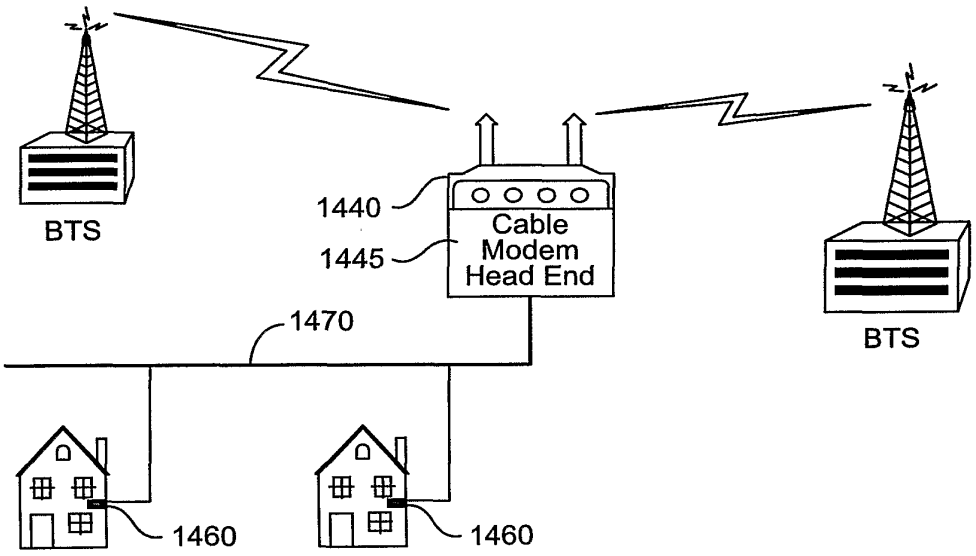


FIG. 15

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

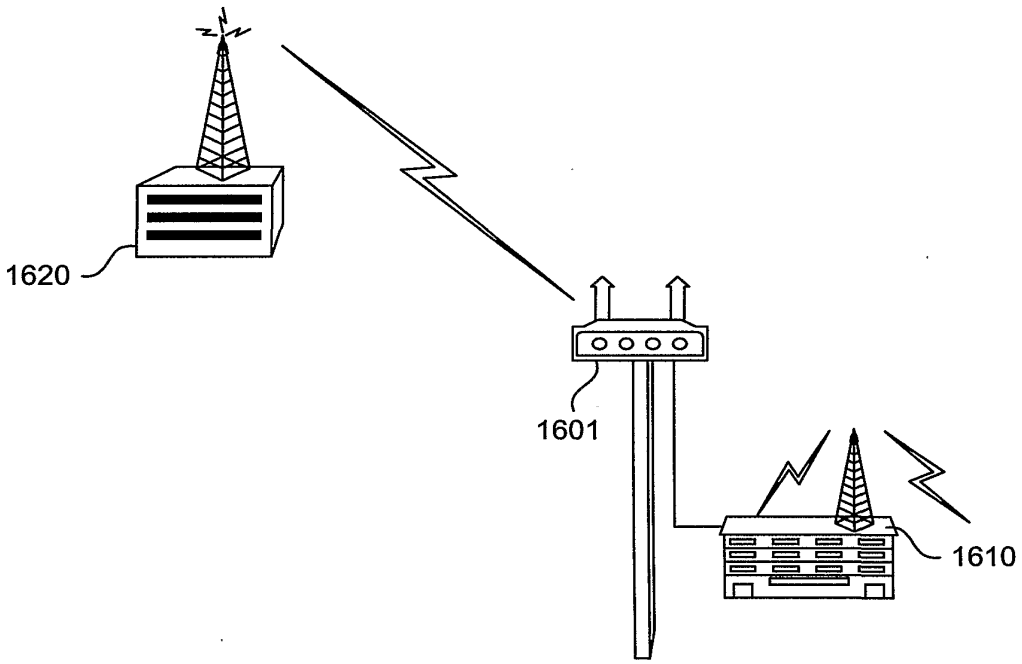


FIG. 16

INTERNATIONAL SEARCH REPORT

Int onal Application No
PCT/US 00/20706

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q7/36 H04B7/005

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04Q H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PAULRAJ A J ET AL: "TAXONOMY OF SPACE-TIME PROCESSING FOR WIRELESS NETWORKS" IEE PROCEEDINGS: RADAR, SONAR & NAVIGATION,GB,INSTITUTION OF ELECTRICAL ENGINEERS, vol. 145, no. 1, 1 February 1998 (1998-02-01), pages 25-31, XP000769921 ISSN: 1350-2395 page 25, paragraph 2.1 -page 26 page 26, paragraph 2.2.2 -page 27 page 27, paragraph 3.1 page 28, column 1 --- -/--	1-76

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the International search	Date of mailing of the International search report
18 October 2000	25/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Dheere, R

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INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/US 00/20706

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 98 09381 A (RALEIGH) 5 March 1998 (1998-03-05) page 1, line 14 - line 18 page 2, line 5 -page 3, line 6 page 6, line 5 - line 25 page 7, line 2 - line 17 page 9, line 22 - line 35 page 10 page 11 page 15, line 5 - line 24 page 19, line 5 -page 20, line 15 figure 5A	1-76
A	WO 98 34424 A (AT&T) 6 August 1998 (1998-08-06) page 3, line 8 - line 13 page 5, line 17 - line 21	1,18,26, 27,29, 34,41, 43-45, 54,56, 58-60, 62-67, 69,70
A	US 5 592 490 A (ARRAYCOMM) 7 January 1997 (1997-01-07) column 11, line 10 - line 15 abstract figure 1	1,18,26, 27,29, 34,41, 43-45, 54,56, 58-60, 62-67, 69,70
P,X	US 6 067 290 A (GIGABIT WIRELESS) 23 May 2000 (2000-05-23) the whole document	1-76

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INTERNATIONAL SEARCH REPORT

Int onal Application No
PCT/US 00/20706

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9809381 A	05-03-1998	AU 4238697 A	19-03-1998
		EP 0920738 A	09-06-1999
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		BR 9510197 A	23-12-1997
		CA 2210859 A	25-07-1996
		CN 1173265 A	11-02-1998
		EP 0804858 A	05-11-1997
		FI 973076 A	16-09-1997
		JP 11504169 T	06-04-1999
		WO 9622662 A	25-07-1996
		WO 9818272 A	30-04-1998
		US 5828658 A	27-10-1998
		AT 183865 T	15-09-1999
		AU 670766 B	01-08-1996
		AU 3145493 A	19-07-1993
		CA 2125571 A	24-06-1993
		DE 69229876 D	30-09-1999
		DE 69229876 T	30-12-1999
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		ES 2137197 T	16-12-1999
		FI 942771 A	10-06-1994
		JP 7505017 T	01-06-1995
		WO 9312590 A	24-06-1993
		US 5625880 A	29-04-1997
		US 5642353 A	24-06-1997
US 6067290 A	23-05-2000	NONE	

Form PCT/ISA/210 (patent family annex) (July 1992)

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
12 September 2003 (12.09.2003)

PCT

(10) International Publication Number
WO 03/075396 A2

(51) International Patent Classification[7]: H01Q

(21) International Application Number: PCT/US03/05642

(22) International Filing Date: 26 February 2003 (26.02.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/361,055	1 March 2002 (01.03.2002)	US
60/365,797	21 March 2002 (21.03.2002)	US
10/174,728	19 June 2002 (19.06.2002)	US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 10/174,728 (CIP)
Filed on 19 June 2002 (19.06.2002)

(71) Applicant *(for all designated States except US)*: **COGNIO, INC.** [US/US]; 101 Orchard Ridge Drive, Suite 350, Gaithersburg, MD 20878 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **SUGAR, Gary, L.** [US/US]; 15307C Diamond Cove Terrace, Rockville, MD 20850 (US). **VAIDYANATHAN, Chandra** [IN/US]; 10411 Montrose Avenue, #202, Bethesda, MD 20814 (US). **TESFAI, Yohannes** [ER/US]; 2230 George C. Marshall Drive, Apartment 104, Falls Church, VA 22043 (US).

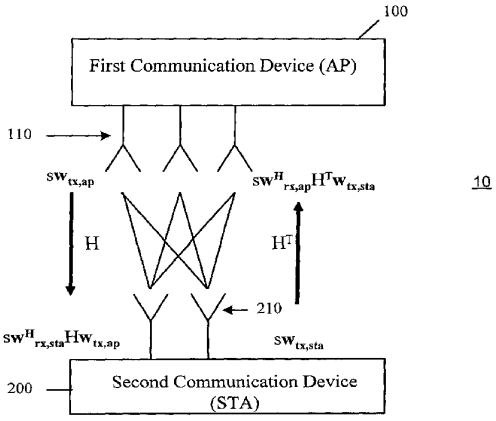
(74) Agent: **FLOAM, D., Andrew**; Cognio, Inc., 101 Orchard Ridge Drive, Suite 350, Gaithersburg, MA 20878 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI,

[Continued on next page]

(54) Title: SYSTEM AND METHOD FOR ANTENNA DIVERSITY USING JOINT MAXIMAL RATIO COMBINING



(57) Abstract: A composite beamforming technique is provided wherein a first communication device has a plurality of antennas and the second communication has a plurality of antennas. When the first communication device transmits to the second communication device, the transmit signal is multiplied by a transmit weight vector for transmission by each the plurality of antennas and the transmit signals are received by the plurality of antennas at the second communication device. The second communication device determines the best receive weight vector for the its antennas, and from that vector, derives a suitable transmit weight vector for transmission on the plurality of antennas back to the first communication device. Several techniques are provided to determine the optimum transmit weight vector and receive weight vector for communication between the first and second communication devices so that there is effectively joint or composite beamforming between the communication devices.

WO 03/075396 A2

SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

SYSTEM AND METHOD FOR ANTENNA DIVERSITY USING JOINT MAXIMAL RATIO COMBINING

This application claims priority to U.S. Provisional Application No. 60/361,055, filed March 1, 2002 and to U.S. Provisional Application No. 60/365,797 filed March 21, 2002, the entirety of both of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention is directed to antenna (spatial) signal processing useful in wireless communication applications, such as short-range wireless applications.

Antenna diversity schemes are well known techniques to improve the performance of radio frequency (RF) communication between two RF devices. Types of antenna diversity schemes include antenna selection diversity and maximal ratio combining. An antenna selection diversity scheme selects one of two antennas for transmission to a particular communication device based on which of the two antennas best received a signal from the particular communication device. On the other hand, maximal ratio combining schemes involve beamforming a signal to be transmitted by two or more antennas by scaling the signal with an antenna weight associated with each antenna. A signal received by a plurality of antennas can also be weighted by a plurality of receive antenna weights. Selection of the antenna weights to optimize communication between two communication devices is critical to the performance of maximal ratio combining schemes.

There is room for improving the maximal ratio combining antenna processing schemes to optimize the link margin between two RF communication devices.

SUMMARY OF THE INVENTION

An antenna signal processing scheme, hereinafter called composite beamforming (CBF), is provided to optimize the range and performance RF communication between two communication devices. Composite beamforming

(CBF) is a multiple-input multiple-output (MIMO) antenna scheme that uses antenna signal processing at both ends of the communication link to maximize the signal-to-noise (SNR) and/or signal-to-noise-plus-interference (SNIR), thereby improving the link margin between two communication devices, as well as to provide for other advantages described herein.

Generally, a first communication device has a plurality of antennas and the second communication has a plurality of antennas. The first communication device transmits to the second communication device using a transmit weight vector for transmission by each the plurality of antennas and the transmit signals are received by the plurality of antennas at the second communication device. The second communication device determines the receive weight vector for its antennas, and from that vector, derives a suitable transmit weight vector for transmission on the plurality of antennas back to the first communication device. Several techniques are provided to determine the optimum frequency dependent transmit weight vector and receive weight vector across the bandwidth of a baseband signal transmitted between the first and second communication devices so that there is effectively joint or composite beamforming between the communication devices. The link margin between communication devices is greatly improved using the techniques described herein.

With the same antenna configuration, 2-antenna CBF (2-CBF) provides an SNR improvement of up to 10 dB over transmit/selection diversity when it is used at both ends of the link. A system design using 4 antennas at a first communication device and 2 antennas at a second communication device (hereinafter referred to as 4x2 CBF) provides nearly 14 dB of SNR improvement. In general, for a fixed number of antennas, CBF outperforms the well-known space-time block codes by up to 4 dB. Moreover, unlike space-time coding, CBF does not require a change to an existing wireless standard.

The above and other objects and advantages will become more readily apparent when reference is made to the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of two communication devices performing an antenna diversity scheme using composite beamforming.

FIG. 2 is a block diagram of a communication device that may be used at either end of a composite beamforming communication link.

FIG. 3 is a flow chart illustrating an adaptive method to obtain antenna beamforming weights for communication between first and second communication devices.

FIGs. 4 and 5 are graphical diagrams illustrating convergence properties of the adaptive method shown in FIG. 3.

FIG. 6 is a diagram showing application of beamforming weights to a baseband signal for transmission in a frequency dependent communication channel.

FIG. 7 is a flow chart illustrating an adaptive algorithm to obtain antenna beamforming weights in a frequency dependent communication channel.

FIG. 8 is a block diagram of a composite beamforming transmission process for a multi-carrier baseband modulation scheme.

FIG. 9 is a block diagram of a composite beamforming reception process for a multi-carrier baseband modulation scheme.

FIG. 10 is a block diagram of a composite beamforming transmission process for a single carrier baseband modulation scheme.

FIG. 11 is a block diagram of a composite beamforming reception process for a single carrier baseband modulation scheme.

FIG. 12 is a flow chart of a beamforming training method where one communication device of a communication link uses antenna selection diversity.

FIG. 13 is a flow chart illustrating a collaborative method to obtain antenna processing parameters for communication between first and second communication devices.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring first to FIG. 1, a system 10 is shown in which a first communication device 100 and a second communication device 200 communicate with each other using radio frequency (RF) communication techniques. The

techniques described herein are useful in any radio frequency (RF) communication application, such as short-range wireless applications. A wireless local area network (WLAN) is only an example of an application. For example, device 100 may be an access point (AP) in a WLAN, and device 200 may be a station (STA).

Generally, the device 100 has Nap antennas 110 and the device 200 has Nsta antennas 210. FIG. 1 shows an example where the device 100 has three antennas 110 and the device 200 has two antennas 210. A complex transmit symbol s at device 100 is scaled (multiplied) using a set of complex transmit antenna weights $\mathbf{w}_{tx,ap} = [w_0 \ldots w_{Nap-1}]^T$ before being transmitted through respective ones of the antennas 110 (^{T} denotes the transpose operator). The received vector at device 200 is $\mathbf{r}_{sta} = sH\,\mathbf{w}_{tx,ap} + n$, where H is an Nsta by Nap channel matrix of unity variance, complex Gaussian random variables (to represent flat Rayleigh fading between each antenna), and n represents noise and interference. At device 200, a combiner $C = (\mathbf{w}_{rx,sta})^H\mathbf{r}$ is applied, C is passed to a detection circuit (e.g., soft-decision QAM detector, etc.). If H is known at both the transmitter and the receiver, $\mathbf{w}_{tx,ap}$ and $\mathbf{w}_{rx,sta}$ may be selected to maximize the signal-to-noise ratio (SNR) at the output of the combiner subject to a transmit power constraint, i.e., $(\mathbf{w}_{tx,ap})^H\,\mathbf{w}_{tx,ap} = 1$.

The SNR for C is maximized over $\mathbf{w}_{tx,ap}$ and $\mathbf{w}_{rx,sta}$ when $\mathbf{w}_{tx,ap}$ is equal to $\mathbf{e}_{max}$, the unit norm eigenvector for the maximum eigenvalue λ_{max} of the matrix H^HH, and $\mathbf{w}_{rx,sta}$ is a matched filter for $H\mathbf{e}_{max}$, i.e., $\mathbf{w}_{rx,sta} = k\,H\mathbf{e}_{max}$ for some nonzero constant k. Under these conditions, the SNR for C is equal to λ_{max}. Since H is a random matrix, λ_{max} is a random variable. The distribution on λ_{max} is well known, and can be found in M. Wennstrom, M. Helin, A. Rydberg, T. Oberg, "On the Optimality and Performance of Transmit and Receive Space Diversity in MIMO Channels", IEEE Technical Seminar on MIMO Systems, London, December, 2001, which is incorporated herein by reference.

The transmit device and the receive device communicate using time-division-duplexing at the same frequency. The channel matrix for the reverse link is $H_r = H^T$, and the optimum transmit weight vector $\mathbf{w}_{tx,ap}$ is equal to the eigenvector for the maximum eigenvalue of $H_r^HH_r = H^*H^T$ (* denotes the conjugate operator). The maximum SNR at either end of the link is the same (since it is a well

known result that the nonzero eigenvalues for both H^*H^T and H^HH are the same). The beamforming technique that results from this analysis is hereinafter referred to as composite beamforming (CBF).

The communication devices at both ends of the link , i.e., devices 100 and 200 may have any known suitable architecture to transmit, receive and process signals. An example of a communication device block diagram is shown in FIG. 2. The communication device 300 comprises an RF section 310, a baseband section 420 and optionally a host 330. There are a plurality of antennas, e.g., four antennas 302, 304, 306, 308 coupled to the RF section 310 that are used for transmission and reception. The RF section 310 has a transmitter (Tx) 312 that upconverts baseband signals for transmission, and a receiver (Rx) 314 that downconverts received RF signals for baseband processing. In the context of the composite beamforming techniques described herein, the Tx 312 upconverts and supplies separately weighted signals to corresponding ones of each of the plurality of antennas via separate power amplifiers. Similarly, the Rx 314 downconverts and supplies received signals from each of the plurality of antennas to the baseband section 320. The baseband section 320 performs processing of baseband signals to recover the information from a received signal, and to convert information in preparation for transmission. The baseband section 320 may implement any of a variety of communication formats or standards, such as WLAN standards IEEE 802.11x, Bluetooth™, as well as other protocol standards, not necessarily used in a WLAN.

The intelligence to execute the computations for the composite beamforming techniques described herein may be implemented in a variety of ways. For example, a processor 322 in the baseband section 320 may execute instructions encoded on a processor readable memory 324 (RAM, ROM, EEPROM, etc.) that cause the processor 322 to perform the composite beamforming steps described herein. Alternatively, an application specific integrated circuit (ASIC) configured with the appropriate firmware to perform the composite beamforming steps. For example, the instructions may be encoded on a medium by programming a field programmable gate array, or by defining digital logic gates in silicon in an integrated circuit. The ASIC may be part of, or the entirety of, the baseband section 320. Still another alternative is for the

beamforming computations to be performed by a host processor 332 (in the host 330) by executing instructions stored in (or encoded on) a processor readable memory 334. The RF section 310 may be embodied by one integrated circuit, and the baseband section 320 may be embodied by another integrated circuit. The communication device on each end of the communication link need not have the same device architecture or implementation.

Regardless of the specific implementation chosen, the composite beamforming process is generally performed as follows. A transmit weight vector (comprising a plurality of complex transmit antenna weights corresponding to the number of transmit antennas) is applied to, i.e., multiplied by, a baseband signal to be transmitted, and each resulting weighted signal is coupled to a transmitter where it is upconverted, amplified and coupled to a corresponding one of the transmit antennas for simultaneous transmission. At the communication device on the other end of the link, the transmit signals are detected at each of the plurality of antennas and downconverted to a baseband signal. Each baseband signal is multiplied by a corresponding one of the complex receive antenna weights and combined to form a resulting receive signal. The architecture of the RF section necessary to accommodate the beamforming techniques described herein may vary with a particular RF design, and many are known in the art and thus is not described herein.

Turning to FIG. 3, a process 400 is shown for achieving optimum CBF between two communication devices. To restate the results from the previous discussion, the optimum receive and transmit weights at the AP are given by $\mathbf{w}_{rx,ap} = \mathbf{e}_{max}(\text{of } H^H H)$, $\mathbf{w}_{tx,ap} = \mathbf{w}_{rx,ap}^*$. The optimum receive and transmit weights at the STA are given by $\mathbf{w}_{rx,sta} = \mathbf{e}_{max}(\text{of } H^* H^T)$, $\mathbf{w}_{tx,sta} = \mathbf{w}_{rx,sta}^*$. Additionally, $\mathbf{w}_{rx,sta} = H\,\mathbf{w}_{tx,ap}$, $\mathbf{w}_{rx,ap} = H^T\,\mathbf{w}_{tx,ap}$. These properties can be utilized to design an adaptive/iterative algorithm that converges to the optimum eigenvector as follows.

Initially, in step 410, the AP uses an arbitrary set of transmit antenna weights to transmit a signal to the STA. When the STA receives the signal, the receive antenna weights at the STA are matched to the receive signal such that $\mathbf{w}_{rx,sta}(0) = H\,\mathbf{w}_{tx,ap}(0)$. That is, the STA receive antenna weights are computed from the received signals at each of the antennas by matching to the received

signals. In step 420, the STA computes the conjugate of the receive weight vector made up of the receive antenna weights for use as the transmit antenna weight vector for transmitting on the STA's antennas back to the AP. The AP receives the signal transmitted by the plurality of antennas of the STA and matches the receive antenna weights to the received signal.

In step 430, the AP updates the new transmit antenna weights by computing the conjugate of the receive weight vector (comprised of the AP receive antenna weights) divided by the norm of the AP receive weight vector. This process repeats in steps 440 through 460, ad infinitum. It can be shown that the weights converge to the eigenvector corresponding to the maximum eigenvalue. See G. Golub, C. V. Loan, "Matrix Computations", 2nd edition, pp. 351.

Within a few iterations, the transmit weight vector and receive antenna weight vector of both devices will converge to values that optimize the SNR at each of the devices. At such point, the first communication device may store in a memory (in the baseband section or host processor section) the current optimum transmit antenna weights for a particular destination communication device indexed against an identifier for that communication device. The first communication device, such as an AP, may store in a look-up-table optimum transmit antenna weights indexed against corresponding identifiers (such as MAC addresses) for a plurality of other communication devices it communicates with.

The adaptive process of FIG. 3 will converge to optimum antenna weights even if one device has multiple antennas and can weight signals supplied thereto, and the other device is a merely a single antenna device. The device on the link with the multiple antennas and combining capability can still converge to its optimum transmit and receive weights for a single antenna device it communicates with.

With reference to FIGs. 4 and 5, the convergence properties of the adaptive algorithm were studied over 1000 randomly generated channels. The average SNR at each receive antenna was set to 10 dB. The normalized antenna array gain at the output of the receive antenna array, $|\mathbf{H}\mathbf{w}_{tx}|^2/\lambda_{max}(H^H H)$ is used to study the performance. In FIG. 4, (Nap = 2, Nsta = 2), it is shown that the adaptive algorithm loss is less than a 1 dB at the 3rd iteration with 95% probability. When

the number of antenna elements is increased to four, only one additional iteration was required for the algorithm converge to less than 1 dB loss with 95% probability.

An advantage of adaptive composite beamforming is that no special training sequence is required for adaptation. In addition, no changes to existing protocols are necessary, and there is no impact on throughput. The antenna weights are updated when real information or data is transmitted between devices. Transmit and receive weight adaptation is the same regardless of whether CBF is implemented at both ends of the link However, if the destination device uses selection diversity the performance can be improved by estimating the channel response.

The indoor wireless channel is a frequency dependent channel. Due to multi-path propagation the signal arrives at the receiver with different delays. The different delays cause the channel transfer function to be frequency selective. Therefore, to account for these delays, the antenna weights need to be adjusted according to the frequency dependent characteristics of the channel transfer function between the transmitting device and the receiving device.

Solutions for optimum antenna processing in a frequency selective channel are described hereinafter. Between any two communication devices, the communication channel will have a frequency response depending on frequency selective fading conditions, etc. The channel transfer function $\mathbf{H}(f)$ describes the frequency response and is used to select the optimum antenna transmit and receive weights for communication between those terminals.

To understand the frequency selective situation, reference is again made to FIG. 1, where the frequency dependent Nsta by Nap transfer function between the first and communication device and the second communication devices is denoted by the $\mathbf{H}(f)$. The Nap by Nsta transfer function between the second communication device and the first communication device is $\mathbf{H}^T(f)$. The transmit weights at the first and second communication devices are denoted by the Nap x 1 vector $\mathbf{w}_{tx,ap}(f)$ and the Nsta x 1 vector $\mathbf{w}_{tx,sta}(f)$, respectively.

$$\mathbf{w}_{tx,ap}(f) = [\mathbf{w}_{tx,ap,1}(f), \mathbf{w}_{tx,ap,2}(f), \ldots \mathbf{w}_{tx,ap,Nap}(f)]^T$$

$$\mathbf{w}_{tx,sta}(f) = [\mathbf{w}_{tx,sta,1}(f), \mathbf{w}_{tx,sta,2}(f), \ldots \mathbf{w}_{tx,sta,Nsta}(f)]^T$$

The receive weights at the first and second communication devices are denoted by the Nap x 1 vector $\mathbf{w}_{rx,ap}(f)$ and the Nsta x 1 vector $\mathbf{w}_{rx,sta}(f)$, respectively

$$\mathbf{w}_{rx,ap}(f) = [w_{rx,ap,1}(f), w_{rx,ap,2}(f), \ldots w_{rx,ap,Nap}(f)]^T$$

$$\mathbf{w}_{rx,sta}(f) = [w_{rx,sta,1}(f), w_{rx,sta,2}(f), \ldots w_{rx,sta,Nsta}(f)]^T$$

The transmit and receive weights (only the first communication device-second communication device link is described below but the results apply in the reverse direction with appropriate change in notation) are computed by optimizing a cost function, C, with a constraint on the maximum transmit power. In a communication system, the ultimate goal is to reduce bit-error rate (BER).

However, optimization using the BER as a cost function is not always analytically feasible. Therefore, cost functions that implicitly reduce the BER are usually selected. The cost function also depends on the receiver structure. Selection of the cost function for different modulation schemes and receiver structures is discussed.

$$\min_{\mathbf{w}_{tx,ap}\,\mathbf{w}_{rx,sta}} \int_{-1/2T}^{1/2T} C(\mathbf{H}(f), \mathbf{w}_{tx,ap}(f), \mathbf{w}_{rx,sta}(f))\,df, \text{ subjectto } \int_{-1/2T}^{1/2T} \left|\mathbf{w}_{tx,ap}(f)\right|^2 df \le P_0$$

For a code division multiple access (CDMA) communication system, such as IEEE 802.11b, the receiver is assumed to be a RAKE receiver and the BER is a function of the SNIR (signal to noise + interference ratio) at the output of the RAKE receiver. Maximizing the SNIR at the output of the RAKE receiver minimizes the BER.

$$\max_{\mathbf{w}_{tx,ap}\,\mathbf{w}_{rx,sta}} \int_{-1/2T}^{1/2T} SNIR(\mathbf{H}(f), \mathbf{w}_{tx,ap}(f), \mathbf{w}_{rx,sta}(f))\,df, \text{ subjectto } \int_{-1/2T}^{1/2T} \left|\mathbf{w}_{tx,ap}(f)\right|^2 df \le P_0$$

For an orthogonal frequency division multiplex (OFDM) system, such as IEEE 802.11a, the receiver is a linear equalizer followed by a Viterbi decoder. Since the Viterbi decoder is a non-linear operator, optimizing the coded BER is very challenging. An alternative is to minimize the mean square error (MSE) at the

output of the linear equalizer (note another possible approach is to minimize the uncoded BER).

$$\min_{\mathbf{w}_{tx,ap}\mathbf{w}_{rx,sta}} \int_{-1/2T}^{1/2T} MSE(\mathbf{H}(f), \mathbf{w}_{tx,ap}(f), \mathbf{w}_{rx,sta}(f))\,df, \text{ subjectto } \int_{-1/2T}^{1/2T} \left|\mathbf{w}_{tx,ap}(f)\right|^2 df \le P_0$$

A single carrier modulation scheme, such as IEEE 802.11b, uses a decision feedback equalizer (DFE) at the receiver. The receiver is a non-linear receiver.

$$\min_{\mathbf{w}_{tx,ap}\mathbf{w}_{rx,sta}B} \int_{-1/2T}^{1/2T} MSE(\mathbf{H}(f), \mathbf{w}_{tx,ap}(f), \mathbf{w}_{rx,sta}(f))\,df, \text{ subjectto } \int_{-1/2T}^{1/2T} \left|\mathbf{w}_{tx,ap}(f)\right|^2 df \le P_0$$

The transmit, receive and feedback weights are computed jointly. This can be achieved by minimizing the MSE at the output of the DFE.

For all cases considered, the optimum transmit weights are given by

$$\mathbf{w}_{tx\_ap}(f) = p(f)\ \mathbf{e}_{max}(\mathbf{H}^H(f)\ \mathbf{H}(f))$$

where $\mathbf{e}_{max}$ is the eigenvector corresponding to the maximum eigenvalue of the matrix $\mathbf{H}^H(f)\ \mathbf{H}(f)$, where p (f) is a weighting function that weights each individual frequency bin and is based on the cost function. Typically, the solution to p(f) follows a waterpouring distribution.

For the linear equalizer case, the solution is given by

$$p^2(f) = \sqrt{\frac{1}{\mu \frac{\sigma_s^2}{\sigma_n^2}\lambda_{\max}(f)}} - \frac{1}{\frac{\sigma_s^2}{\sigma_n^2}\lambda_{\max}(f)} \qquad SNR = \frac{\sigma_s^2}{\sigma_n^2}$$

For the DFE case, the solution is

$$p^2(f) = \frac{1}{\mu} - \frac{1}{\frac{\sigma_s^2}{\sigma_n^2}\lambda_{\max}(f)}$$

where μ is selected to satisfy the power constraint

$$\int_{-1/2T}^{1/2T} p^2(f)\,df = P_0$$

An optimal solution for p(f) requires knowledge of the channel and SNR at the receiver. A suboptimal solution is obtained by setting p(f) to a constant, p, across frequency.

$$\mathbf{w}_{tx\_ap}(f) = p\ \mathbf{e}_{max}(\mathbf{H}^{H}(f)\ \mathbf{H}(f))$$

This is referred to herein as a frequency shaping constraint. To explain further, the frequency shaping constraint requires that at each frequency of the baseband signal to be transmitted (e.g., frequency sub-band or frequency sub-carrier k), the sum of the power of signals across all of the transmit antennas is equal to a constant value, P_{tx}/K. This constraint is useful to ensure that, in an iterative process between two communication devices, the transmit weights of the two devices will converge to optimal values. An additional benefit of this constraint is that the transmitting device can easily satisfy spectral mask requirements of a communication standard, such as IEEE 802.11x.

This solution does not require knowledge of the receiver SNR and simulations have shown that the loss in performance over the optimal solution is negligible. However, this solution requires knowledge of the channel response at the transmitter.

For the cost functions maximizing the SNIR or minimizing the MSE for a linear equalizer, the optimum receive weights are given by

$$\mathbf{w}_{rx,sta}(f) = \mathbf{R}_{ss}^{-1}(f)\mathbf{v}_{mf,sta}(f)$$

where $\mathbf{v}_{mf,sta}(f)$ is matched to the received signal

$$\mathbf{v}_{mf,sta}(f) = \mathbf{H}(f)\mathbf{w}_{tx,ap}(f)$$

and $\mathbf{R}_{ss}(f)$ is the correlation matrix defined as

$$\begin{aligned}\mathbf{R}_{ss}(f) &= \sigma_s^2\mathbf{H}(f)\mathbf{w}_{tx,ap}(f)\mathbf{w}_{tx,ap}^{H}\mathbf{H}^{H}(f) + \sigma_n^2\mathbf{I} \\ &= \sigma_s^2\mathbf{v}_{mf,sta}(f)\mathbf{v}_{mf,sta}^{H}(f) + \sigma_n^2\mathbf{I}\end{aligned}$$

When the MSE of the DFE is the minimized, the optimum receive weights are given by

$$\mathbf{w}_{rx,sta}(f) = \mathbf{R}_{ss}^{-1}(f)\mathbf{v}_{mf,sta}(f)(1+B(f))$$

where B(f) is the feedback filter.

The weights for the reverse link are similar to the forward link and is summarized below. The optimum transmit weights at the second communication are given by

$$\mathbf{w}_{tx\_sta}(f) = p(f)\ \mathbf{e}_{max}(\mathbf{H}^{*}(f)\ \mathbf{H}^{T}(f))$$

and the suboptimal transmit weights are

$$\mathbf{w}_{tx\_sta}(f) = p\ \mathbf{e}_{max}(\mathbf{H}^{*}(f)\ \mathbf{H}^{T}(f))$$

Similarly, the receive weights at the first communication device are given by

$$\mathbf{w}_{rx,ap}(f) = \mathbf{R}_{aa}^{-1}(f)\mathbf{v}_{mf,ap}(f)$$

where $\mathbf{v}_{mf,ap}(f) = \mathbf{H}^{T}(f)\mathbf{w}_{tx,sta}(f)$

and for DFE case

$$\mathbf{R}_{aa}(f) = \sigma_s^2\mathbf{v}_{mf,ap}(f)\mathbf{v}_{mf,ap}^{H}(f) + \sigma_n^2\mathbf{I}$$

$$\mathbf{w}_{rx,ap}(f) = \mathbf{R}_{xx}^{-1}(f)\mathbf{v}_{mf,ap}(f)(1+B(f))$$

In the presence of co-channel interference $\mathbf{R}_{ss}(f)$ is given by

$$\mathbf{R}_{ss}(f) = \sigma_s^2\mathbf{H}(f)\mathbf{w}_{tx,ap}(f)\mathbf{w}_{tx,ap}^{H}(f)\mathbf{H}^{H}(f) + \sum_{k\neq 0}\sigma_k^2\mathbf{H}_k(f)\mathbf{w}_k(f)\mathbf{w}_k^{H}(f)\mathbf{H}_k^{H}(f) + \sigma_n^2\mathbf{I}$$

where the terms in the summation are the contribution due to the interferers. In this case, the optimum receive antenna weights minimize the contribution of the interferers and the noise. Therefore, in addition to diversity gain, optimum antenna combining at the receiver also provides interference suppression capability.

FIG. 6 illustrates how frequency selective beamforming weights are applied to a baseband signal. The baseband signal may be a single carrier signal or a multi-carrier signal. In either case, the baseband signal will have a bandwidth or spectrum. According to the composite beamforming (CBF) technique described herein, when communication device 100 transmits a signal to communication device 200, it applies (i.e., multiplies or scales) a baseband signal *s* to be

transmitted by a transmit weight vector associated with a particular destination device, e.g., communication device 200, denoted $\mathbf{w}_{tx,1}$. Similarly, when communication device 200 transmits a baseband signal *s* to communication device 100, it multiplies the baseband signal *s* by a transmit weight vector $\mathbf{w}_{tx,2}$, associated with destination communication device 100. The (M x N) frequency dependent channel matrix from the N plurality of antennas of the first communication device 100 to M plurality of antennas of the second communication device 200 is $\mathbf{H}(k)$, and the frequency dependent communication channel (N x M) matrix between the M plurality of antennas of the second communication device and the N plurality of antennas of the first communication device is $\mathbf{H}^{T}(k)$. The variable k denotes the frequency dependent characteristic as explained further hereinafter.

The transmit weight vectors $\mathbf{w}_{tx,1}$ and $\mathbf{w}_{tx,2}$ each comprises a plurality of transmit weights corresponding to each of the N and M antennas, respectively. Each transmit weight is a complex quantity. Moreover, each transmit weight vector is frequency dependent; it varies across the bandwidth of the baseband signal *s* to be transmitted. For example, if the baseband signal *s* is a multi-carrier signal of K sub-carriers, each transmit weight for a corresponding antenna varies across the K sub-carriers. Similarly, if the baseband signal *s* is a single-carrier signal (that can be divided into K frequency sub-bands), each transmit weight for a corresponding antenna varies across the bandwidth of the baseband signal. Therefore, the transmit weight vector is dependent on frequency, or frequency sub-band/sub-carrier k, such that $\mathbf{w}_{tx}$ becomes $\mathbf{w}_{tx}(f)$, or more commonly referred to as $\mathbf{w}_{tx}(k)$, where k is the frequency sub-band/sub-carrier index.

While the terms frequency sub-band/sub-carrier are used herein in connection with beamforming in a frequency dependent channel, it should be understood that the term "sub-band" is meant to include a narrow bandwidth of spectrum forming a part of a baseband signal. The sub-band may be a single discrete frequency (within a suitable frequency resolution that a device can process) or a narrow bandwidth of several frequencies.

The receiving communication device also weights the signals received at its antennas with a frequency dependent receive antenna weight vector $\mathbf{w}_{rx}(k)$. Communication device 100 uses a receive antenna weight vector $\mathbf{w}_{rx,1}(k)$ when

receiving a transmission from communication device 200, and communication device 200 uses a receive antenna weight vector $\mathbf{w}_{rx,2}(k)$ when receiving a transmission from communication device 100. The receive antenna weights of each vector are matched to the received signals by the receiving communication device.

Generally, transmit weight vector $\mathbf{w}_{tx,1}$ comprises a plurality of transmit antenna weights $w_{tx,1,i} = \beta_{1,i}(k)e^{j\phi 1,i,(k)}$, where $\beta_{1,i}(k)$ is the magnitude of the antenna weight, $\phi 1,i,(k)$ is the phase of the antenna weight, i is the antenna index (up to N), and k is the frequency sub-band or sub-carrier index (up to K frequency sub-bands/sub-carriers). The subscripts tx,1 denote that it is a vector that communication device 100 uses to transmit to communication device 2. Similarly, the subscripts tx,2 denote that it is a vector that communication device 200 uses to transmit to communication device 100.

The frequency shaping constraint described above may be imposed on the transmit weights for each antenna. As mentioned above, the constraint requires that at each frequency of the baseband signal to be transmitted (e.g., frequency sub-band or frequency sub-carrier k), the sum of the power of signals across all of the transmit antennas ($|w_{tx,i}(k)|^2$ for i = 1 to N) is equal to a constant value, P_{tx}/K.

The relationship between transmit and receive weights are summarized below:

The optimum receive and transmit weights at the first communication device are related as follows.

$$\mathbf{w}_{tx,ap}(f) = \mathbf{e}\max(\mathbf{H}^H(f)\,\mathbf{H}(f)),\ \mathbf{v}_{mf,sta}(f) = \mathbf{H}(f)\,\mathbf{w}_{tx,ap}(f)$$

Similarly at the second communication device, the optimum receive and transmit weights are related as follows.

$$\mathbf{w}_{tx,sta}(f) = \mathbf{e}\max(\mathbf{H}^*(f)\,\mathbf{H}^T(f)),\ \mathbf{v}_{mf,ap}(f) = \mathbf{H}^T(f)\,\mathbf{w}_{tx,sta}(f)$$

Additionally,

$$\mathbf{v}_{mf,ap}(f) = \mathbf{w}_{tx,ap}^*(f),\ \mathbf{v}_{mf,sta}(f) = \mathbf{w}_{tx,ap}^*(f)$$

The properties outlined above can be utilized in an adaptive/iterative process 480 shown in FIG. 7 that is similar to the process shown in FIG. 3. The antenna weight parameters in FIG. 4 are written with indexes to reflect communication between an AP and a STA, but without loss of generality, it should

be understood that this process is not limited to a WLAN application, and is useful in any wireless application, such as a short-range application. The AP has Nap antennas and the STA has Nsta antennas. Assuming the AP begins with the first transmission to the STA, the initial AP transmit weight vector $\mathbf{w}_{T,AP,0}(k)$ is [1,1,...1], normalized by $1/(Nap)^{1/2}$ for all antennas and all frequency sub-bands/sub-carriers k. Phase for the transmit antenna weights are also initially set to zero. The index T indicates it is a transmit weight vector, index AP indicates it is an AP vector, index 0 is the iteration of the vector, and (k) indicates that it is frequency sub-band/sub-carrier dependent. In step 482, a baseband signal is scaled by the initial AP transmit weight vector $\mathbf{w}_{T,AP,0}(k)$, upconverted and transmitted to the STA by the Nap antennas. The transmitted signal is effectively altered by the frequency selective channel matrix $\mathbf{H}(k)$ from AP-STA. The STA receives the signal and matches its initial receive weight vector $\mathbf{w}_{R,STA,0}(k)$ to the signals received at its antennas. In step 484, the STA normalizes the receive weight vector $\mathbf{w}_{R,STA,0}(k)$ and computes the conjugate of normalized receive weight vector to generate the STA's initial transmit weights for transmitting a signal back to the AP. In step 486, the STA processes the signal to be transmitted to the AP by the initial transmit weight vector, upconverts that signal and transmits it to the AP. The transmitted signal is effectively altered by the frequency selective channel matrix $\mathbf{H}^T(k)$. At the AP, the receive weight vector is matched to the signals received at its antennas. The AP then computes the conjugate of the gain-normalized receive weight vector as the next transmit weight vector $\mathbf{w}_{T,AP,1}(k)$ and transmits a signal to the STA with that transmit weight vector. The STA receives the signal transmitted from the AP with this next transmit weight vector and matches to the received signals to compute a next receive weight vector $\mathbf{w}_{R,STA,1}(k)$. Again, the STA computes the conjugate of the gain-normalized receive weight vector $\mathbf{w}_{R,STA,1}(k)$ as its next transmit weight vector $\mathbf{w}_{T,STA,1}(k)$ for transmitting a signal back to the AP. This process repeats for several iterations as shown by steps 488 and 490, ultimately converging to transmit weight vectors that achieve nearly the same performance as non-equal gain composite beamforming. This adaptive process works even if one of the devices, such as a STA, has a single antenna for transmission and reception.

When storing the transmit weights of a frequency transmit weight vector, in order to conserve memory space in the communication device, the device may store, for each antenna, weights for a subset or a portion of the total number of weights that span the bandwidth of the baseband signal. For example, if there are K weights for K frequency sub-bands or sub-carrier frequencies, only a sampling of those weights are actually stored, such as weights for every other, every third, every fourth, etc., k sub-band or sub-carrier. Then, the stored subset of transmit weights are retrieved from storage when a device is to commence transmission of a signal, and the remaining weights are generated by interpolation from the stored subset of weights. Any suitable interpolation can be used, such as linear interpolation, to obtain the complete set of weights across the K sub-bands or sub-carriers for each antenna.

It may be desirable for a first device initiating communication with a second device to transmit an initial packet to the second device using transmit delay diversity (TDD) techniques to increase the likelihood that the second device will receive the initial packet, and therefore be able to beamform back a packet to the first device. TDD techniques essentially increase the range of the initial packet and are particularly useful when the channel with the other device is not known, hence transmit beamforming a signal to that device would not ensure reception by the other device. This is the case when transmitting a packet for the first time. This may be useful when one communication device has not been in communication with another particular communication device for a significant period of time. The channel may be different due to a new location of one or both of the devices and when new objects or obstructions have been placed in the channel between the devices. Also, an existing communication link may be lost, and efforts to re-establish it with composite beamforming may not work.

In any event, the initial packet is transmitted, in step 482 of FIG. 7, using TDD techniques rather than with an arbitrary transmit weight vector, e.g., $[1,1,1, \ldots 1]^T$. For example, the AP may transmit the initial packet to a STA using TDD. The initial packet may be a broadcast packet, such as a beacon in IEEE 802.11 parlance, or a directed packet. When transmitting an initial packet using TDD, the signal to be transmitted is multiplied by a transmit weight vector that performs the

TDD function, i.e., $x(t + \tau)$ in the time domain, which is analogous to $X(f)e^{-j2\pi f\tau}$ in the frequency domain, where the transmit weight at frequency f is $e^{-j2\pi f\tau}$. The TDD transmit weight vector has unit normalized gain, and for N antennas can be expressed as a transmit weight vector $[e^{-j2\pi f\tau 1}, e^{-j2\pi f\tau 2}, e^{-j2\pi f\tau i}, \ldots, e^{-j2\pi f\tau N}]^T$ for i = 1 to N, where $\tau 1$ is a time delay for antenna 1, $\tau 2$ is a time delay for antenna 2, and in general τi is a time delay for antenna i. As an example, the time delay $\tau 1$ is 0, the time delay $\tau 2$ is s (where is a sample time), the time delay $\tau 3$ is 2s, and in general the time delay for antenna i would be (i-1)s. The STA would receive the initial packet sent using TDD, receive match to the received initial packet and then generate transmit weights (as described above in conjunction with FIG. 7) from the receive weights used to combine the received signals, for transmitting a packet to the AP as shown in step 484. From then on, the process continues as shown in FIG. 7. That is, the AP receives the packet from the STA, and will receive match to it (gaining knowledge about the channel) to compute transmit weights for transmitting to that STA.

The same technique may be used in the reverse direction, whereby the STA transmits an initial packet to the AP using TDD. For example, in the IEEE 802.11 WLAN example, a STA may turn on and either listen for a beacon from an AP or transmit a probe request to the AP. If the STA receives a beacon signal, it can receive match to it, generate a transmit weight vector, and transmit a packet back to the AP using transmit beamforming, and the process of FIG. 7 will proceed as described above. On the other hand, if the STA does not wait for a beacon, and instead transmits a probe request signal to the AP, it will transmit the probe request signal using TDD to increase the range of the probe request to increase the chance that the AP will receive it. Then, the AP can receive match, and beamform back to the STA, and the process of FIG. 7 will proceed as described above.

With reference to FIG. 8, a beamforming transmission process 500 is shown for a multi-carrier baseband modulation scheme. For an orthogonal frequency division multiplexed (OFDM) system used, for example, by the IEEE 802.11a standard, the data symbols are in the frequency domain. K symbols are assigned to K sub-carriers (K = 52 for 802.11a). For convenience, each of the transmit antenna weights are described as a function of (k), the sub-carrier frequency. Each of the N

antennas has a transmit antenna weight w_{tx} that is a function of k, i.e., $w_{tx}(k)$ over k = 1 to K. The transmit antenna weights are computed by any of the processes described above at each of the sub-carrier frequencies. There is a signal processing path for each of the N antennas. In each signal processing path, a multiplier 510 multiplies the frequency domain symbol s(k) by the corresponding transmit antenna weight $w_{tx}(k)$ and because $w_{tx}(k)$ has K values, there are K results from the multiplication process. The results are stored in a buffer 520 for k = 1 to K. An inverse Fast Fourier Transform (IFFT) 530 is coupled to the buffer to convert the frequency domain results stored in buffer 520 to a digital time domain signal for each of the K sub-carriers. There is some adjustment made for cyclic prefixes caused by the OFDM process. A filter 540 provides lowpass filtering of the result of the IFFT process. The digital results of the filtering process are converted to analog signals by a D/A 550. The outputs of the D/A 550 are coupled to RF circuitry 560 that upconverts the analog signals to the appropriate RF signal which is coupled via a power amplifier (PA) 570 to one of the N antennas 580. In this manner, for each antenna 580, the signal s(k) is multiplied by respective transmit antenna weights whose values may vary as a function of the sub-carrier frequency k. The frequency shaping constraint described above can also be applied to the antenna weights.

FIG. 9 shows a beamforming reception process 600 that is essentially the inverse of the transmission process shown in FIG. 8. There is a signal processing channel for each of the antennas 580. RF circuitry 610 downconverts the RF signals detected at each antenna 580 for each of the sub-carriers. An A/D 620 converts the analog signal to a digital signal. A lowpass filter 630 filters the digital signal. There is some adjustment made for cyclic prefixes caused by the OFDM process. A buffer 640 stores the time domain digital signal in slots associated with each sub-carrier frequency k. An FFT 650 converts the time domain digital signal in buffer 640 to a frequency domain signal corresponding to each sub-carrier frequency k. The output of the FFT 650 is coupled to a multiplier 660 that multiplies the digital signal for each sub-carrier k by a corresponding receive antenna weight $w_{rx}(k)$ for the corresponding one of the N antennas. The outputs of each of the multipliers 660 are combined by an adder 670 to recover the digital

frequency domain symbol s(k). The signal s(k) is then mapped back to symbol b(k).

FIGs. 10 and 11 show transmission and reception processes, respectively, for frequency dependent beamforming applied to a single carrier baseband modulation scheme, such as that used by the IEEE 802.11b standard. The data symbols in such a system are in the time domain. FIG. 10 shows a beamforming transmission process 700 suitable for a single carrier modulation scheme. Since in a frequency dependent channel, the transmit antenna weights are frequency dependent, the passband of the baseband signal is synthesized into frequency bins (K bins) and transmit beamforming weights are computed for each frequency bin using any of the processes described above. There are processing channels for each antenna. In each processing channel, transmit filters 710 are synthesized with the frequency response specified by the beamforming weights. Thus, each transmit filter 710 has a frequency response defined by the transmit antenna weight $wt_x(f)$ associated with that antenna. The data symbol s(n) is passed through the transmit filter 710 which in effect applies the frequency selective antenna weight to the data symbol s(n). The D/A 720 converts the digital output of the transmit filter 710 to an analog signal. The RF circuitry 730 upconverts the analog signal and couples the upconverted analog signal to an antenna 750 via a power amplifier 740. The frequency shaping constraint described above can also be applied to the antenna weights.

FIG. 11 shows a reception process 800 suitable for a single carrier modulation scheme. There is a processing channel for each antenna 750. In each processing channel, RF circuitry 810 downconverts the received RF signal. An A/D 820 converts the downconverted analog signal to a digital signal. Like the frequency dependent transmit antenna weights, the receive antenna weights are computed for several frequency sub-bands. Receive filters 830 are synthesized with the frequency response specified by the receive beamforming weights $w_{rx}(f)$ and the received digital signal is passed through filters 830 for each antenna, effectively applying a frequency dependent antenna weight to the received signal for each antenna. The results of the filters 830 are combined in an adder 850, and then passed to a demodulator 860 for demodulation.

Referring next to FIG. 12, a procedure is shown for use when only one of the two devices supports beamforming. For example, N-CBF is supported at a first communication device (an AP) but not at a second communication device (a STA). In this case, the STA is likely to support 2-antenna Tx/Rx selection diversity as discussed previously. If this is the case, it is possible for the AP to achieve 3 dB better performance than Nth order maximal ratio combining (MRC) at both ends of the link.

When the STA associates or whenever a significant change in channel response is detected, the AP sends a special training sequence to help the STA select the best of its two antennas. The training sequence uses messages entirely supported by the applicable media access control protocol, which in the following example is IEEE 802.11x.

The sequence consists of 2 data units (such as an IEEE 802.11 MSDU ideally containing data that is actually meant for the STA so as not to incur a loss in throughput). In step 900, the first communication device sends the first data unit using the Tx weight vector $[1\ 0\ ..\ 0]^T$. That is, the first communication device sends the first data unit exclusively by one of its N antennas. In step 910, the second communication device responds by transmitting a message using one of its' two antennas. The first device decodes the message from the second device, and obtains one row of the H matrix (such as the first row h_{r1}). In step 920, the first device sends the second MSDU using a weight vector which is orthogonal to the first row of H (determined in step 910). When the second device receives the second MSDU, in step 930, standard selection diversity logic forces it to transmit a response message in step 930 using the other antenna, allowing the first device to see the second row of the H matrix, h_{r2}. Now the first device knows the entire H matrix. The first device then decides which row of the H matrix will provide "better" MRC at the second device by computing a norm of each row, h_{r1} and h_{r2}, of the H matrix and, and selecting the row that has the greater norm as the transmit weight vector for further transmissions to that device until another change is detected in the channel.

For the frequency sensitive case, the process shown in FIG. 11 is repeated at each of a plurality of frequency sub-bands that span the bandwidth of a single

carrier baseband signal to be communicated between the devices, or at each of the sub-carrier frequencies of a multi-carrier baseband signal to be communication between the devices.

Turning to FIG. 13 with continued reference to FIG. 1, a method is described for a collaborative approach for maintaining channel response information at one communication device for transmission with another communication device. Initially, in step 1000, one communication device determines which other communication devices are CBF-capable using a special CBF-capability request message. For example, this message is sent by an AP whenever a new STA associates with the AP. Non-CBF-capable devices will not respond to the message since they will not recognize it without CBF capability. Once it has confirmed CBF capability, whenever a CBF-capable device (AP or STA) sends information to the other device, in step 1010, a CBF training sequence is generated and appended to a data unit. For example, in the context of IEEE 802.11x, when a directed media access control (MAC) Protocol Data Unit (MPDU) to another CBF-capable terminal, it appends a small (2*N orthogonal frequency division multiplexed (OFDM) symbols, N = the number of antennas of the transmitting device) CBF training sequence containing channel response information at the end of the MPDU data segment. For example, the CBF training sequence may comprise N consecutive 2-symbol long preamble sequences as defined in 802.11a. These N sequences are multiplied by respective ones of N linearly independent vectors that span the column matrix of the channel response matrix. Such N linearly independent vectors may be, for example, the transmitted using the transmit weight vectors $[1\ 0\ ...\ 0]^T$, $[0\ 1\ 0\ ...\ 0]^T$, ..., $[0\ 0\ ...\ 1]^T$. These vectors essentially cause individual sequences to be transmitted exclusively on separate ones of the antennas, and nevertheless produce a column vector of the channel response matrix H at the receiving terminal. The CBF training sequence is appended to the MPDU and transmitted to the destination communication device in step 1020. The transmitting terminal uses the optimum transmit weight vector when transmitting all other portions of the MPDU.

In step 1030, the destination device receives and decodes the normal portion of the incoming MPDU using a matched filter derived using the long preamble at

the beginning of the incoming burst to determine the optimum phase and gain relationships on each receive antenna. Also, in step 1040, the destination device updates the transmit weight vector to use when transmitting to the source device (including the ACK to the incoming MPDU, for example) using the channel response matrix H derived from the CBF training sequence.

For example, suppose there are three antennas at the AP and two antennas at the STA. The CBF training sequence that the AP sends to the STA is transmitted using the transmit weight vectors $[1\ 0\ 0]^T$, $[0\ 1\ 0]^T$ and $[0\ 0\ 1]^T$. The channel response H vector between these two devices is a 2 x 3 matrix defined as $[h_{11}\ h_{12}]^T$, $[h_{21}\ h_{22}]^T$ and $[h_{31}\ h_{32}]^T$. When these transmit weight vectors are applied to the symbol s and transmitted, the result is $s[h_{11}\ h_{12}]^T$, $s[h_{21}\ h_{22}]^T$ and $s[h_{31}\ h_{32}]^T$. Therefore, the column vectors $[h_{11}\ h_{12}]^T$, $[h_{21}\ h_{22}]^T$ and $[h_{31}\ h_{32}]^T$ of the H matrix can be computed by dividing each receive vector ($[r_{11}\ r_{12}]^T$, $[r_{21}\ r_{22}]^T$ and $[r_{31}\ r_{32}]^T$, the receive output of the antennas at the STA) by s since the transmit symbol s is known at the STA because the STA will know the symbols used by the AP for the training sequence.

Using the method described above, a communication device may store the optimum transmit weight vectors for each of the other communication devices it communicates with. For example, an AP maintains a table mapping the MAC address for each STA to the optimum Tx weight vector for that STA. CBF-capable STAs may also store a table of such information when supporting communication in a peer-peer or ad-hoc network. All transmit weight vectors may be initially set to $[1\ 0\ ...\ 0]^T$.

For a 4-CBF scheme (4 antennas at the AP) using 1500 byte packets at 54 Mbps, the loss in throughput for the above approach is approximately 8%. The loss in throughput could be made smaller using the following enhancements: one symbol long preambles instead of 2 in the training sequence; use the channel response training sequence only when it is needed; and/or transmitting the training sequence during the IEEE 802.11 SIFS interval.

The training sequence scheme described above can be applied to generate frequency dependent antenna weights. Steps 1010 through 1030 are repeated for each of a plurality of frequencies. For example, in the multi-carrier signal case,

steps 1010 through 1040 are repeated K times, for each sub-carrier frequency. Similarly, for a single carrier modulation scheme, the training sequence would be applied for each of a plurality of frequency sub-bands that span the bandwidth of the baseband signal to be transmitted. In addition, the transmit weights can be frequency shaped so that the sum of the power across all of the antennas at a given frequency is constant.

The antenna processing techniques described herein can be incorporated into devices in a variety of ways. For example, an RF chip can be built that supports 2 Tx/Rx antenna ports, and one baseband chip that supports 2 x to 4 x CBF. One RF chip together with one baseband chip can be used in a network interface card, and two RF chips together with one baseband chip can be used in an AP for a system that supports 4-CBF at an AP, and 2-CBF in a STA. This system will perform up to 12 dB better than current state-of-the-art system.

From simulations for 2-antenna selection diversity in an indoor office environment w/50 ns RMS delay spread, 8 dB (4 dB) SNR is required for 802.11a (802.11b) at the lowest data rate. Including 6 dB of additional path loss for 802.11a at 5 GHz, a total of 6+8-4 = 10 dB of additional received signal power is required for 802.11a. For a path loss coefficient of 3.3 (indoor environment), 10 dB of additional signal power corresponds to ½ the range.

In addition, the antenna processing schemes described herein help reduce the performance degradation caused by interference. It has been shown through simulations that the interference immunity for a CBF-enhanced 802.11b network is approximately 2.2 times that of a non-CBF network. In other words, a CBF enhanced communication between two devices permits an interference source to be 2.2 times close to a receiving device without degrading reception performance at that device.

To again summarize, the antenna processing techniques described above provide up to a 14 dB (25x) SNR improvement over existing 802.11a/b implementations without requiring a change to the communication protocol or standard. Moreover, compared to current 2-antenna implementations, these techniques provide nearly three times more range per AP; 7.3 times more coverage area; four times less infrastructure cost at a fixed throughput per user; 7-10 times

less infrastructure cost when optimized for coverage; 5 times more throughput per user at a fixed infrastructure cost; normalized and improved range for dual-mode 802.11a/b networks; and better interference immunity and higher data rates. As much as 10 times fewer APs are required to support a similar coverage area when CBF-enhanced APs are used.

To summarize, a method is provided that accomplishes communication between a first communication device and a second communication device using radio frequency (RF) communication techniques, comprising steps of applying a transmit antenna vector to a baseband signal to be transmitted from the first communication device to the second communication device, the transmit antenna weight vector comprising a complex transmit antenna weight for each of the N plurality of antennas, wherein each complex transmit antenna weight has a magnitude and a phase whose values may vary with frequency across a bandwidth of the baseband signal, thereby generating N transmit signals each of which is weighted across the bandwidth of the baseband signal; receiving at the N plurality of antennas of the first communication device a signal that was transmitted by the second communication device; determining a receive weight vector comprising a plurality of complex receive antenna weights for the N plurality of antennas of the first communication device from one or more signals received by the N plurality of antennas from the second communication device, wherein each receive antenna weight has a magnitude and a phase whose values may vary with frequency; and updating the transmit weight vector for the plurality of antennas of the first communication device for transmitting signals to the second communication device by computing a conjugate of the receive weight vector of the first communication device divided by a norm of the conjugate of the receive weight vector. This same method may be embodied in the form of instructions encoded on a medium or in a communication device.

Also provided is a method that accomplishes communication between a first communication device and a second communication device, comprising steps of transmitting a first signal by one of N plurality of antennas of the first communication device; receiving a first response signal at the plurality of antennas of the first communication device transmitted from a first of two antennas of the

second communication device; deriving a first row of a channel response matrix that describes the channel response between the first communication device and the second communication device; transmitting a second signal by the plurality of antennas of the first communication device using a transmit weight vector that is orthogonal to the first row of the channel response matrix; receiving a second response signal transmitted by a second of the two antennas of the second communication device and deriving therefrom a second row of the channel response matrix; and selecting one of the first and second rows of the channel response matrix that provides better signal-to-noise at the second communication device as the transmit weight vector for further transmission of signals to the second communication device. This same method may be embodied in the form of instructions encoded on a medium or in a communication device.

Still further provided is a method that accomplishes communication between first and second communication devices comprising steps of generating a training sequence comprising a sequence of N consecutive symbols, where N is a number of antennas of the first communication device, and the N symbols are multiplied by respective ones of N linearly independent vectors that span columns of a channel response matrix between the plurality of antennas of the first communication device and a plurality of antennas of the second communication device, thereby producing N transmit signals; transmitting the N transmit signals from the plurality of antennas of the first communication device; receiving the N transmit signals at each of a plurality of antennas at the second communication device; at the second communication device, deriving from signals received by the plurality of antennas the channel response matrix between the first communication device and the second communication device; and at the second communication device, generating a transmit weight vector from the channel response matrix for transmitting a signal from the second communication device to the first communication device using the plurality of antennas of the second communication device. This same method may be embodied in the form of instructions encoded on a medium or in a communication device.

The above description is intended by way of example only.

What is claimed is:

1. A method for communicating signals between a first communication device and a second communication device using radio frequency (RF) communication techniques, comprising:

a. applying a transmit antenna vector to a baseband signal to be transmitted from the first communication device to the second communication device, the transmit antenna weight vector comprising a complex transmit antenna weight for each of the N plurality of antennas, wherein each complex transmit antenna weight has a magnitude and a phase whose values may vary with frequency across a bandwidth of the baseband signal, thereby generating N transmit signals each of which is weighted across the bandwidth of the baseband signal;

b. receiving the N transmit signals at one or more antennas of the second communication device;

c. determining a receive weight vector comprising one or more complex receive antenna weights for the one or more antennas of the second communication device from the N transmit signals received by the one or more antennas, wherein each receive antenna weight has a magnitude and a phase whose values may vary with frequency across a bandwidth of the baseband signal;

d. computing a transmit weight vector comprising a plurality of complex transmit antenna weights for the one or more antennas of the second communication device by computing a conjugate of the receive weight vector divided by the norm of the receive weight vector; and

e. applying the transmit weight vector to a baseband signal to be transmitted from the second communication device to the first communication device, thereby generating one or more transmit signals each of which is weighted across the bandwidth of the baseband signal to be transmitted.

2. The method of claim 1, and further comprising steps of:

f. receiving at the N plurality of antennas of the first communication device the one or more transmit signals transmitted by the second communication device;

g. determining a receive weight vector from the signals received by the N plurality of antennas; and

h. updating the transmit weight vector for the N plurality of antennas of the first communication device for transmitting signals to the second communication device by computing a conjugate of the receive weight vector of the first communication device divided by a norm of the conjugate of the receive weight vector.

3. The method of claim 2, and further comprising repeating steps (a) through (h) for a predetermined number iterations to converge to transmit weight vectors and receive weight vectors of the first and second communication devices that optimize a signal-to-noise ratio for communication between the first and second communication devices.

4. The method of claim 1, wherein the step of determining the receive weight vector at the second communication device comprises matching the receive antenna weights to the received signal.

5. The method of claim1, wherein at substantially all frequencies of the baseband signal, the sum of the magnitude of the complex transmit antenna weights across the plurality of antennas of the first communication device is constant.

6. The method of claim 2, and further comprising storing in the first communication device optimum transmit antenna weights indexed against an identifier for the second communication device.

7. The method of claim 2, and further comprising storing in the first communication device optimum transmit antenna weights indexed against corresponding identifiers for each of a plurality of communication devices that the first communication device communicates with.

8. The method of claim 1, wherein steps (a) through (e) are performed for each of K frequency sub-bands of the baseband signal that correspond to sub-

carriers of a multi-carrier baseband signal or to synthesized frequency sub-bands of a single carrier baseband signal.

9. The method of claim 8, and further comprising storing in the first communication device, for each of the N antennas, complex transmit antenna weights for a subset of the K frequency sub-bands or sub-carriers.

10. The method of claim 9, and further comprising retrieving the stored subset of complex transmit antenna weights and generating therefrom the complete set of antenna weights for all of the K frequency sub-bands or sub-carriers using interpolation techniques.

11. The method of claim 1, wherein the step of receiving the N transmit signals at the second communication device comprises receiving the N transmit signals at each of M plurality of antennas, the step of determining the receive weight vector comprises determining a receive antenna weight for each of the M plurality of antennas comprising a magnitude and phase component at each of the frequency sub-bands that span the bandwidth of the baseband signal that was received, and wherein the step of applying the transmit antenna vector to the baseband signal to be transmitted from the second communication device to the first communication device generates M plurality of transmit signals each of which is weighted across the bandwidth of the baseband signal.

12. The method of claim 1, wherein the step (a) of applying a transmit weight vector comprises applying a transmit weight vector $[e^{-j2\pi f\tau 1}, e^{-j2\pi f\tau 2}, e^{-j2\pi f\tau i}, \ldots, e^{-j2\pi f\tau N}]^T$, for i = 1 to N, where τi is a time delay for antenna i, an initial packet to be transmitted from the first communication device to the second communication device.

13. A method for communicating signals between a first communication device and a second communication device using radio frequency (RF) communication techniques, comprising:

a. applying a transmit antenna vector to a baseband signal to be transmitted from the first communication device to the second communication device, the transmit antenna weight vector comprising a complex transmit antenna weight for each of the N plurality of antennas,

wherein each complex transmit antenna weight has a magnitude and a phase whose values may vary with frequency across a bandwidth of the baseband signal, thereby generating N transmit signals each of which is weighted across the bandwidth of the baseband signal;

b. receiving at the N plurality of antennas of the first communication device a signal that was transmitted by the second communication device;

c. determining a receive weight vector comprising a plurality of complex receive antenna weights for the N plurality of antennas of the first communication device from one or more signals received by the N plurality of antennas from the second communication device, wherein each receive antenna weight has a magnitude and a phase whose values may vary with frequency; and

d. updating the transmit weight vector for the plurality of antennas of the first communication device for transmitting signals to the second communication device by computing a conjugate of the receive weight vector of the first communication device divided by a norm of the conjugate of the receive weight vector.

14. The method of claim 13, wherein at substantially all frequencies of the baseband signal, the sum of the magnitude of the complex transmit antenna weights across the plurality of antennas of the first communication device is constant.

15. The method of claim 13, wherein steps (a) through (d) are performed for each of K frequency sub-bands of the baseband signal that correspond to sub-carriers of a multi-carrier baseband signal or to synthesized frequency sub-bands of a single carrier baseband signal.

16. The method of claim 15, and further comprising storing in the first communication device, for each of the N antennas, complex transmit antenna weights for a subset of the K frequency sub-bands or sub-carriers.

17. The method of claim 16, and further comprising retrieving the stored subset of complex transmit antenna weights and generating therefrom the complete

set of antenna weights for all of the K frequency sub-bands or sub-carriers using interpolation techniques.

18. The method of claim 13, and further comprising storing in the first communication device optimum transmit antenna weights indexed against an identifier for the second communication device.

19. The method of claim 18, and further comprising storing in the first communication device optimum transmit antenna weights indexed against corresponding identifiers for each of a plurality of communication devices that the first communication device communicates with.

20. The method of claim 13, wherein the step (a) of applying a transmit weight vector comprises applying a transmit weight vector $[e^{-j2\pi f\tau 1}, e^{-j2\pi f\tau 2}, e^{-j2\pi f\tau i}, \ldots, e^{-j2\pi f\tau N}]^T$, for i = 1 to N, where τi is a time delay for antenna i, an initial packet to be transmitted from the first communication device to the second communication device.

21. A medium encoded with instructions that, when executed, perform a method comprising steps of:

a. applying a transmit antenna vector to a baseband signal to be transmitted from a first communication device to a second communication device, the transmit antenna weight vector comprising a complex transmit antenna weight for each of the N plurality of antennas, wherein each complex transmit antenna weight has a magnitude and a phase whose values may vary with frequency across a bandwidth of the baseband signal, thereby generating N transmit signals each of which is weighted across the bandwidth of the baseband signal;

b. determining a receive weight vector comprising a plurality of complex receive antenna weights for the N plurality of antennas of the first communication device from one or more signals received by the N plurality of antennas from the second communication device, wherein each receive antenna weight has a magnitude and a phase whose values may vary with frequency; and

c. updating the transmit weight vector for the plurality of antennas of the first communication device for transmitting signals to the second

communication device by computing a conjugate of the receive weight vector of the first communication device divided by a norm of the conjugate of the receive weight vector.

22. The medium of claim 21, and further comprising instructions for performing steps (a) through (c) at each of K frequency sub-bands of the baseband signal that correspond to sub-carriers of a multi-carrier baseband signal or to synthesized frequency sub-bands of a single carrier baseband signal.

23. The medium of claim 22, and further comprising instructions for storing in the first communication device, for each of the N antennas, complex transmit antenna weights for a subset of the K frequency sub-bands or sub-carriers.

24. The medium of claim 23, and further comprising instructions for retrieving the stored subset of complex transmit antenna weights and generating therefrom the complete set of antenna weights for all of the K frequency sub-bands or sub-carriers using interpolation techniques.

25. The medium of claim 21, and further comprising instructions for setting the magnitude of the complex transmit antenna weights such that at substantially all frequencies of the baseband signal, the sum of the power across the plurality of antennas of the first communication device is constant.

26. The medium of claim 21, wherein the instructions for applying a transmit weight vector to a baseband signal to be transmitted from the first communication device to the second communication device comprises instructions for applying a transmit weight vector $[e^{-j2\pi f\tau 1}, e^{-j2\pi f\tau 2}, e^{-j2\pi f\tau i}, \ldots, e^{-j2\pi f\tau N}]^T$, for i = 1 to N, where τi is a time delay for antenna i, an initial packet to be transmitted from the first communication device to the second communication device.

27. The medium of claim 21, wherein instructions encoded on the medium define digital logic gates that perform steps (a) through (c).

28. The medium of claim 21, wherein the instructions are processor readable instructions, that when executed by a processor, cause the processor to perform steps (a) through (c).

29. An integrated circuit comprising the medium of claim 21.

30. In combination, the integrated circuit of claim 29, and further comprising a processor that executes the instructions encoded on the medium.

31. A communication device comprising the medium of claim 21, and further comprising:

a. a transmitter that upconverts transmit signals for transmission;

b. a receiver that downconverts received signals; and

c. a processor coupled to the transmitter and to the receiver that processes instructions encoded on the medium.

32. A method for communicating signals from a first communication device to a second communication device using radio frequency (RF) communication techniques, comprising:

a. transmitting a first signal by one of N plurality of antennas of the first communication device;

b. receiving the first signal transmitted by the first communication device at two antennas of the second communication device;

c. transmitting a first response signal from the second communication device to the first communication device using a first of two antennas at the second communication device;

d. at the first communication device, receiving at the plurality of antennas the first response signal transmitted by the first antenna of the second communication device and deriving therefrom a first row of a channel response matrix that describes the channel response between the first communication device and the second communication device;

e. transmitting a second signal by the plurality of antennas of the first communication device using a transmit weight vector that is orthogonal to the first row of the channel response matrix;

f. receiving the second signal transmitted at the second communication device at the two antennas;

g. transmitting a second response signal from the second communication device using a second of the two antennas;

h. at the first communication device, receiving the second response signal transmitted by the second antenna of the second communication device and deriving therefrom a second row of the channel response matrix; and

i. at the first communication device, selecting one of the first and second rows of the channel response matrix that provides better signal-to-noise at the second communication device as the transmit weight vector for further transmission of signals to the second communication device.

33. The method of claim 32, and further comprising the step of computing a norm of each row of the channel response matrix, and wherein the step of selecting comprises selecting the row that has the greater norm.

34. The method of claim 32, wherein the steps (a) through (i) are performed at each of a plurality of frequencies corresponding to sub-carrier frequencies of a multi-carrier baseband signal or synthesized frequency sub-bands of a single carrier baseband signal.

35. The method of claim 34, and further comprising storing in the first communication device, for each of the N antennas, complex transmit antenna weights for a subset of the frequency sub-bands or sub-carriers.

36. The method of claim 35, and further comprising retrieving the stored subset of complex transmit antenna weights and generating therefrom the complete set of antenna weights for all of the frequency sub-bands or sub-carriers using interpolation techniques.

37. The method of claim 32, wherein the second communication device selects one of the two antennas for transmitting signals to the first communication device based on which of the two antennas more strongly received a signal from the first communication device.

38. The method of claim 32, wherein the step of transmitting the second signal from the first communication device to the second communication device using a transmit weight vector that is orthogonal to the row of the channel response matrix forces the second communication device to select the

second antenna based on received signal strength at each of two antennas of second communication device.

39. The method of claim 32, wherein at substantially all frequencies of the baseband signal, the magnitude of the complex transmit antenna weights are such that the sum of the power across the plurality of antennas of the first communication device is constant.

40. A method for communicating signals from a first communication device to a second communication device using radio frequency (RF) communication techniques, comprising:

a. transmitting a first signal by one of N plurality of antennas of the first communication device;

b. receiving a first response signal at the plurality of antennas of the first communication device transmitted from a first of two antennas of the second communication device;

c. deriving a first row of a channel response matrix that describes the channel response between the first communication device and the second communication device;

d. transmitting a second signal by the plurality of antennas of the first communication device using a transmit weight vector that is orthogonal to the first row of the channel response matrix;

e. receiving a second response signal transmitted by a second of the two antennas of the second communication device and deriving therefrom a second row of the channel response matrix; and

f. selecting one of the first and second rows of the channel response matrix that provides better signal-to-noise at the second communication device as the transmit weight vector for further transmission of signals to the second communication device.

41. The method of claim 40, and further comprising the step of determining when a signal received at the first communication device from the second communication device indicates at least a minimum difference in a row of the channel response matrix, and repeating steps (a)-(f) in response thereto.

42. The method of claim 40, and further comprising the step of computing a norm of each row of the channel response matrix, and wherein the step of selecting comprises selecting the row that has the greater norm.

43. The method of claim 40, wherein the steps (a) through (f) are performed at each of a plurality of frequencies corresponding to sub-carrier frequencies of a multi-carrier baseband signal or synthesized frequency sub-bands of a single carrier baseband signal.

44. The method of claim 43, and further comprising storing in the first communication device, for each of the N antennas, complex transmit antenna weights for a subset of the frequency sub-bands or sub-carriers.

45. The method of claim 43, and further comprising retrieving the stored subset of complex transmit antenna weights and generating therefrom the complete set of antenna weights for all of the frequency sub-bands or sub-carriers using interpolation techniques.

46. The method of claim 40, wherein at substantially all frequencies of the baseband signal, the magnitude of the complex transmit antenna weights are such that the sum of the power across the plurality of antennas of the first communication device is constant.

47. A medium encoded with instructions that, when executed, perform steps of:

a. generate a first signal for transmission by one of a plurality of antennas of a first communication device to a second communication device;

b. process a first response signal received at the plurality of antennas that was transmitted from a first of two antennas of the second communication device and generating a first row of a channel response matrix that describes the channel response with the other communication device;

c. applying to a second signal a transmit weight vector that is orthogonal to the first row of the channel response matrix for transmission via the plurality of antennas of the first communication device to the second communication device;

d. processing a second response signal received at the plurality of antennas that was transmitted from a second of two antennas of the second

communication device and generating therefrom a second row of the channel response matrix; and

e. selecting one of the first and second rows of the channel response matrix that provides better signal-to-noise at the second communication device as the transmit weight vector for further transmission of signals to the other communication device.

48. The medium of claim 47, and further comprising instructions to compute a norm of each row of the channel response matrix, and select the row that has the greater norm as the transmit weight vector.

49. The medium of claim 47, wherein the instructions perform steps (a) through (e) are performed at each of a plurality of frequencies corresponding to sub-carrier frequencies of a multi-carrier baseband signal or synthesized frequency sub-bands of a single carrier baseband signal.

50. The medium of claim 47, wherein the instructions encoded on the medium define digital logic gates that perform steps (a) through (e).

51. The medium of claim 47, wherein the instructions are processor readable instructions, that when executed by a processor, cause the processor to perform steps (a) through (e).

52. A communication device comprising the medium of claim 47, and further comprising:

a. a transmitter that upconverts signals to be transmitted;

b. a receiver that downconverts received signals;

c. a processor coupled to the transmitter and to the receiver that processes the instructions encoded on the medium.

53. An integrated circuit comprising the medium of claim 47.

54. The integrated circuit of claim 47, and further comprising a processor that executes the instructions encoded on the medium.

55. A method for communicating signals between a first communication device and a second communication device using radio frequency (RF) communication techniques, comprising:

a. generating a training sequence comprising a sequence of N consecutive symbols, where N is a number of antennas of the first communication

device, and the N symbols are multiplied by respective ones of N linearly independent vectors that span columns of a channel response matrix between the plurality of antennas of the first communication device and a plurality of antennas of the second communication device, thereby producing N transmit signals;

b. transmitting the N transmit signals from the plurality of antennas of the first communication device;

c. receiving the N transmit signals at each of a plurality of antennas at the second communication device;

d. at the second communication device, deriving from signals received by the plurality of antennas the channel response matrix between the first communication device and the second communication device; and

e. at the second communication device, generating a transmit weight vector from the channel response matrix for transmitting a signal from the second communication device to the first communication device using the plurality of antennas of the second communication device.

56. The method of claim 55, and further comprising:

a. appending the training sequence to a data unit for transmission from the first communication device to the second communication device;

b. transmitting the data unit with the appended training sequence by the antennas of the first communication device; and

c. at the second communication device, receiving the data unit and the appended training sequence and decoding the data unit.

57. The method of claim 55, wherein the step of appending the training sequence comprises appending the training sequence to a directed media access control (MAC) protocol data unit in accordance with the IEEE 802.11 communication standard.

58. The method of claim 55, wherein the step of generating the training sequence comprises generating N consecutive 2-symbol long preamble sequences in accordance with the IEEE 802.11 communication standard.

59. The method of claim 55, wherein the step of generating the transmit weight vector comprises updating the transmit weight vector for transmitting a signal to the first communication device.

60. The method of claim 55, and further comprising the step of storing at the second communication device information describing the transmit weight vector to be used for transmitting signals to the first communication device.

61. The method of claim 60, wherein the step of storing comprises storing at the second communication device information describing transmit weight vectors to be used for transmitting signals to each of a plurality of corresponding communication devices.

62. The method of claim 55, and further comprising the step of transmitting a message to the second communication device to determine whether the second communication device is capable of transmitting signals back to the first communication device using an adjustable transmit weight vector.

63. The method of claim 55, wherein steps (a) through (e) are performed at each of a plurality of frequencies corresponding to sub-carrier frequencies of a multi-carrier baseband signal or synthesized frequency sub-bands of a single carrier baseband signal so as to generate frequency dependent transmit antenna weights for the transmit weight vector.

64. The method of claim 55, wherein the step of generating the training sequence comprises applying to the N symbols respective ones of the transmit weight vectors $[1\ 0\ \ldots\ 0]_0^T$, $[0\ 1\ 0\ \ldots\ 0]_1^T$, ..., $[0\ 0\ \ldots\ 1]_{N-1}^T$.

FIG. 1

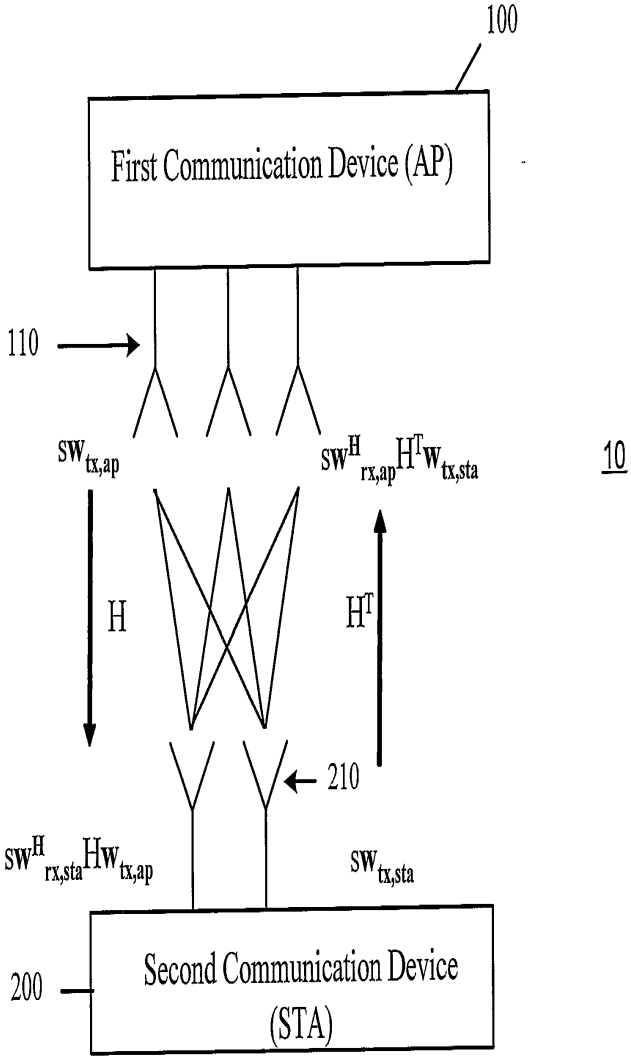

100
First Communication Device (AP)
110
$SW_{tx,ap}$
$SW^{H}_{rx,ap}H^{T}W_{tx,sta}$
10
H
H^{T}
210
$SW^{H}_{rx,sta}HW_{tx,ap}$
$SW_{tx,sta}$
200
Second Communication Device (STA)

FIG. 2

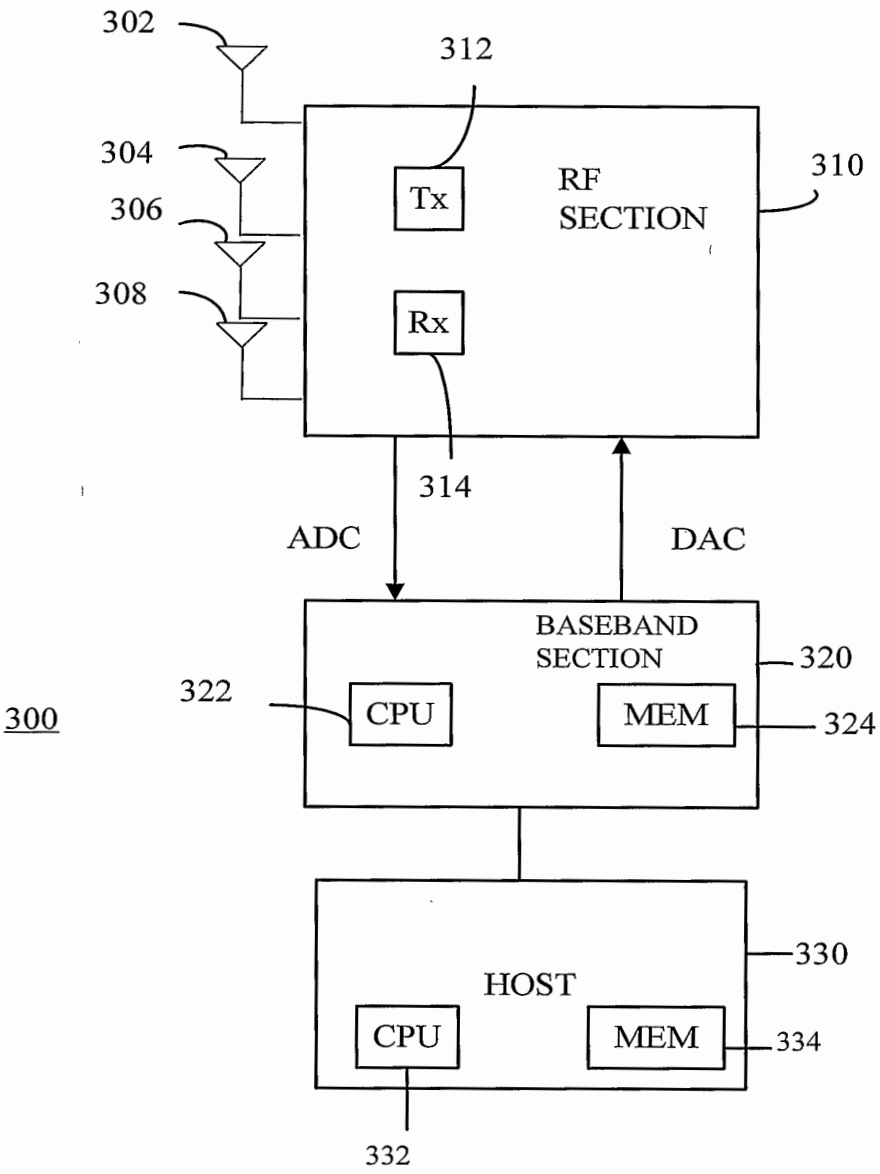

302
312
304
306
308
Tx
RF
SECTION
310
Rx
314
ADC
DAC
BASEBAND
SECTION
320
322
300
CPU
MEM
324
330
HOST
CPU
MEM
334
332

FIG. 3

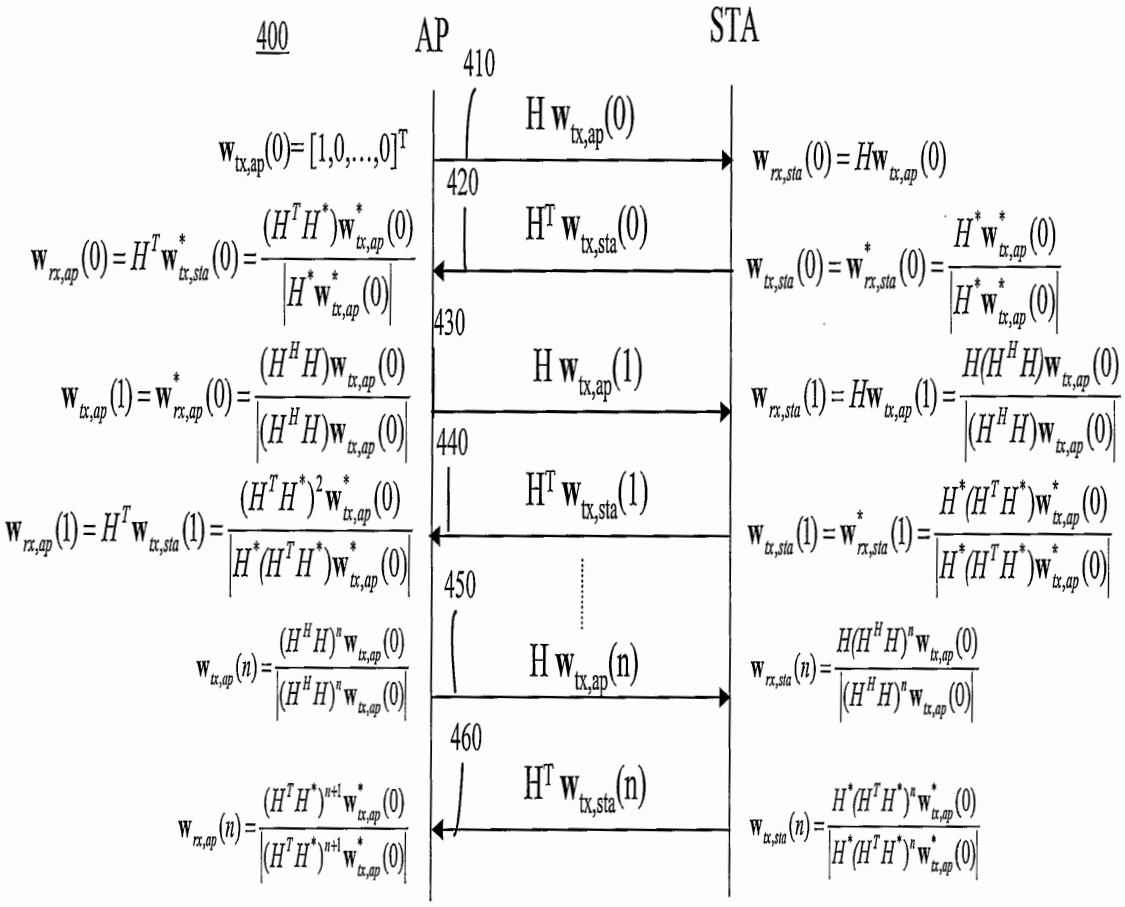
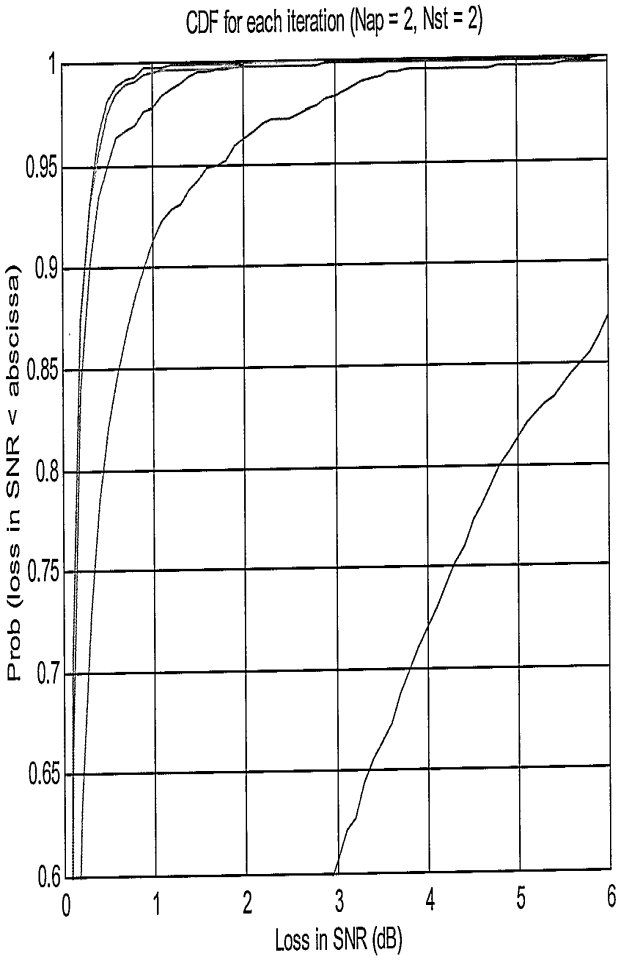
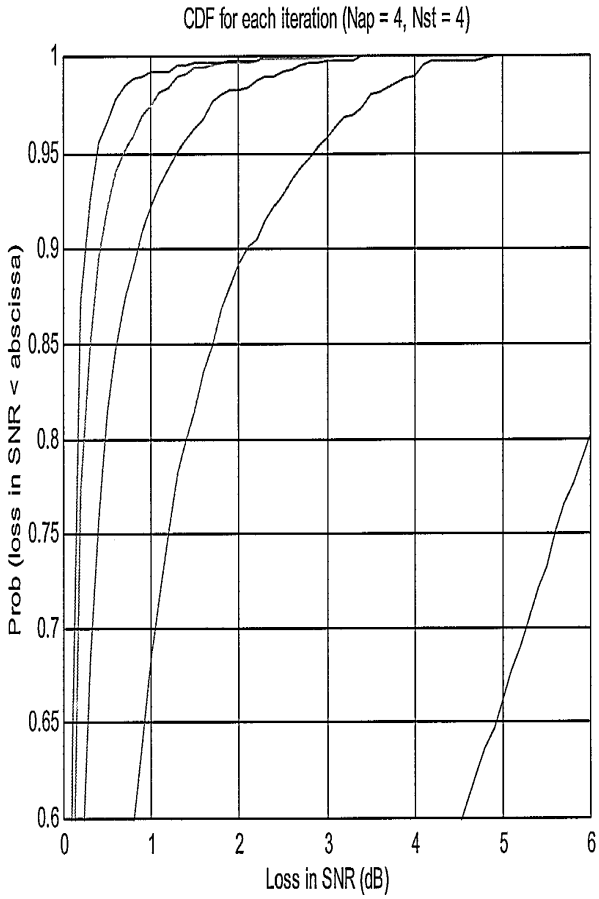

400
AP
STA
410
$\mathbf{w}_{tx,ap}(0)=[1,0,\ldots,0]^T$
$H\,\mathbf{w}_{tx,ap}(0)$
$\mathbf{w}_{rx,sta}(0)=H\mathbf{w}_{tx,ap}(0)$
420
$\mathbf{w}_{rx,ap}(0)=H^T\mathbf{w}^*_{tx,sta}(0)=\frac{(H^TH^*)\mathbf{w}^*_{tx,ap}(0)}{\left|H^*\mathbf{w}^*_{tx,ap}(0)\right|}$
$H^T\mathbf{w}_{tx,sta}(0)$
$\mathbf{w}_{tx,sta}(0)=\mathbf{w}^*_{rx,sta}(0)=\frac{H^*\mathbf{w}^*_{tx,ap}(0)}{\left|H^*\mathbf{w}^*_{tx,ap}(0)\right|}$
430
$\mathbf{w}_{tx,ap}(1)=\mathbf{w}^*_{rx,ap}(0)=\frac{(H^HH)\mathbf{w}_{tx,ap}(0)}{\left|(H^HH)\mathbf{w}_{tx,ap}(0)\right|}$
$H\,\mathbf{w}_{tx,ap}(1)$
$\mathbf{w}_{rx,sta}(1)=H\mathbf{w}_{tx,ap}(1)=\frac{H(H^HH)\mathbf{w}_{tx,ap}(0)}{\left|(H^HH)\mathbf{w}_{tx,ap}(0)\right|}$
440
$\mathbf{w}_{rx,ap}(1)=H^T\mathbf{w}_{tx,sta}(1)=\frac{(H^TH^*)^2\mathbf{w}^*_{tx,ap}(0)}{\left|H^*(H^TH^*)\mathbf{w}^*_{tx,ap}(0)\right|}$
$H^T\mathbf{w}_{tx,sta}(1)$
$\mathbf{w}_{tx,sta}(1)=\mathbf{w}^*_{rx,sta}(1)=\frac{H^*(H^TH^*)\mathbf{w}^*_{tx,ap}(0)}{\left|H^*(H^TH^*)\mathbf{w}^*_{tx,ap}(0)\right|}$
450
$\mathbf{w}_{tx,ap}(n)=\frac{(H^HH)^n\mathbf{w}_{tx,ap}(0)}{\left|(H^HH)^n\mathbf{w}_{tx,ap}(0)\right|}$
$H\,\mathbf{w}_{tx,ap}(n)$
$\mathbf{w}_{rx,sta}(n)=\frac{H(H^HH)^n\mathbf{w}_{tx,ap}(0)}{\left|(H^HH)^n\mathbf{w}_{tx,ap}(0)\right|}$
460
$\mathbf{w}_{rx,ap}(n)=\frac{(H^TH^*)^{n+1}\mathbf{w}^*_{tx,ap}(0)}{\left|(H^TH^*)^{n+1}\mathbf{w}^*_{tx,ap}(0)\right|}$
$H^T\mathbf{w}_{tx,sta}(n)$
$\mathbf{w}_{tx,sta}(n)=\frac{H^*(H^TH^*)^n\mathbf{w}^*_{tx,ap}(0)}{\left|H^*(H^TH^*)^n\mathbf{w}^*_{tx,ap}(0)\right|}$

FIG. 4



Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 5



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IPR2024-00148

FIG. 6

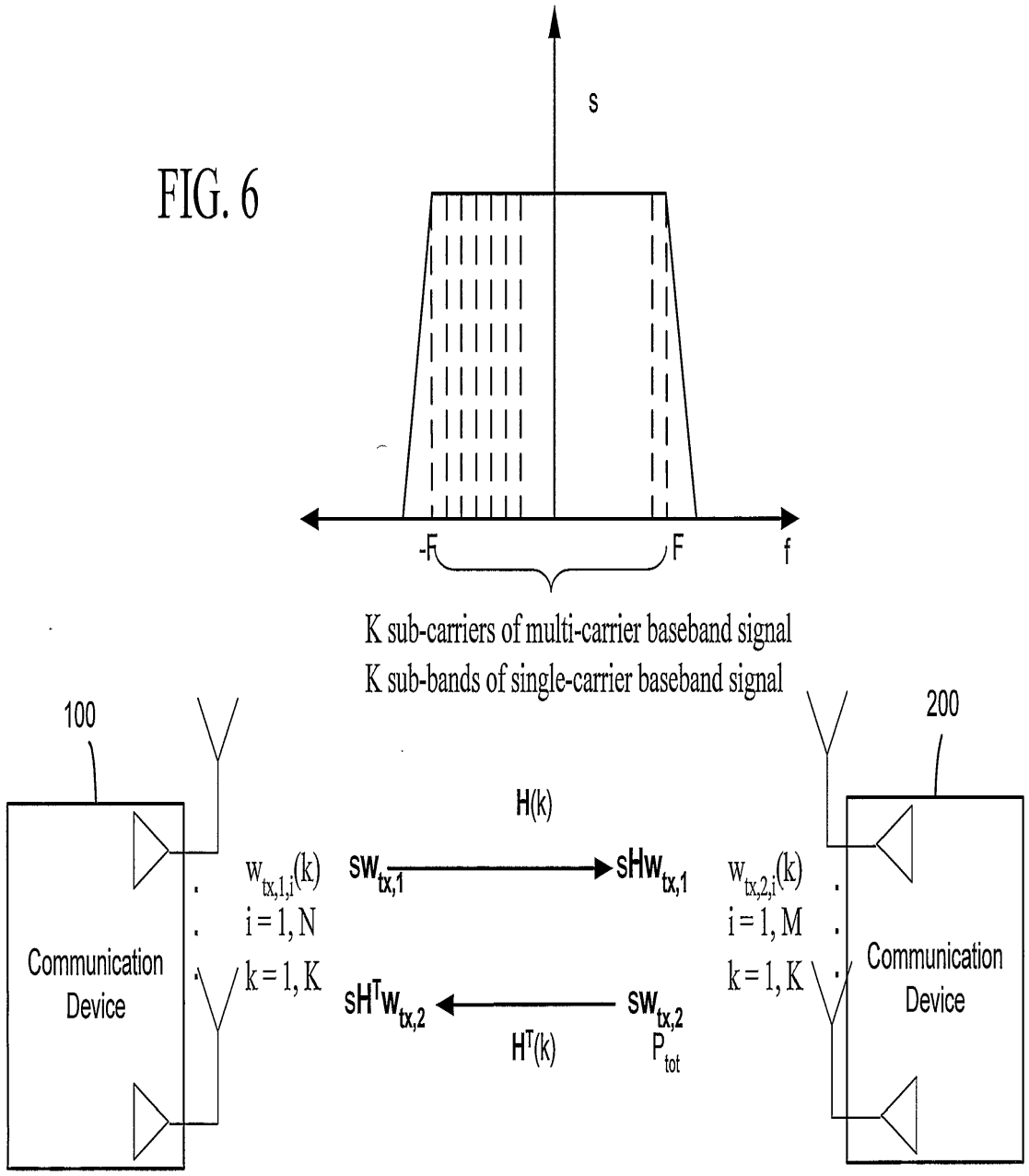

s
-F
F
f
K sub-carriers of multi-carrier baseband signal
K sub-bands of single-carrier baseband signal
100
200
H(k)
$w_{tx,1,i}(k)$
i = 1, N
k = 1, K
$sw_{tx,1}$
$sHw_{tx,1}$
$sH^Tw_{tx,2}$
$sw_{tx,2}$
$H^T(k)$
P_{tot}
$w_{tx,2,i}(k)$
i = 1, M
k = 1, K
Communication Device
Communication Device

FIG. 7

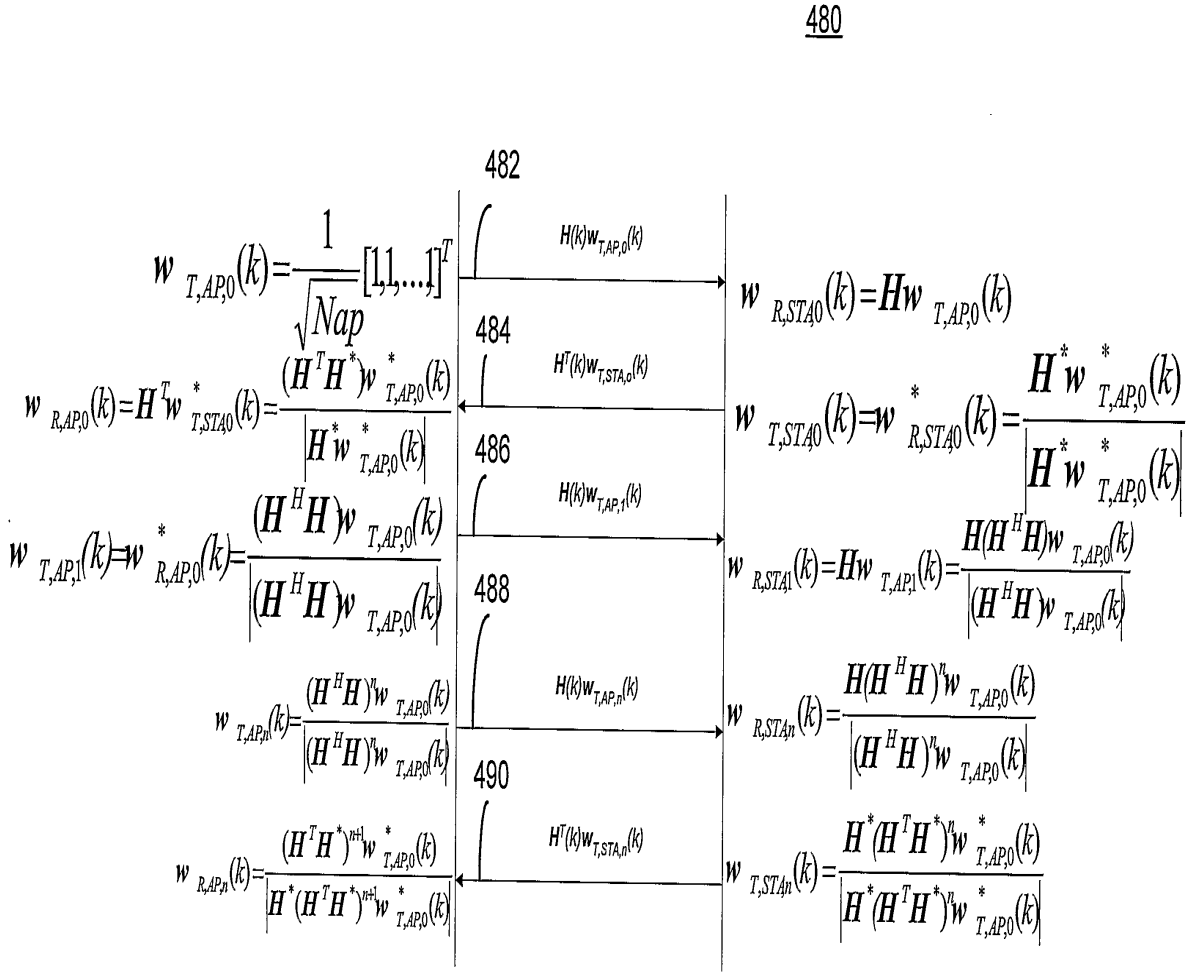

480
482
$w_{T,AP,0}(k)=\frac{1}{\sqrt{Nap}}[1,1,\ldots,1]^T$
$H(k)w_{T,AP,0}(k)$
$w_{R,STA,0}(k)=Hw_{T,AP,0}(k)$
484
$H^T(k)w_{T,STA,0}(k)$
$w_{R,AP,0}(k)=H^T w^*_{T,STA,0}(k)=\frac{(H^T H^*)w^*_{T,AP,0}(k)}{\left|H^* w^*_{T,AP,0}(k)\right|}$
$w_{T,STA,0}(k)=w^*_{R,STA,0}(k)=\frac{H^* w^*_{T,AP,0}(k)}{\left|H^* w^*_{T,AP,0}(k)\right|}$
486
$H(k)w_{T,AP,1}(k)$
$w_{T,AP,1}(k)=w^*_{R,AP,0}(k)=\frac{(H^H H)w_{T,AP,0}(k)}{\left|(H^H H)w_{T,AP,0}(k)\right|}$
$w_{R,STA,1}(k)=Hw_{T,AP,1}(k)=\frac{H(H^H H)w_{T,AP,0}(k)}{\left|(H^H H)w_{T,AP,0}(k)\right|}$
488
$H(k)w_{T,AP,n}(k)$
$w_{T,APn}(k)=\frac{(H^H H)^n w_{T,AP,0}(k)}{\left|(H^H H)^n w_{T,AP,0}(k)\right|}$
$w_{R,STAn}(k)=\frac{H(H^H H)^n w_{T,AP,0}(k)}{\left|(H^H H)^n w_{T,AP,0}(k)\right|}$
490
$H^T(k)w_{T,STA,n}(k)$
$w_{R,APn}(k)=\frac{(H^T H^*)^{n+1} w^*_{T,AP,0}(k)}{\left|H^*(H^T H^*)^{n+1} w^*_{T,AP,0}(k)\right|}$
$w_{T,STAn}(k)=\frac{H^*(H^T H^*)^n w^*_{T,AP,0}(k)}{\left|H^*(H^T H^*)^n w^*_{T,AP,0}(k)\right|}$

FIG. 8

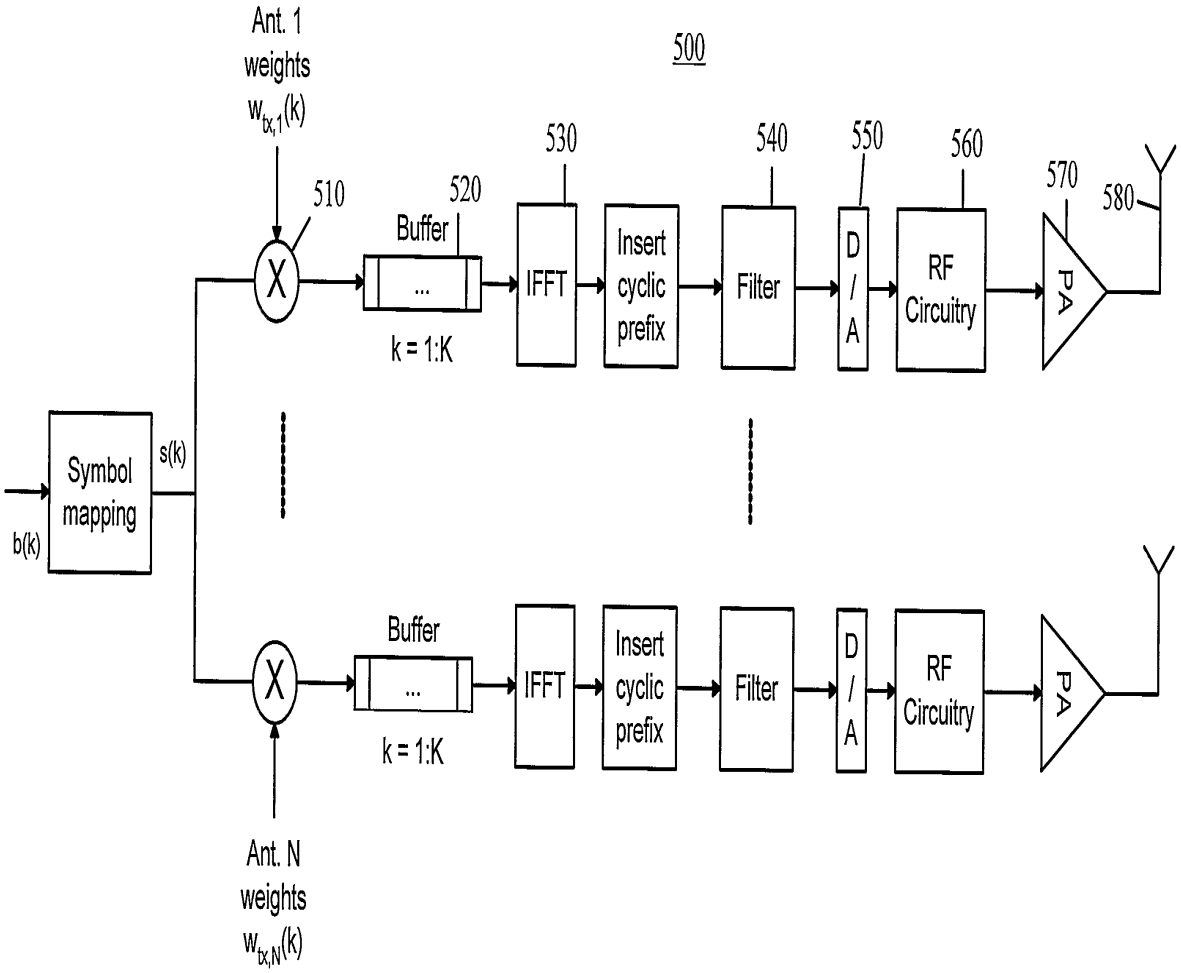

500
Ant. 1 weights $w_{tx,1}(k)$
510
520
Buffer
...
k = 1:K
530
IFFT
Insert cyclic prefix
540
Filter
550
D / A
560
RF Circuitry
570
PA
580
Symbol mapping
b(k)
s(k)
Buffer
...
k = 1:K
IFFT
Insert cyclic prefix
Filter
D / A
RF Circuitry
PA
Ant. N weights $w_{tx,N}(k)$

FIG. 9

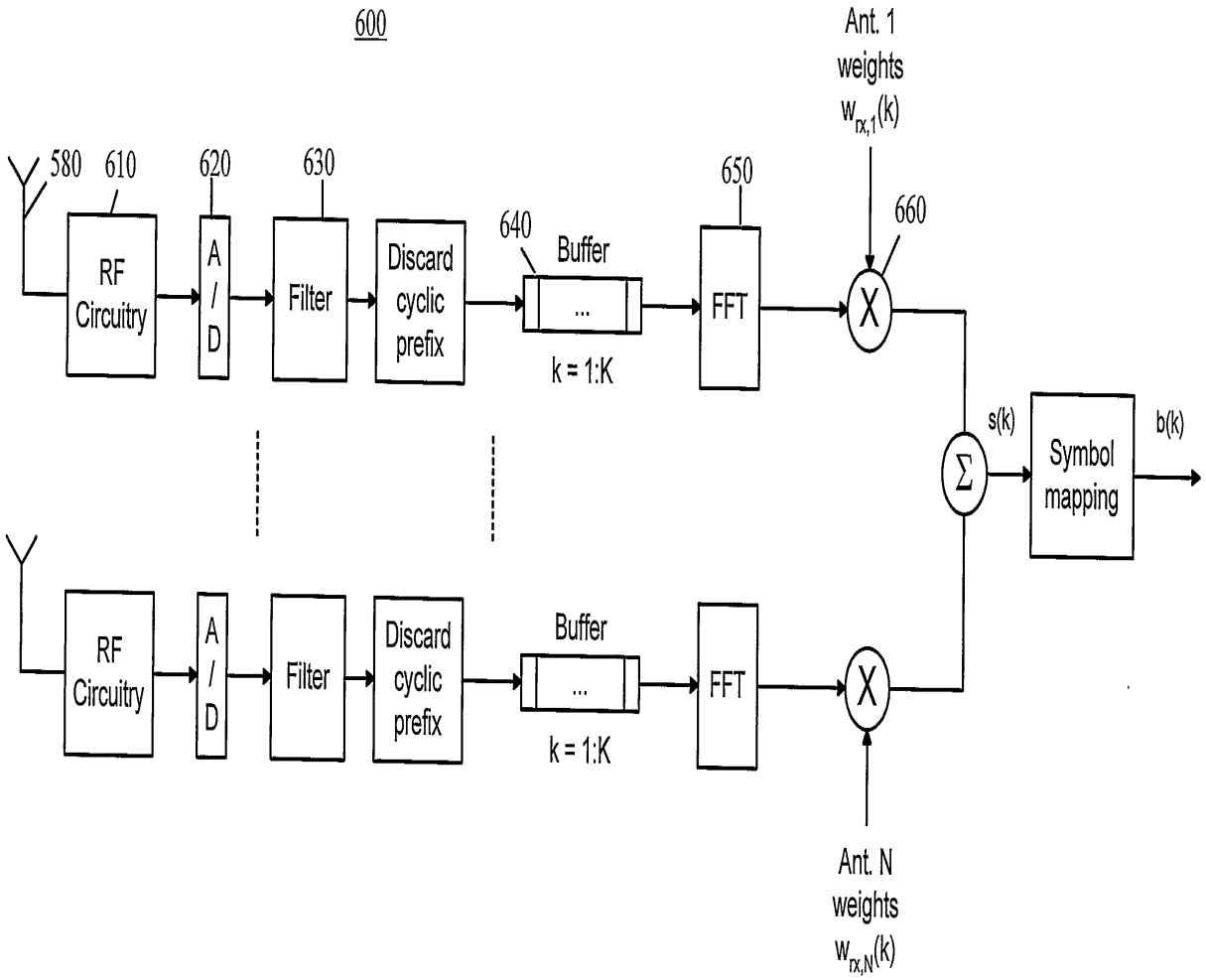

600
Ant. 1 weights $w_{rx,1}(k)$
580
610
620
630
650
640
Buffer
660
RF Circuitry
A / D
Filter
Discard cyclic prefix
...
k = 1:K
FFT
X
s(k)
Σ
Symbol mapping
b(k)
RF Circuitry
A / D
Filter
Discard cyclic prefix
Buffer
...
k = 1:K
FFT
X
Ant. N weights $w_{rx,N}(k)$

FIG. 10

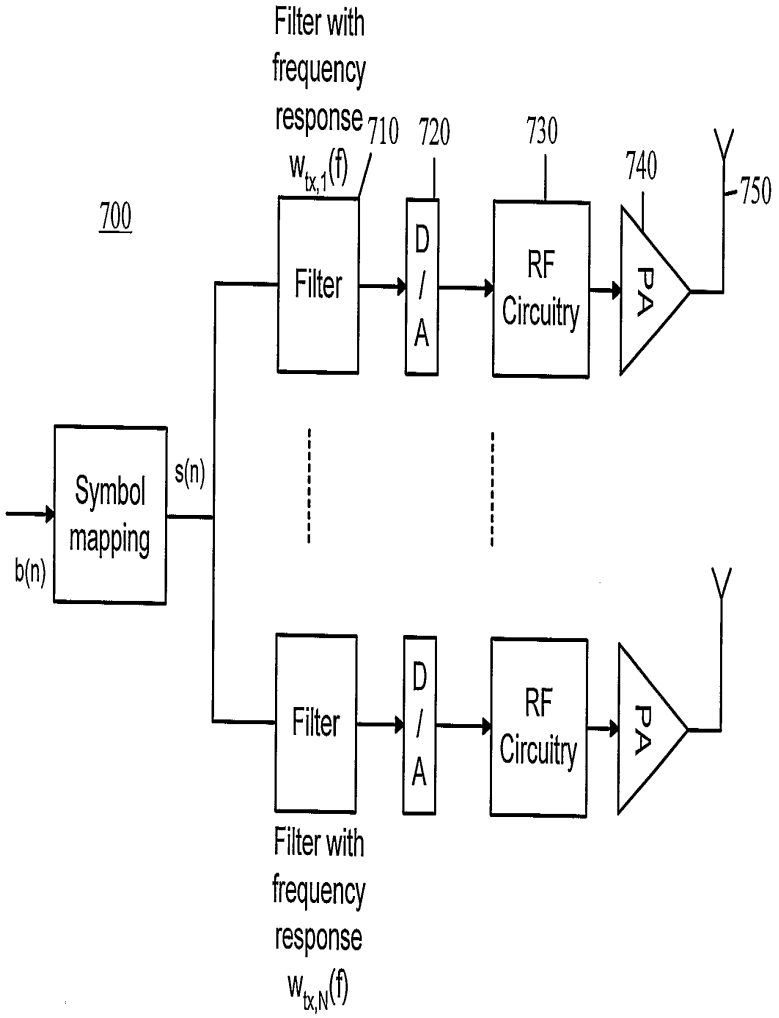
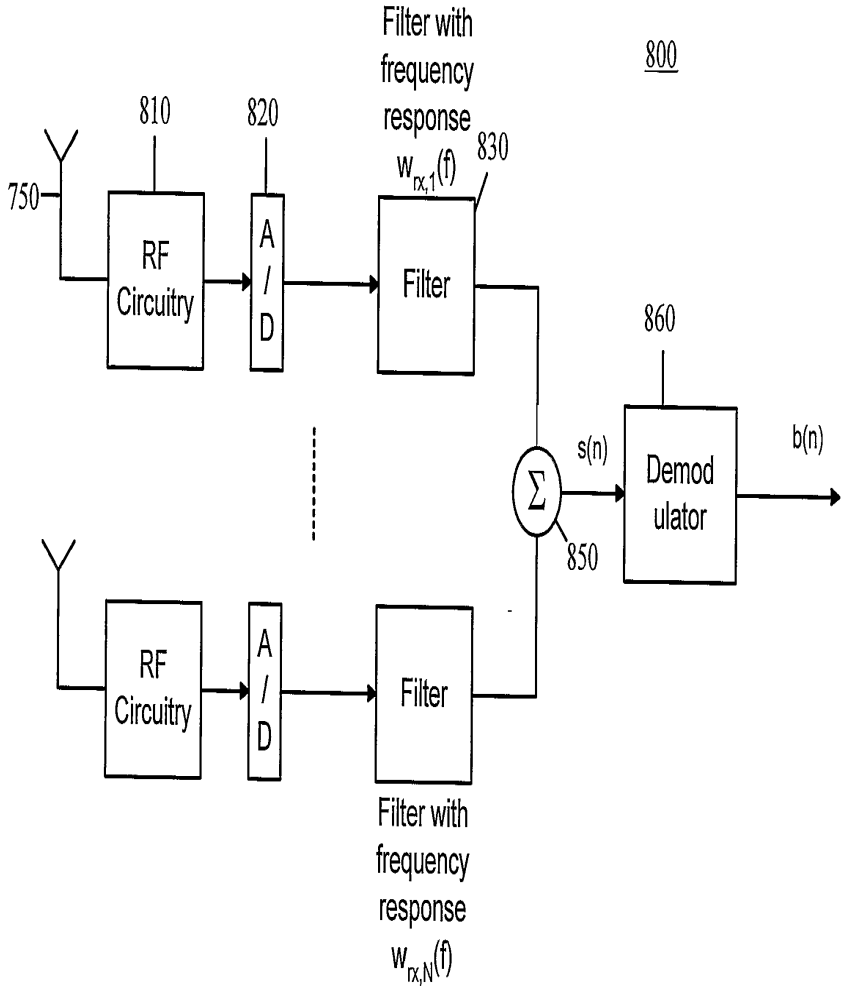

Filter with frequency response $w_{tx,1}(f)$
710
720
730
740
750
700
Filter
D / A
RF Circuitry
PA
Symbol mapping
s(n)
b(n)
Filter
D / A
RF Circuitry
PA
Filter with frequency response $w_{tx,N}(f)$

FIG. 11



Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

FIG. 12

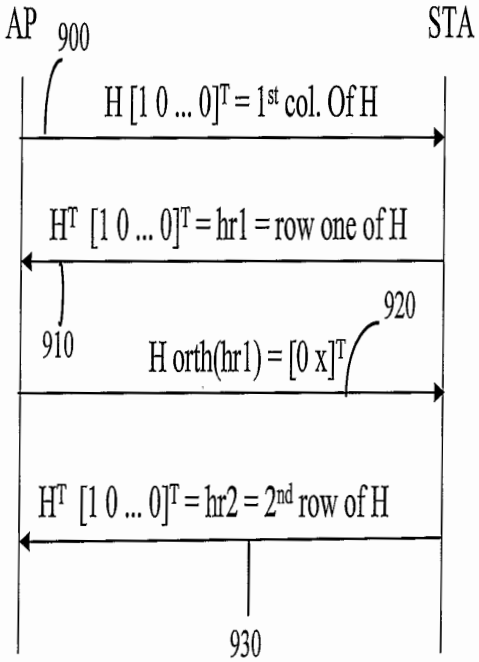
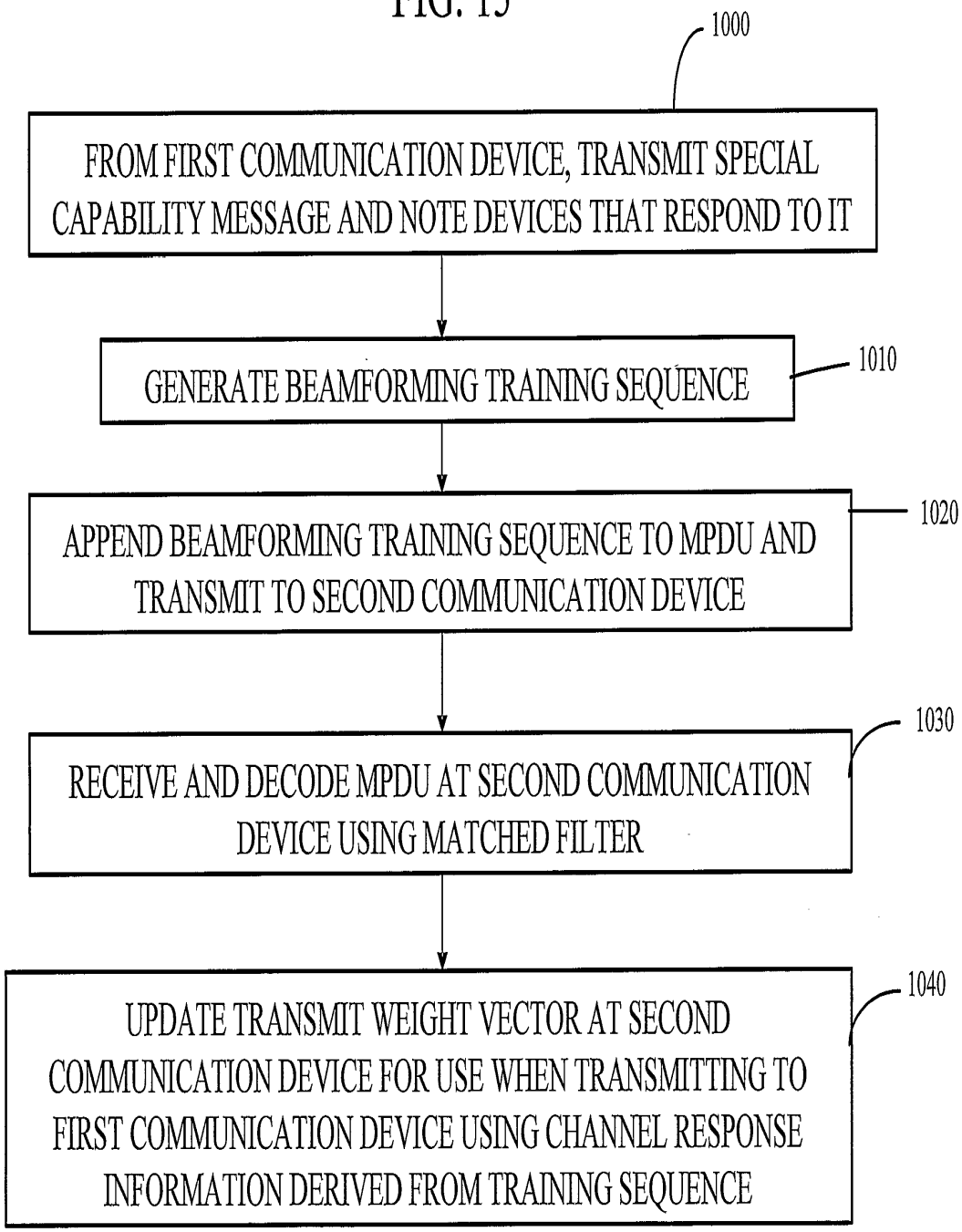

AP
STA
900
H [1 0 ... 0]T = 1st col. Of H
HT [1 0 ... 0]T = hr1 = row one of H
910
920
H orth(hr1) = [0 x]T
HT [1 0 ... 0]T = hr2 = 2nd row of H
930

FIG. 13


1000
FROM FIRST COMMUNICATION DEVICE, TRANSMIT SPECIAL CAPABILITY MESSAGE AND NOTE DEVICES THAT RESPOND TO IT
GENERATE BEAMFORMING TRAINING SEQUENCE
1010
APPEND BEAMFORMING TRAINING SEQUENCE TO MPDU AND TRANSMIT TO SECOND COMMUNICATION DEVICE
1020
RECEIVE AND DECODE MPDU AT SECOND COMMUNICATION DEVICE USING MATCHED FILTER
1030
UPDATE TRANSMIT WEIGHT VECTOR AT SECOND COMMUNICATION DEVICE FOR USE WHEN TRANSMITTING TO FIRST COMMUNICATION DEVICE USING CHANNEL RESPONSE INFORMATION DERIVED FROM TRAINING SEQUENCE
1040

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(71) Applicant *(for all designated States except US)*: AUTOMOTIVE PRODUCTS FRANCE S.A. [FR/FR]; 43, avenue du Gros-Chêne, F-95520 Herblay-Cergy-Pontoise (FR).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: TOBIASZ, Andre [FR/FR]; 4, allée Rude, F-93800 Epinay-sur-Seine (FR). VO, Remy [FR/FR]; 66, rue Sainte-Catherine, F-45000 Orléans (FR). PLATTEAUX, Paul [FR/FR]; 284, rue des Pointes, F-45410 Sougy (FR). NIX, Richard [US/FR]; 92, avenue des Bonshommes, F-95290 L'Isle-Adam (FR).

(74) Agent: MORRALL, Roger; Automotive Products plc, Tachbrook Road, Leamington Spa, Warwickshire CV31 3ER (GB).

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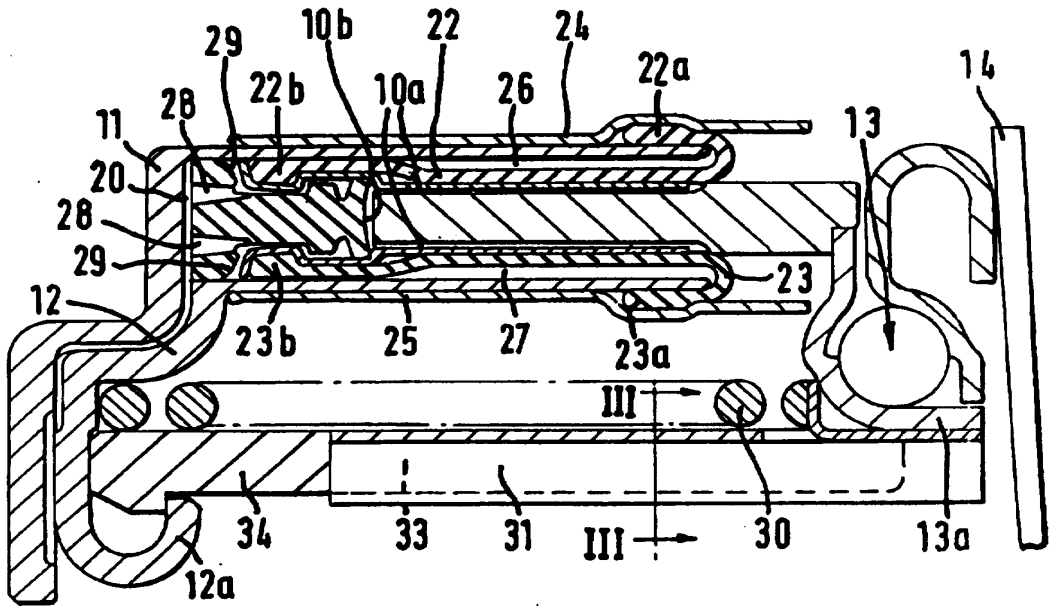

(57) Abstract

An actuator, particularly for the operation of a vehicle clutch in which an annular piston (10) slides between cylinder walls (11, 12) to define an annular working chamber (20). A sealing means (15) seals the piston to the cylinder walls and an overflow chamber (26, 27) retains any fluid which leaks past the sealing means from the working chamber. A return means (28) is also provided for returning fluid from the overflow chamber when the piston is not undertaking a working stroke.

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Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

ACTUATORS

This invention relates to actuators hereinafter referred to as actuators "of the kind specified" in which an annular piston defines an annular working chamber in combination with co-operating cylinder walls, the piston being axially displaceable relative to the cylinder walls by pressurisation of fluid within the working chamber.

Actuators of the kind specified are used for a variety of purposes but are particularly suitable for the actuation of a vehicle clutch release bearing when the actuator can be installed concentrically around a gearbox input shaft of the vehicle.

Problems arise with such actuators in that actuating fluid leaks past seals which seal the piston to the cylinder walls and can then contaminate the associated clutch. Also, on rapid movements of the piston, or sudden depressions in the fluid pressure in the working chamber, air may be drawn into the working chamber past the piston seals.

It is an object of the present invention to provide an actuator of the kind specified which is less susceptible to leakage and to the ingress of air.

Thus according to the present invention there is provided an

actuator of the kind specified having sealing means for sealing the piston to the cylinder walls, an overflow chamber which retains any fluid which leaks past the sealing means from the working chamber, and return means for returning fluid from the overflow chamber when the piston is not undertaking a working stroke.

The return means may comprise valve means which controls communication between the working chamber and over flow chamber, the valve means opening up communication between said chambers when the piston is not undertaking a working stroke.

Such an actuator is less susceptible to leakage and air ingress since the overflow chamber retains any fluid which leaks past the seals and the valve means enables the piston to suck back fluid into the working chamber from the overflow chamber instead of sucking in air.

The valve means may conveniently be built into the sealing means.

For example, pressurisation of the working chamber may cause deflection of the sealing means to close-off communication between the working and overflow chambers.

Alternatively the return means may comprise a valve means separate from the sealing means, said valve means being arranged to be normally biased to a closed position but

being opened on a return stroke of the piston following a working stroke.

The overflow chamber may be defined by diaphragm means in combination with the walls.

In an arrangement in which the piston is displaceable between inner and outer cylinder walls one diaphragm may extend between the piston and the inner cylinder wall and a second diaphragm may extend between the piston and the outer cylinder wall.

In an alternative arrangement the overflow chamber may be defined by a diaphragm means and a portion of the outer cylinder wall, passageway means being provided to direct any fluid which leaks past the sealing means to the overflow chamber.

Where the actuator is to be used to operate a vehicle clutch a clutch release bearing is carried by the piston.

Several embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings in which:-

Figure 1 is a radial section through an actuator according to the present invention for the operation of a vehicle clutch;

Figure 2 shows half of figure 1 on a larger scale with half

of the actuator seal shown in its open position and the other half in its closed position;

Figure 3 is a section on line III-III of Figure 1;

Figure 4 shows a similar view to Figure 2 with an alternative sealing/valve arrangement;

Figure 5 is a radial section through an alternative clutch actuator according to the invention which is constructed largely from plastics material;

Figure 6 is an enlarged view of the sealing/valve arrangement used in Figure 5, and

Figure 7 is a radial section through a further alternative clutch actuator which employs a separate return valve.

Referring to figure 1 this shows a vehicle clutch actuator in which an annular piston 10 is displaceable between an inner cylinder member 11 and an outer cylinder member 12. Piston 10 carries a clutch release bearing 13 which operates, for example, the diaphragm spring 14 of an associated clutch (not shown). A spring 30 acts between outer cylinder member 12 and release bearing 13 to maintain a pre-load on diaphragm spring 14.

Mounted on the left hand end of piston 10 is a combined sealing and valve member 15 which is held in position on

piston 10 by inner and outer sheet metal rings 16 and 17 which restrain a base portion 18 of the sealing member 15.

A head portion 19 of the sealing member 15 is disposed in a working chamber 20 defined by the sealing member and the inner and outer cylinder walls 11 and 12. Pressurised fluid may be admitted to working chamber 20 via an inlet 21 from an associated clutch operating master cylinder or other source of fluid pressure (not shown) in order to displace piston 10 to the right and hence disengage the associated clutch.

Extending between the piston 10 and the inner and outer cylinder members 11 and 12 are two rolling lobe diaphragms 22 and 23 respectively. A bead 22a of diaphragm 22 is secured to inner cylinder member 11 by an inner sheet metal ring 24 and a bead 23a of diaphragm 23 is secured to outer cylinder member 12 via an outer sheet metal ring 25.

Diaphragms 22 and 23 are constrained to move axially with piston 10 by portions 16a and 17a of rings 16 and 17 which entrap bead portions 22b and 23b of these diaphragms.

Thus overflow chambers 26 and 27 are defined by either side of piston 10.

Head portion 19 of sealing member 15 is provided with axially extending openings 28 through which fluid can flow from working chamber 20 into and out of overflow chambers 26

and 27 along flow paths X shown open in the bottom half of figure 1 and also in the top half of the seal arrangement of figure 2. As can be seen from figure 2, flow paths X are via flutes 22c and 23c in the outer surface of diaphragms 22 and 23.

When the pressure within working chamber 20 increases in order to move piston 10 to the right to operate diaphragm spring 14, the pressure in working chamber 20 displaces the sealing member 15 to the right relative to piston 10 so that the base portion 18 of sealing member 15 occupies the position shown in the top half of figure 1 in which sealing surfaces 29 on the head portion 19 of the sealing member close-off flow path X by contact with the adjacent portions of rings 16 and 17. The ability of sealing member 15 to move to the right is ensured by passages 10a in piston 10 which place chamber 10b beneath the base portion 18 of sealing member 15 in communication with the atmosphere.

Thus when piston 10 is being displaced to the right whilst undertaking a working stroke the communication between working chamber 20 and overflow chamber 26 and 27 is closed-off so that diaphragms 22 and 23 are not exposed to the full operating pressure within working chamber 20.

When the working pressure in chamber 20 is released and the piston 10 is retracted, sealing member 15 assumes the non-deformed condition shown in the lower half of figure 1 in which communication between overflow chambers 26 and 27 and

working chamber 20 is again restored so that any fluid which has leaked into overflow chambers 26 and 27 around the head portion of sealing member 15 can flow back into working chamber 20. As will be appreciated, should piston 10 make any rapid movement, or a rapid depression in working chamber pressure occur, which might tend to draw air into working chamber 20, this will then simply result in fluid being sucked into working chamber 20 from overflow chambers 26 and 27.

In normal operation of the actuator overflow chambers 26 and 27 are full of actuating fluid and any leakage of fluid past sealing member 15 during a given working stroke of piston 10 is accommodated by slight stretching of the diaphragms 22 and 23. This fluid which has leaked past sealing member 15 is returned to working chamber 20 on the next opening of flow paths X when chamber 20 is depressurised.

Figure 3 shows the manner in which rotation of piston 10 relative to outer cylinder member 12 is prevented. As can be seen from figure 3, an outer sheet metal guide member 31 is secured to the outer race 13a of release bearing 13 which is also non-rotatably secured to piston 10. Guide member 31 is provided with castellations 32 which engage legs 33 formed on an outer plastics sleeve member 34 which is secured to outer cylinder member 12 via rolled proportion 12a. The total axial displacement of release bearing 13 is also controlled by tangs 35 formed in guide member 31 which extend into slots 36 in legs 33.

Figure 4 shows an alternative sealing arrangement in which annular piston 10 carries a sealing member 40 which is retained on piston 10 by an annular retaining member 41 which is an interference fit in an annular groove 42 in piston 10. Retaining member 41 also retains diaphragm gripping rings 42 and 43 in position on piston 10.

As can be seen from figure 4, sealing member 40 is provided with two sealing lips 46 and 47 for engagement with cylinder members 11 and 12 respectively.

The lip 47 is shown in figure 4 in its undeflected condition which it occupies when the fluid pressure in the working chamber 20 is low. When the pressure in chamber 20 is increased in order to move piston 10 to the right the seal 40 and its lips 46 and 47 are deflected by the fluid pressure to the position shown occupied by the lip 46 in figure 4. This seals off the communication between overflow chambers 26 and 27 so that the diaphragms 22 and 23 are again not subjected to the full pressure developed in working chamber 20. The ability of seal 40 to deflect is ensured by connecting chamber 10b beneath seal 40 to atmosphere via clearances 10a between piston 10 and retaining member 41.

As can clearly be seen from figure 4, the portions of diaphragms 22 and 23 are provided with axially extending flutes 22c and 23c which promote communication between working chamber 20 and the associated overflow chamber 26

and 27. Flow around sealing member 40 when lips 46 and 47 are not sealing is facilitated by flutes 46a and 47a in sealing member 40.

Figures 5 and 6 show an alternative actuator construction which is manufactured primarily from plastics material and in which the clutch release bearing 50 is carried on an annular plastics piston 51 which is axially displaceable between inner and outer cylinder walls 52 and 53 respectively. Walls 52 and 53 are formed integrally with a main body portion 54 of the actuator which also includes an integral fluid inlet 55.

A compression spring 56 again acts between the release bearing 50 and the main body portion 54 of the actuator to provide the desired diaphragm spring pre-load.

Piston 51 carries annular sealing member 58 (see figure 6) which has retaining lobes 59 which engage in grooves 60 in the piston. Sealing member 58 includes sealing lips 61 and 62 for engagement with the inner and outer cylinder portions 52 and 53 respectively. The upper portion of figure 6 shows lip 62 in its unpressurised condition in which flow is possible from working chamber 63 down the clearances between piston 51 and cylinder members 52 and 53 into an overflow chamber 65 defined between a diaphragm 66 and the outer cylinder member 53. Communication between working chamber 63 and overflow chamber 65, as indicated above, is via the clearances between piston 51 and the cylinder members 52 and

53 and also via passageway 67 provided in outer cylinder member 53 and cross drillings 68 in piston 51. Secondary annular seals 70 and 71 seal the outer ends of the clearances between piston 51 and cylinder members 52 and 53.

Again flow around the sealing member 58 when the lips 61 and 62 are not sealing is facilitated by flutes 61a and 62a formed in the sealing member 58.

When working chamber 63 is pressurised sealing member 58 is deflected to the position shown in the bottom half of figure 6 in which the lips 61 and 62 seal against the cylinder members 52 and 53 to cut-off communication with the overflow chamber 65. The ability of sealing member 58 to deflect is ensured by passage 51a in piston 51 which connects chamber 51b behind sealing member 58 with atmosphere.

Figure 7 shows a further actuator consruction in which both metals and plastics materials are used. In this construction a clutch release bearing 80 is secured on an annular plastics piston 81 which is axially displaceable between an inner metal cylinder wall 82 and an outer plastics cylinder wall 83. Walls 82 and 83 are sealed together by a seal 84 and wall 83 includes an integral fluid inlet 85.

Piston 81 is sealed at the bearing end to walls 82 and 83 by seals 86 and 87 respectively. A main seal 88 acts as the primary seal for working chamber 90. An overflow chamber 91

is defined by a diaphragm 92 whose natural shape is as shown in figure 7. The ends of the diaphragm 92 are received in grooves 93 and 94 provided in outer plastics cylinder wall 83. Any fluid which leaks past main seal 88 is fed to overflow chamber 91 via drillings 95 and 96.

Fluid within overflow chamber 91 can be returned to working chamber 90 and hence to fluid inlet 85 via a one way valve 97. Valve 97 is lightly loaded to its closed position by spring 98 and is opened either by the occurence of a depression in working chamber 90 and/or by force applied to the stem 99 of valve 97 by a ring 100 as a result of atmospheric pressure acting on diaphragm 92 as indicated by arrows P in figure 7.

Thus figure 7 is an example of a construction in which the valve means which controls communication with the overflow chamber 91 does not form part of the main seal 88.

All the actuators described above may form part of a pre-filled clutch hydraulic system of the form described in, for example, earlier US patents Nos. 4407125, 4599860, 4624290 and 5113657 in which the system is pre-filled with hydraulic fluid before being fitted on the associated vehicle. Alternatively the actuators may be filled after mounting on the vehicle.

The actuators are conveniently filled by being subjected to a vacuum to evacuate air followed by the introduction of

hydraulic fluid under pressure. The presence in each actuator shown in figures 1 to 3 or 4 or 5 or 6 of passages 10a which admit atmospheric pressure to chamber 10b helps to ensure that valve member 15 assume its open position so that flow path X is maintained open during the filling process thus ensuring that the overflow chambers are fully evacuated and filled.

In the Figure 7 construction valve 97 is held open during filling both by the depression created in the working chamber 90 during evacuation of air and by the atmospheric pressure P acting on diaphragm 92 and hence on valve stem 99 via ring 100 during the initial introduction of hydraulic fluid under pressure.

CLAIMS

1. An actuator of the kind specified having sealing means for sealing the piston to the cylinder walls, an overflow chamber which retains any fluid which leaks past the sealing means from the working chamber, and return means for returning fluid from the overflow chamber when the piston is not undertaking a working stroke.

2. An actuator according to claim 1 in which the return means comprises valve means which controls communication between the working chamber and overflow chamber, the valve means opening up communication between said chambers when the piston is not undertaking a working stroke.

3. An actuator according to claim 2 in which the valve means is built into the sealing means.

4. An actuator according to claim 3 in which pressurisation of the working chamber causes deflection of the sealing means to close off communication between the working and overflow chambers.

5. An actuator according to any one of claims 1 to 4 in

which the annular piston is displaceable between inner and outer cylinder walls and an annular sealing means contacts said walls to seal the working chamber and is axially displaceable relative to the piston when the working chamber is pressurised to move the piston, said axial movement of the sealing means closing-off communication between the working and overflow chambers.

6. An actuator according to any one of claims 1 to 4 in which the annular piston is displaceable between inner and outer cylinder walls and the sealing means has inner and outer sealing lips which are pressed against the co-operating inner and outer walls respectively when the working chamber is pressurised thus sealing the working chamber and also to cutting off communication between the working and overflow chambers.

7. An actuator according to any one of claims 1 to 6 in which the overflow chamber is defined by diaphragm means in combination with the cylinder walls.

8. An actuator according to claim 7 in which the piston is displaceable between inner and outer cylinder walls with one diaphragm extending between the piston and the inner cylinder wall and a second diaphragm extending between the piston and the outer cylinder wall.

9. An actuator according to claim 7 in which the piston is displaceable between inner and outer cylinder walls and the overflow chamber is defined by the diaphragm means and a portion of the outer cylinder wall, passageway means being provided to direct any fluid which leaks past the sealing means to the overflow chamber.

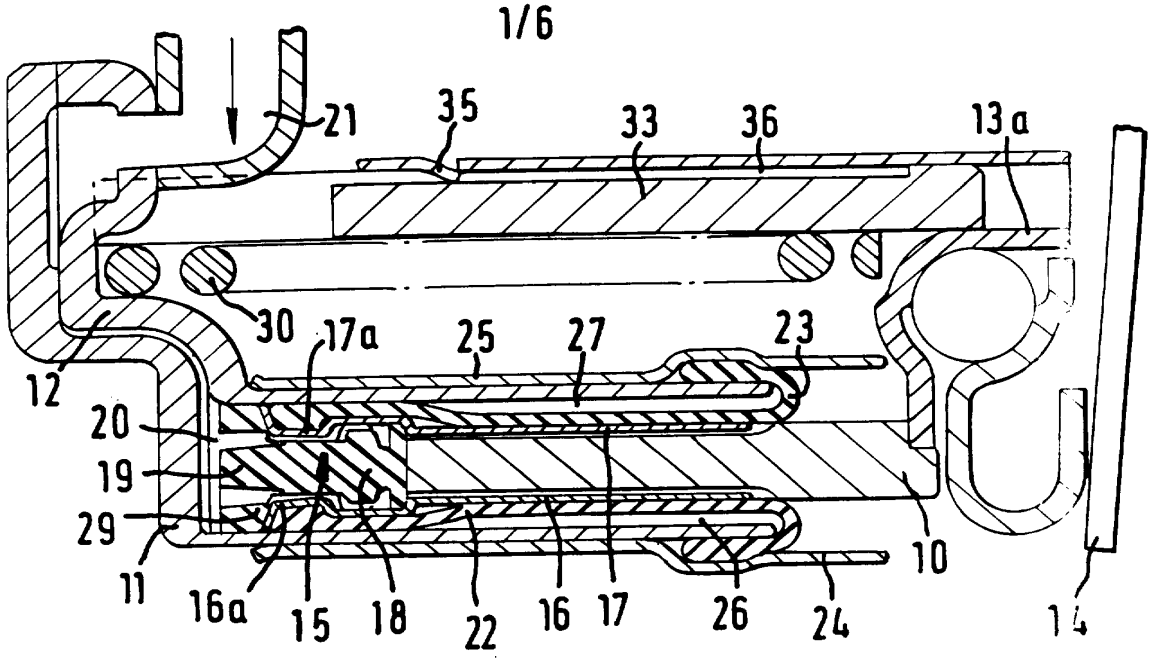
10. An actuator according to claim 9 in which the piston and cylinder walls are made from plastics material.

11. An actuator according to any one of claims 1 to 10 in which rotation of the piston relative to the cylinder wall is prevented by a guide means which is operatively associated with the piston and which engages an anti-rotation formation associated with the cylinder walls.

12. An actuator according to claim 1 or claim 9 when dependent on claim 1 in which the return means comprises valve means separate from the sealing means, said valve means being arranged to be normally biased to a closed position but being opened on a return stroke of the piston following a working stroke.

13. An actuator according to any one of claims 1 to 12 for the operation of a vehicle clutch, the actuator including a clutch release bearing carried by the piston.

14. An actuator constructed and arranged substantially as hereinbefore described with reference to and as shown in figures 1 to 3 or 4 or 5 and 6 or 7 of the accompanying drawings.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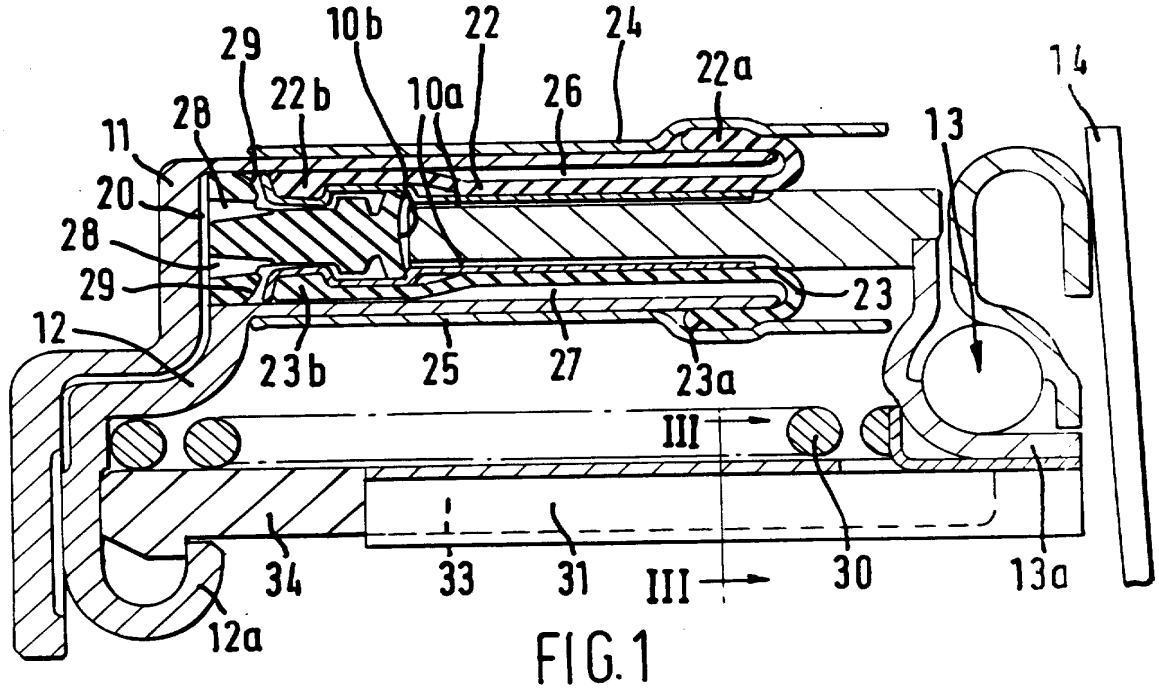
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FIG.1

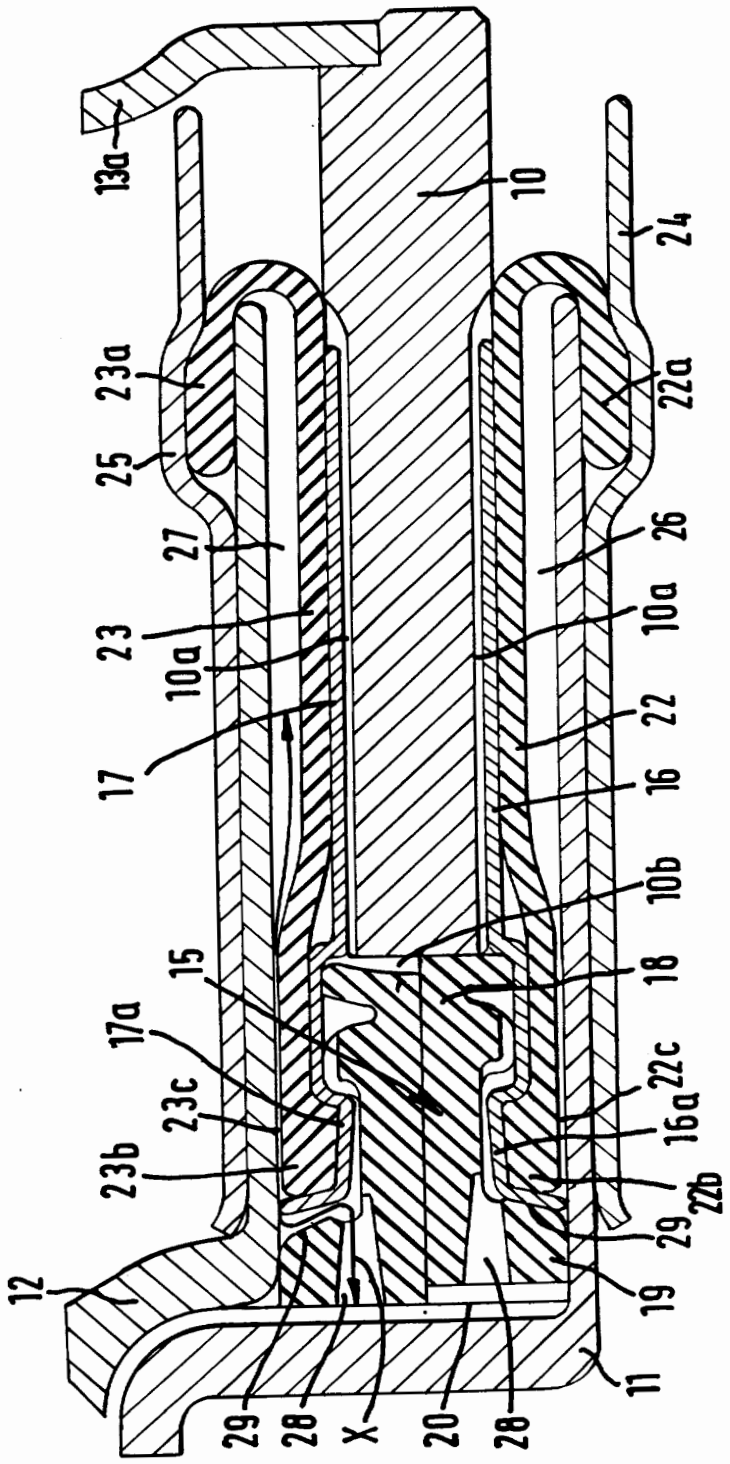

FIG.2

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Exhibit 1002
Page 0668 of 1285

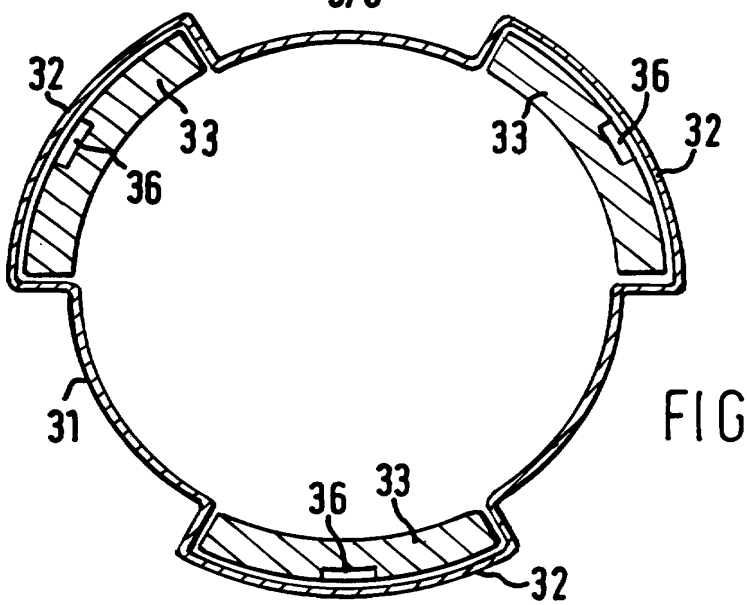

FIG.3

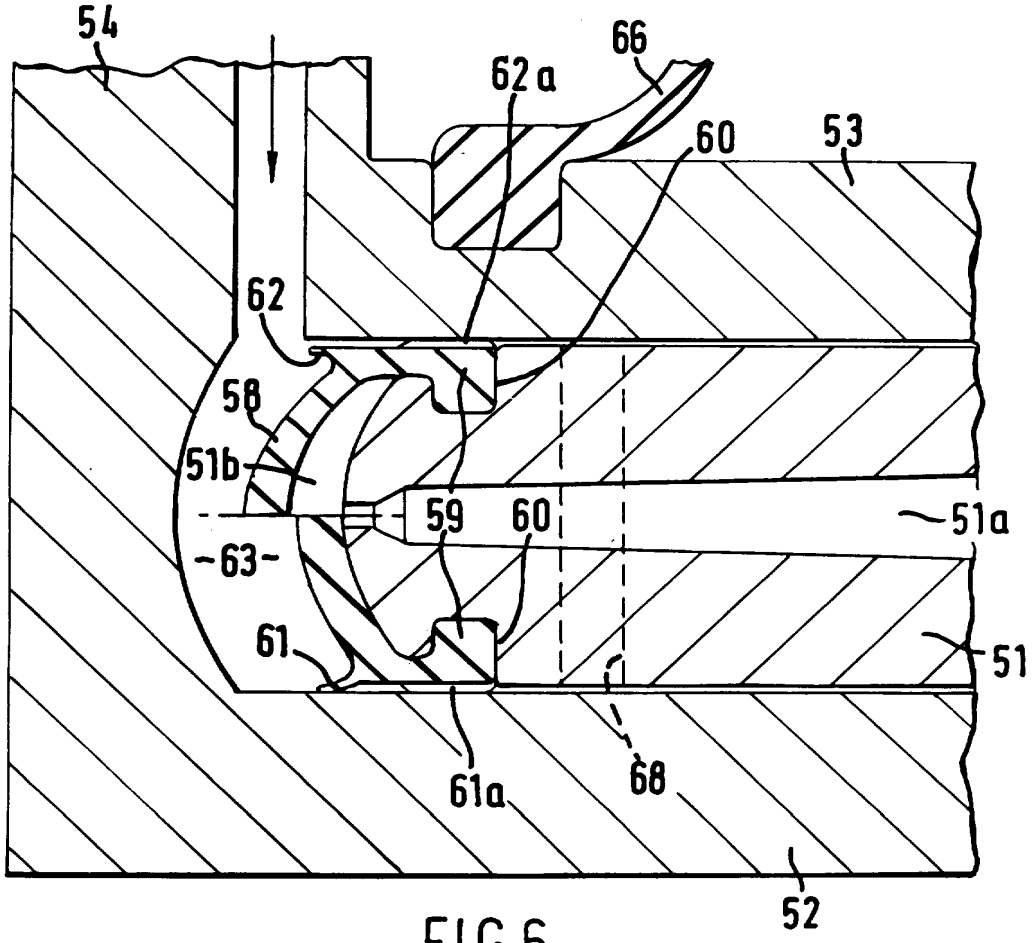

FIG.6

Exhibit 1002
Page 0669 of 1285
Ubiquiti Inc. v. XR. Comm.
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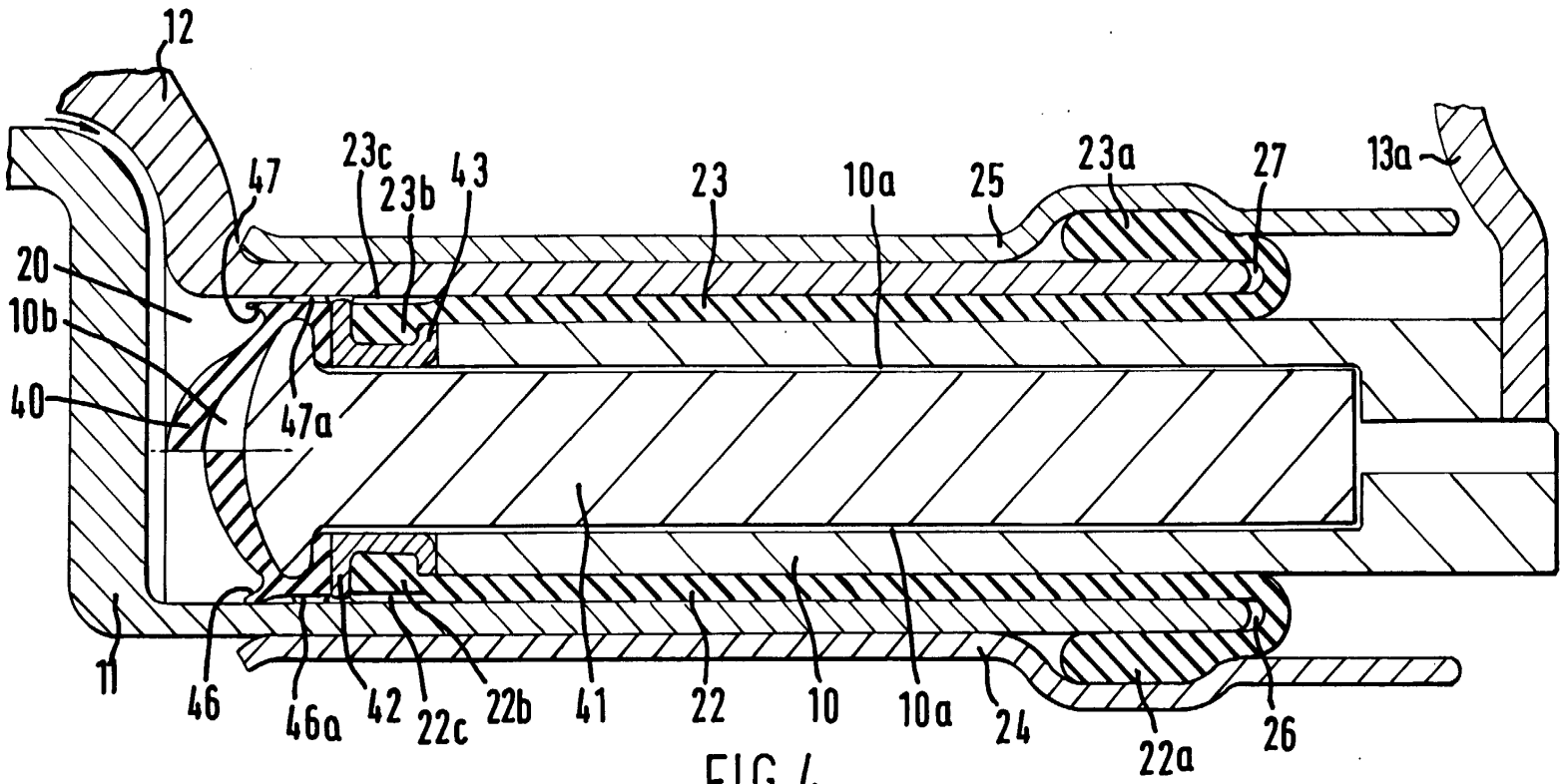
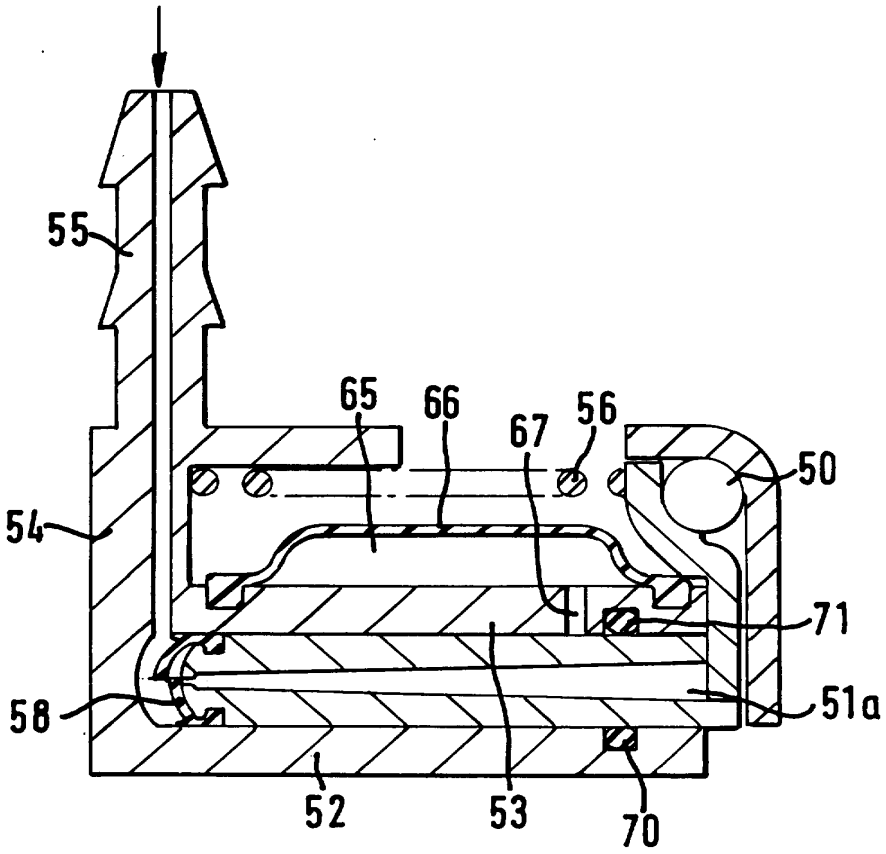


FIG.4



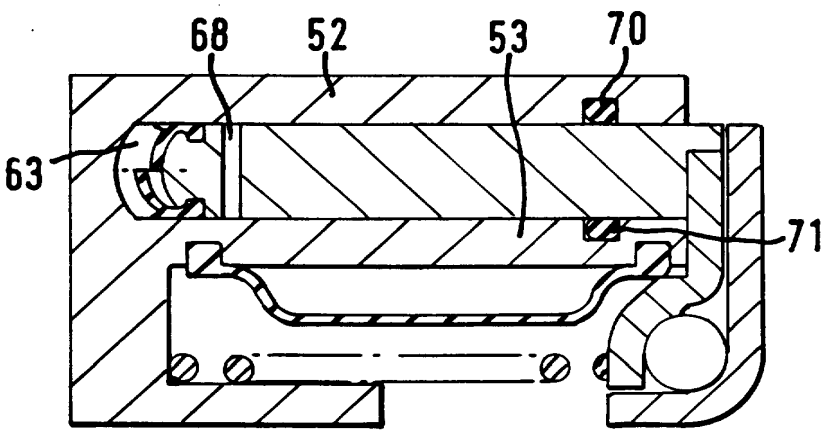


FIG.5

Exhibit 1002
Page 0671 of 1285
Ubiquiti Inc. v. XR. Comm.
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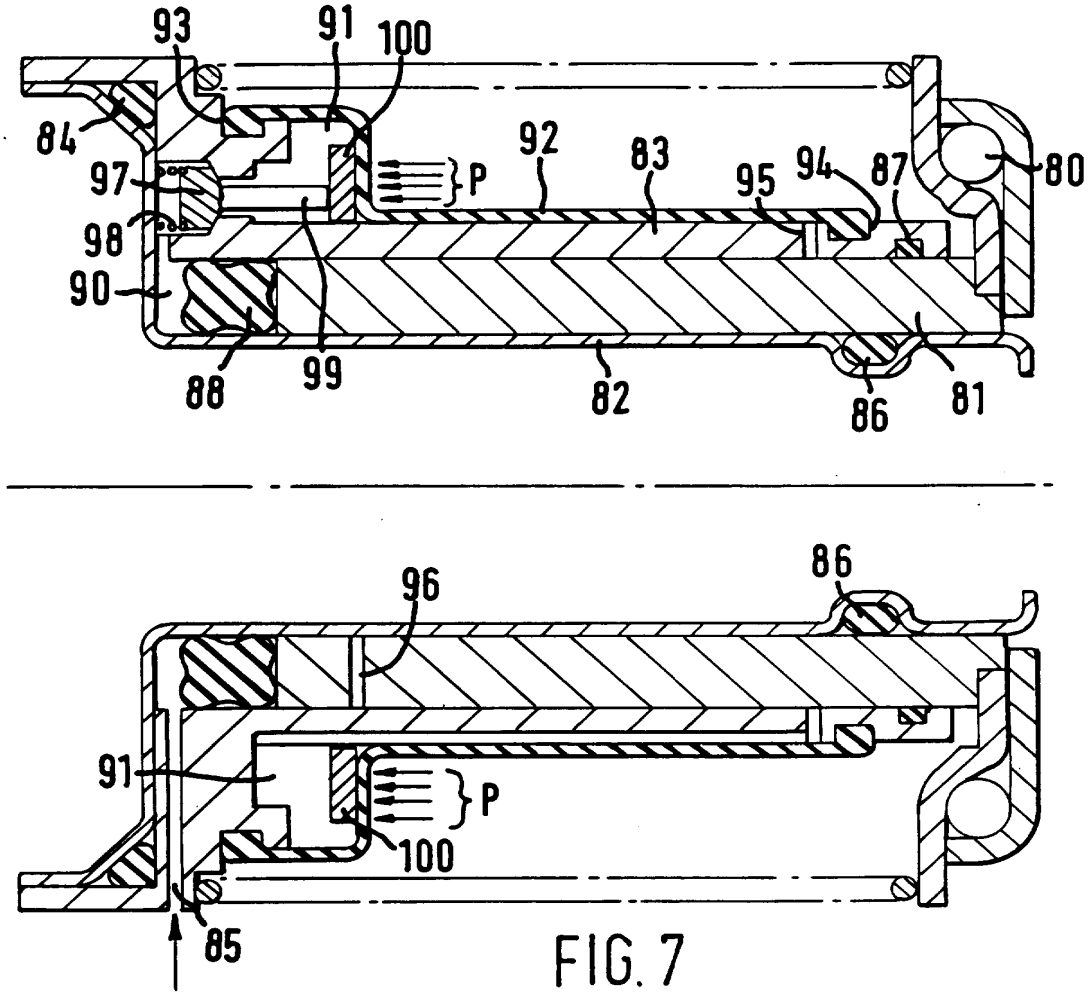
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FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP 95/05141

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: F16J 15/56, F15B 15/10, F16D 25/08
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: F16J, F15B, F16D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 5113991 (KAJITANI ET AL), 19 May 1992 (19.05.92) --	1-14
A	US, A, 4869355 (CORRAL ET AL), 26 Sept 1989 (26.09.89) --	1-14
A	US, A, 4660702 (FLOTOW), 28 April 1987 (28.04.87) -- --------	1-14

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Date of the actual completion of the international search	Date of mailing of the international search report
11 April 1996	08/05/96
Name and mailing address of the ISA: European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl. Fax: (+ 31-70) 340-3016	Authorized officer: S-E Bergdahl

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INTERNATIONAL SEARCH REPORT

Information on patent family members

05/02/96

International application No.
PCT/EP 95/05141

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		JP-A- 1234578	19/09/89
		EP-A,B- 0304069	22/02/89
		US-A- 4905016	27/02/90
US-A- 4869355	26/09/89	FR-A,B- 2611838	09/09/88
US-A- 4660702	28/04/87	AU-B,B- 577188	15/09/88
		AU-A- 5572986	30/10/86
		CA-A- 1275676	30/10/90
		DE-A- 3611602	06/11/86
		FR-A- 2581146	31/10/86
		GB-A,B- 2174169	29/10/86
		JP-A- 61248922	06/11/86
		SE-A- 8601868	25/10/86

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A1

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(71) Applicants: WATKINS-JOHNSON COMPANY [US/US]; Stanford Research Park, 3333 Hillview Avenue, Palo Alto, CA 94304-1223 (US). THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY [US/US]; Suite 350, 900 Welch Road, Palo Alto, CA 94304 (US).

(72) Inventors: RALEIGH, Gregory, G.; 539 San Juan Avenue, El Granada, CA 94018 (US). DIGGAVI, Suhas, N.; 21F Escondido Village, Stanford, CA 94305 (US). JONES, Vincent, K., IV; 85 Shell Parkway, Redwood Shores, CA 94065 (US). PAULRAJ, Arogyaswami, J.; 59 Peter Coutts Circle, Stanford, CA 94305 (US).

(74) Agents: TEST, Aldo, J. et al.; Flehr, Hohbach, Test, Albritton & Herbert, Suite 3400, 4 Embarcadero Center, San Francisco, CA 94111-4187 (US).

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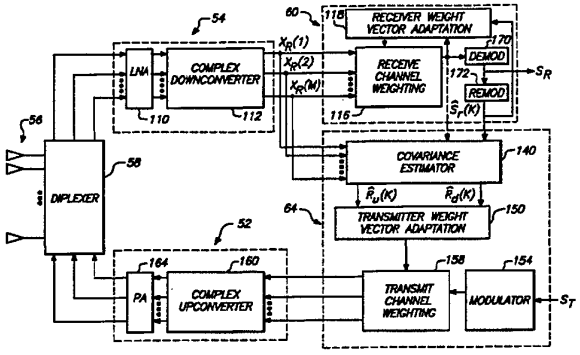
With international search report.

(54) Title: METHOD AND APPARATUS FOR ADAPTIVE TRANSMISSION BEAM FORMING IN A WIRELESS COMMUNICATION SYSTEM



(57) Abstract

A method for forming an adaptive phased array transmission beam pattern at a base station without any knowledge of array geometry or mobile feedback is described. The approach is immune to the problems which plague methods which attempt to identify received angles of arrival from the mobile and map this information to an optimum transmit beam pattern. In addition, this approach does not suffer the capacity penalty and mobile handset complexity increase associated with mobile feedback. Estimates of the receive vector propagation channels are used to estimate transmit vector channel covariance matrices which form objectives and constraints in quadratic optimization problems leading to optimum beam former solutions for the single user case, and multiple user case. The new invention is capable of substantial frequency re-use capacity improvement in a multiple user cellular network.

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METHOD AND APPARATUS FOR ADAPTIVE TRANSMISSION BEAM FORMING IN A WIRELESS COMMUNICATION SYSTEM

BACKGROUND OF THE INVENTION

This is a continuation in part of U.S. Patent Application Serial No. 08/394,652, filed February 22, 1995.

I. Field of the Invention

The present invention relates to the formation of antenna beam patterns (beamforming), and more particularly to a technique for adaptive transmit beamforming based on the result of adaptive receive beamforming.

II. Description of the Related Art

Within wireless mobile communication systems, directive antennas may be employed at base station sites as a means of increasing the signal level received by each mobile user relative to the level of received signal interference. This is effected by increasing the energy radiated to a desired recipient mobile user, while simultaneously reducing the interference energy radiated to other remote mobile users. Such reduction in the interference energy radiated to mobile users over other wireless channels may be achieved through generation of spatially selective, directive transmission beam patterns. Unlike "line-of-sight" radio links, a number of signal transmission paths typically comprise each wireless communication channel.

FIG. 1 shows an illustrative representation of a wireless "multipath" communication channel between a base station 2 and a remote mobile user 4. The various signal transmission paths within each such multipath communication channel arise from reflection of the transmitted signal by dominant reflection surfaces 6, and by minor reflection surfaces 12, between the base station 2 and remote mobile user 4. Accordingly, techniques for improving signal reception in line-of-sight radio systems are often not directly applicable to multipath signal environments. For example, in line-of-sight system the "gain" of an antenna

typically varies inversely to antenna beam width. However, if a given antenna beam width is made less than the angular region encompassing the various signal paths comprising a multipath communication channel, further reduction in the beam width may reduce the energy radiated along some of the angular paths. In turn, this may actually decrease the effective time average gain of the antenna.

Within wireless mobile communication systems, three techniques have been developed for improving communication link performance using directive transmit antennas: (i) selection of a particular fixed beam from an available set of fixed beams, (ii) adaptive beam forming based on receive signal angle estimates, (iii) adaptive transmission based on feedback provided by the remote mobile user, and (iv) adaptive transmit beam forming based upon the instantaneous receive beam pattern. Each of these techniques is described briefly below.

In the first technique, one of several fixed base station antenna beam patterns is selected to provide a fixed beam steered in a particular direction. The fixed antenna beams are often of equal beam width, and are often uniformly offset in boresight angle so as to encompass all desired transmission angles. The antenna beam selected for transmission typically corresponds to the beam pattern through which the largest signal is received. The fixed beam approach offers the advantage of simple implementation, but provides no mechanism for reducing the signal interference power radiated to remote mobile users within the transmission beam of the base station. This arises because of the inability of the traditional fixed beam approach to sense the interference power delivered to undesired users.

The second approach involves "adapting" the beam pattern produced by a base station phase array in response to changing multipath conditions. In such beamforming antenna arrays, or "beamformers", the antenna beam pattern is generated so as to maximize signal energy transmitted to ("transmit beamforming"), and received from ("receive beamforming"), an intended recipient mobile user.

While the process of transmit beamforming to a fixed location over a line-of-sight radio channel may be performed with relative ease, the task of transmitting to a mobile user over a time-varying multipath communication channel is typically considerably more difficult. One adaptive transmit

beamforming approach contemplates determining each angle of departure (AOD) at which energy is to be transmitted from the base station antenna array to a given remote mobile user. Each AOD corresponds to one of the signal paths of the multipath channel, and is determined by estimating each angle of arrival (AOA) at the base station of signal energy from the given user. A transmit beam pattern is then adaptively formed so as to maximize the radiation projected along each desired AOD (i.e, the AOD spectrum), while minimizing the radiation projected at all other angles. Several well known algorithms (e.g., MUSIC, ESPRIT, and WSF) may be used to estimate an AOA spectrum corresponding to a desired AOD spectrum.

Unfortunately, obtaining accurate estimates of the AOA spectrum for communications channels comprised of numerous multipath constituents has proven problematic. Resolving the AOA spectrum for multiple co-channel mobile units is further complicated if the average signal energy received at the base station from any of the mobile units is significantly less than the energy received from other mobile units. This is due to the fact that the components of the base station array response vector contributed by the lower-energy incident signals are comparatively small, thus making it difficult to ascertain the AOA spectrum corresponding to those mobile units. Moreover, near field obstructions proximate base station antenna arrays tend to corrupt the array calibration process, thereby decreasing the accuracy of the estimated AOA spectrum.

In the third technique mentioned above, feedback information is received at the base station from both the desired mobile user, and from mobile users to which it is desired to minimize transmission power. This feedback permits the base station to "learn" the "optimum" transmit beam pattern, i.e., the beam pattern which maximizes transmission to the desired mobile user and minimizes transmission to all other users. One disadvantage of the feedback approach is that the mobile radio needs to be significantly more complex than would otherwise be required. Moreover, the information carrying capacity of each radio channel is reduced as a consequence of the bandwidth allocated for transmission of antenna training signals and mobile user feedback information. The resultant capacity reduction may be significant when the remote mobile users move at a high average

velocity, as is the case in most cellular telephone systems.

The fourth conventional technique for improving communication link performance involves use of an optimum receive beam pattern as the preferred transmission beam pattern. After calibrating for differences between the antenna array and electronics used in the transmitter and receiver, it is assumed that the instantaneous estimate of the nature of the receive channel is equivalent to that of the transmit channel. Unfortunately, multipath propagation and other transient channel phenomenon can substantially eliminate any significant equivalence between frequency-duplexed transmit and receive channels, or between time-division duplexed transmit and receive channels separated by a significant time interval. As a consequence, communication link performance fails to be improved.

OBJECTS OF THE INVENTION

Accordingly, it is an object of the invention to provide an adaptive transmit beamforming technique which enhances remote user received signal quality by utilizing the uplink signal energy received from remote users without the need for feedback from the mobile user.

It is another object of the invention to provide an adaptive transmit beamforming technique which accounts for the presence of multipath fading inherent in the communication channel.

It is yet another object of the invention that the beamforming technique be independent of antenna array geometry, array calibration, or of explicit feedback control signals from remote users.

It is another object of the invention to provide adaptive transmit beam forming which improves signal quality received by a desired user and while simultaneously reducing interference energy received by other undesired users so as to, within a cellular communication network, improve communication traffic capacity, and/or to increase base station coverage area, and/or to improve call quality.

SUMMARY OF THE INVENTION

The adaptive transmission approach of the invention offers the advantages of adaptive transmission using feedback without the associated mobile radio complexity increase and information capacity penalty. The technique has been developed to exploit structured variation which occurs in the multipath fading present in the wireless antenna array channel. Thus, multipath propagation effects are explicitly accounted for in the problem approach. The technique is blind in that the antenna beam is formed in the absence of explicit knowledge of the array geometry, and without the necessity of array calibration or mobile feedback. The basic approach is to estimate the optimum transmit antenna beam pattern based on certain statistical properties of the received antenna array signals. Recently developed results in blind signal copy of multiple co-channel signals using antenna arrays are thus exploited to make possible the estimation of the receive signal statistics. The optimum transmit beam pattern is then found by solving a quadratic optimization subject to quadratic constraints. The adaptive transmission system is suitable for use in conjunction with either a diplexed transmit/receive antenna array, or with separate transmit and receive arrays.

BRIEF DESCRIPTION OF THE DRAWINGS

Additional objects and features of the invention will be more readily apparent from the following detailed description and appended claims when taken in conjunction with the drawings, in which:

FIG. 1 is an illustrative representation of a multipath propagation channel between a base station and a remote user station.

FIG. 2A is a block diagram of the physical implementation of a beamforming network configured to perform adaptive beam forming in accordance with the present invention.

FIG. 2B is a block diagram of the physical implementation of a beamforming network in which a diplexor is employed to allow the antenna array to be used for both transmit and receive operation.

FIG. 3 is a functional block diagrammatic representation of a beamforming network of the present invention.

FIG. 4 provides a flowchart summarizing an exemplary procedure for using an optimization function to determine an optimum transmit weight vector.

FIG. 5 is a flowchart outlining a general procedure for determining an optimum transmit weight vector by using transmit criteria in conjunction with network agreement criteria.

FIG. 6 is a block diagram of an exemplary calibration system incorporated within the adaptive beamforming network of FIG. 3.

FIG. 7 shows an implementation of a calibration system within an adaptive beamforming network having different transmit and receive arrays.

FIG. 8 provides a block diagram of a self-calibrated adaptive beamforming network in which the receive section of the beamforming network is advantageously utilized in lieu of a transmit section calibration receiver.

FIG. 9 is a block diagram of an implementation of a calibration equalizer and channelizer in which a single wideband calibration equalizer is coupled to each of the outputs of a complex downconverter within an RF receiver.

FIG. 10 depicts a block diagram of an implementation of a transmitter calibration equalizer & channel combiner in which a single transmit wideband calibration equalizer precedes each of the inputs to a complex upconverter.

FIG. 11 is a block diagram of an implementation of a calibration equalizer and channelizer which utilizes a plurality of sets of narrowband calibration equalizers.

FIG. 12 depicts a transmitter calibration equalizer & channel combiner within which the equalization function is performed separately for each channel.

DETAILED DESCRIPTION OF THE INVENTION

I. Overview of Beamforming Network

Turning now to FIG. 2A, a block diagram is shown of the physical organization of a beamforming network 50 configured to perform adaptive beam forming in accordance with the present invention. In an exemplary embodiment the beamforming network 50 is disposed within a base station of a cellular communications network, in which is included a transceiver comprised of a radio frequency (RF) transmitter 52 and an RF receiver 54.

In the embodiment of FIG. 2A, a base station antenna array 56 serves to produce independent transmit and receive antenna beams for facilitating communication with one or more mobile units (not shown). The term "receive channel vector" is employed to indicate that each antenna element within the base station antenna array 56 will form a propagation channel to a given remote user. The composite array channel may be represented as a vector having elements corresponding to each individual antenna channel. As is described herein, statistical characterization of the receive channel vector provides information which may be used by the base station to determine an "optimal" transmit beam pattern, i.e., a transmit beam pattern which maximizes the average signal-to-interference power delivered to a given mobile user. This obviates the need for the mobile unit to provide feedback information to the base station relating to propagation characteristics of the transmit channel. This in turn simplifies implementation of the mobile unit, and preserves channel resources for data transmission by eliminating the need for "mobile unit feedback" relating channel characteristics to the base station.

As is indicated by FIG. 2A, a diplexer 58 can be employed to allow the antenna array 56 to be used for both transmit and receive operation by isolating the RF receiver 54 from the RF transmitter 52. A receive channel beamformer 60 cooperates with the RF receiver 54 to adaptively optimize the receive antenna beam in order to improve received signal quality. Similarly, a transmit channel beamformer 64 cooperates with the RF transmitter 52 to adapt the transmit antenna beam to optimize some characteristic of transmission quality. In an exemplary embodiment the transit channel beamformer 64 and receive channel beamformer 60 are each implemented as a special purpose digital signal processor (DSP).

In another embodiment of the invention, distinct antenna arrays are used for signal reception and transmission as illustrated in FIG. 2B. In the embodiment of FIG. 2B, a diplexer is not required since a dedicated receive antenna array (not shown) is connected to the RF receiver 54, and a dedicated transmit antenna array (not shown) is connected to the RF transmitter 52. The receive and transmit antenna arrays are designed to provide identical radiation characteristics when operated at the receive and transmit frequencies, respectively. Accordingly, in

many instances the physical geometries of the transmit and receive antenna arrays are simply physically scaled to account for the fractional difference in the receive and transmit RF wavelengths. The embodiment of FIG. 2B substantially eliminates the potential introduction of error arising from use of a single antenna array and diplexer.

Turning now to FIG. 3, a functional block diagrammatic representation is provided of a beamforming network of the present invention. In FIG. 3, solid lines are used to represent functional elements and dashed lines are employed to identify the physical components of FIG. 2. The RF receiver 54 is functionally comprised of a low-noise amplifier (LNA) network 110, and a complex downconverter 112. The complex downconverter 112 is disposed to frequency downconvert the received RF signal energy after processing by the LNA network 110. The downconverted signal energy is then digitally sampled and provided to a receive channel weighting module 116 of the receive channel beamformer 60. The weights applied by the receive channel beamformer 60 to each of the M downconverted antenna element outputs $x_{R,m}(k)$, m =1 to M, of the complex frequency downconverter 112 are determined by a receiver weight vector adaptation module 118. In the exemplary embodiment the receiver weight vector adaptation module 118 determines a receive channel weight vector, $\mathbf{w_R}$, which maximizes the signal quality received over the desired inbound frequency channel.

In the embodiment of FIG. 3, a vector channel covariance estimator 140 within the transmit beamformer 64 operates to produce a statistical characterization of a receive channel vector using: (i) the outputs $x_{R,m}(k)$, m =1 to M, of the complex frequency downconverter 112, and (ii) an estimate of the desired signal $\hat{S}_r(k)$ generated in the receive channel beamformer 60. For present purposes the receive channel vector may be viewed as being representative of the multipath communications channel from a mobile user (not shown in FIG. 3) to the antenna array 56. In an exemplary embodiment the statistical characterization carried out within the covariance estimator 140 yields an estimated receive channel covariance matrix used during the transmit beamforming process. Throughout the following description, scalar quantities are represented using lower case characters of standard type, vector quantities are represented using lower case characters of bold

type, and matrix quantities are represented using upper case characters of bold type.

Within the transmit channel beamformer 64, an optimal transmit beam pattern weight vector is generated by a transmit channel weight vector adaptation module 150 based on the results of the statistical characterization of the receive channel vector. This weight vector, $\mathbf{w}_T(t)$, optimizes a particular aspect (e.g., average desired signal to undesired interference ratio) of the signal energy within the transmission range of the base station array 56. In the exemplary embodiment, the optimal transmit beam pattern weight vector is generated using the estimated desired receive channel covariance matrix, $\hat{\mathbf{R}}_d(k)$, and undesired interference covariance matrix, $\hat{\mathbf{R}}_u(k)$, both of which are compiled within the covariance estimator 140.

As is indicated by FIG. 3, the signal information (S_T) to be transmitted to the desired mobile radio unit is used to modulate a digital baseband carrier within a modulator 154. The modulated signal is then applied to a transmit channel weighting module 158
disposed to weight, on the basis of the optimized transmit pattern weight vector, the input signals corresponding to each element of the antenna array 56. The weighted set of input signals produced by the weighting module 158 are then upconverted in frequency within a complex frequency upconverter 160 of the RF transmitter 52. The resultant frequency-upconverted signals are then amplified by a bank of power amplifiers 164, and provided to the antenna array 56 for transmission via diplexer 58.

In the exemplary embodiment an improved estimate of the received signal is obtained through utilization of a demodulator 170 and remodulator 172. The received signal is demodulated within demodulator 170 in order to recover the essential characteristics of the modulating signal. In the case of an analog FM signal, this involves recovery of the FM waveform. In the case of a digitally modulated signal (BPSK, FSK, QPSK, etc.), the demodulator 170 forms hard decisions as to the value of each digital symbol. The demodulated signal is then processed based upon some predefined characteristic of the signal and modulation pattern. For example, a demodulated analog FM signal could be lowpass filtered

based upon a known signal information bandwidth as a means of obtaining an improved post-demodulation signal estimate. In the case of digital modulation, error correction could be implemented in order to remove bit errors, thus improving estimated signal quality. In addition, training signals (i.e., pilot tones, SAT tones, etc.) may optionally be employed in lieu of, or in conjunction with, the aforementioned "blind" techniques.

Again referring to FIG. 3, the processed demodulated signal is then used by demodulator 172 to remodulate an RF carrier, thereby producing an improved modulated signal estimate. The improved signal estimate is then used by the receiver weight vector adaptation block 118 and the covariance estimate 140. Other techniques, which do not rely upon such a demodulation/remodulation procedure, can be devised for obtaining a sufficiently accurate received signal estimate. FIG. 3 simply illustrates a particular exemplary embodiment incorporating a demodulator and remodulator.

In the present embodiment, the demodulator 170 and remodulator 172 or the receive channel beamformer 60 are operative to produce a received signal estimate $\hat{s}_r$. The quantity $\hat{S}_r$ is then employed by the covariance estimator 140 to estimate the covariance matrix of the receive channel. The receive channel beamformer 60 could of course be replaced by numerous alternative structures including, for example, multi-antenna sequence estimators, maximum likelihood receiver structures, or multiple element decision feedback equalizers. Any of these alternative structures could also be used to provide the quantity $\hat{s}_r$ for use in estimating the received channel covariance statistics.

A detailed description of the adaptive transmit beamforming contemplated by the invention is provided in the following sections. Specifically, section II sets forth a description of transmit and receive multipath antenna channel models, as well as an introduction to the approach of utilizing receive channel statistics during transmission channel beamforming. Section III discusses the extension of the single-user beamforming approach of section II to an environment which includes multiple mobile users.

In section IV, an exemplary method is described for estimating receive channel statistics useful for effecting the transmit channel beam forming of the

present invention. Finally, section V provides a description of various techniques for calibrating the transmit and receive channel beamforming apparatus.

II. Blind Beamforming Using Multipath Signals

As mentioned above, an initial step within the present invention involves statistically characterizing a receive channel vector representative of the multipath communications channel from a mobile user to a base station antenna array 56. In order to facilitate understanding of this process, a mathematical description will first be provided of an exemplary receive channel vector corresponding to a multi-element antenna array. It will then be shown that a high degree of similarity exists between a covariance characterization of the receive channel vector, and a covariance characterization of the transmit channel vector. The present invention makes use of the similarity between the receive and transmit channel covariance characterizations, notwithstanding the typical lack of correlation between the instantaneous transmit and receive channel vectors. As will also be described, the similarity between receive and transmit covariance makes it possible to determine an advantageous transmit beam pattern in the absence of explicit knowledge of the antenna array configuration. In this sense, the optimal beamforming of the present invention may be considered to be "blind" with respect to antenna array configuration.

The optimal transmit beamforming technique of the present invention is of particular utility in multipath propagation environments, in which mountains, buildings and the like create multipath interference (FIG. 1). In FIG. 1, energy radiated from the antenna array at each base station 2 is reflected by the dominant reflectors 6. Many local reflectors 12 nearby the mobile unit 4 also contribute to energy reflection. As the position of the mobile unit 4 varies, the phase length to each dominant reflector 6 and to each local 12 reflector correspondingly varies, which results in a time-variant vector propagation channel from the base station 2 to the mobile unit 4.

A vector channel model for the energy $y_R(t)$ received by a mobile unit from the base station may be expressed as:

$$y_R(t)=s_T(t)w_T(t)^H\left[\sum_{l=1}^{L}\alpha_{T,l}(t)a_T(\theta_l)\right]+n_T(t) \quad (1)$$
$$=s_T(t)w_T(t)^H h_T(t) + n_T(t)$$

where $s_T(t)$ denotes the complex-valued signal transmitted to the mobile unit, where $\mathbf{n_T(t)}$ represents the complex-valued M-element noise vector received at the mobile unit, where $\mathbf{w_T(t)^H}$ corresponds to the Hermetian transpose of the M-element complex-valued weight vector $\mathbf{w_T(t)}$ representative of the M-element base station transmit antenna array 56, and where $\mathbf{h_T(t)}$ represents the M-element time varying transmit channel array response vector. In addition, the time-varying amplitude loss for the lth of **L** signal propagation paths between the base station transit antenna array 56 and the mobile unit is given by $\alpha_{Tl}(t)$. Finally, $\mathbf{a_T}(\theta_l)$ corresponds to the transmit array response vector due to the propagation path along the lth path of departure Θ_l. Each element within $\mathbf{a_T}(\theta_l)$ represents the complex magnitude of the field radiated in the direction Θ_l by an antenna element when a unit amplitude radiation signal is applied to the antenna element. Although for purposes of clarity, the base station transit antenna array 56 is assumed to be comprised of M omnidirectional elements and the mobile unit equipped with a single omnidirectional antenna, the following analysis may be readily extended to embodiments in which directional antenna elements are employed.

In a particular single-user implementation of the invention, a primary objective is to generate a base station transmit beam pattern which maximizes the signal relative to the noise within the received mobile signal $y_R(t)$. Since in the single-user case one is not concerned with minimizing interference to mobile units within other cells operative on the same frequency channel, this objective may be attained by simply maximizing the signal received at the single mobile unit. The single user case approximates conditions in cellular networks characterized by large geographic separation between base stations utilizing the same frequency channels. Ideally, the value of the transmit channel array response vector $\mathbf{h_T(t)}$ would be determined on an instantaneous basis, which could easily be shown to allow determination of the transmit beam weight vector $\mathbf{w_T(t)}$ resulting in the reception of the maximum possible signal power at the mobile unit.

Unfortunately, it is not generally possible to instantaneously determine an accurate transmit channel array response vector $\mathbf{h}_T(t)$ by instantaneously characterizing the receive channel from the mobile unit. This is a consequence of the frequency duplexed operation typical of most cellular systems, in which each frequency-duplexed communication channel is assigned different uplink and downlink frequencies. The difference in transmit and receive frequencies results in minimal correlation existing between the instantaneous transmit and receive channel array response vectors. This tends to preclude determination of an optimal transmit beam weighting vector $\mathbf{w}_T(t)$ using instantaneous values of the receive channel array response vector.

In contrast, it has been found that there exists significant correlation between time-averaged covariance behavior of frequency-duplexed transmit and receive channel pairs. Since what follows will pertain to time-averaged channel covariance behavior, a time-independent transmit beam weight vector notation $\mathbf{w}_T$ will be used in lieu of a time-dependent transmit beam weight vector $\mathbf{w}_T(t)$. This does not imply that the weight vector $\mathbf{w}_T$ will be completely time-independent, but rather that the weight vector $\mathbf{w}_T$ will not vary significantly over the time periods within which are accumulated the channel statistics required for the covariance characterization of the channel described hereinafter.

An optimum average power transmit weight vector, $\hat{\mathbf{w}}_T$, will now be defined as that beam pattern vector which maximizes the average signal power received by a given mobile unit, wherein $\hat{\mathbf{w}}_T$ is expressed as follows:

$$\begin{aligned}\hat{w}_T &= arg\left[\max_{w_T}\left[E(w_T^H h_T(t) s_T^*(t) s_T(t) h_T(t)^H w_T)\right]\right] \\ &= arg\left[\max_{w_T}\left[w_T^H R_{h,T} w_T\right]\right]\end{aligned} \tag{2}$$

where $\mathbf{R}_{hT}$ denotes the transmit vector channel covariance matrix evaluated at zero time shift and E(◦) denotes the statistical expectation operator. It may be assumed within equation (2) that the total power radiated by the base station antenna array

is less than or equal to some predefined maximum base station power $P_{T\max}$, or, equivalently, that $\mathbf{w}_T^H \mathbf{w}_T \leq P_{T\max}$. One solution to equation (2) is obtained by setting the optimum weight vector $\hat{\mathbf{w}}_T$ equal to the principal unit-norm eigenvector for $\mathbf{R}_{h,T}$ scaled by $\sqrt{P_{T\max}}$.

If the transmit vector channel covariance matrix $\mathbf{R}_{h,T}$ could be derived by the covariance estimator 140 in the absence of feedback from the mobile unit, the foregoing makes clear that the optimum transmit weight vector $\hat{\mathbf{w}}_T$ could be straightforwardly determined. However, since the transmit channel information is generally unavailable to the base station, an estimation of the receive channel array response vector is manipulated within the covariance estimator 140 in order to closely approximate the transmit vector channel covariance matrix $\mathbf{R}_{h,T}$. Once $\mathbf{R}_{h,T}$ has been approximated, the transmit weight vector $\hat{\mathbf{w}}_T$ is easily obtained within the transmitter weight vector adaptation module 150 in the manner described above.

In an alternate embodiment, the optimum transmit beam pattern weight vector is selected from a finite set of pre-determined weight vectors, $\{\mathbf{W}_T\}$ giving rise to a corresponding set of predefined transmit beam patterns. In this case the beam pattern may be formed by, for example, selectively assigning fixed amplitude and phase weights to each antenna element via a network of switched RF phased array elements. Rather than finding a closed form eigenvector solution to equation (2), in this embodiment a discrete search is performed for the one of the predefined transmit beam pattern weight vectors having the highest inner product with the desired covariance matrix $\mathbf{R}_{h,T}$ per equation (2).

Various differences will now be examined between the frequency-duplexed transmit and receive channels over which communication occurs between a base station and a mobile unit. In a single-user environment, the vector $\mathbf{x}_R(t)$ is representative of the set of output signals produced by the base station antenna array 56 in response to a signal $s_R(t)$ received from the mobile unit, and is given by:

where $\mathbf{n}_R(t)$ is an M-element noise vector representative of the noise added by the base station receiver. In a multipath signal propagation environment, it has been

$$x_R(t)=\sum_{l=1}^{L} a_R(\theta_l)\alpha_{R_l}(t)s_R(t)+n_R(t) \qquad (3)$$
$$=h_R(t)s_R(t)+n_R(t)$$

generally found that little correlation exists between: (i) the instantaneous amplitude $\alpha_{R,\ell}(t)$ along each angle of arrival θ_ℓ, and (ii) the instantaneous propagation path amplitude $\alpha_{T,\ell}(t)$ along each angle of departure θ_ℓ for the transmit channel. Accordingly, it is expected that attempting to map the instantaneous receive channel array response vector $\mathbf{h}_R(t)$ to an instantaneous transmit channel weight vector $\mathbf{w}_T(t)$, will generally not maximize the power delivered to the mobile unit.

While there is often little correlation between the instantaneous values of the transmit and receive vector channels, it has been found that if the transmit and receive antenna arrays are properly configured, there exists a high degree of similarity between $\mathbf{R}_{h,T}$ and $\mathbf{R}_{h,R}$. As a consequence, the covariance estimator 140 is designed to estimate an optimum transmit channel covariance matrix $\mathbf{R}_{h,T}$ from a time-averaged receive channel covariance matrix $\mathbf{R}_{h,R}$. It has been found that under the conditions described below, the substitution of the receive channel covariance matrix $\mathbf{R}_{h,R}$ within equation (2) yields a value for $\hat{\mathbf{w}}_T$ resulting in the base station delivering nearly as much power to the mobile user as would have been delivered had $\mathbf{R}_{h,T}$ been used to derive $\hat{\mathbf{w}}_T$.

From equations (1) and (2), the transmit channel covariance matrix may be expressed as:

$$R_{h,T} = E\left\{\left[\sum_{l=1}^{L} a_T(\theta_l)\alpha_{T,l}(t)\right]\left[\sum_{k=1}^{L} a_T(\theta_k)\alpha_{T,k}(t)\right]^H\right\} \qquad (4)$$
$$= \sum_{l=1}^{L} E\left\{|\alpha_{T,l}(t)|^2\right\} a_T(\theta_l)a_T(\theta_l)^H$$

where $\mathbf{E}(*)$ denotes the probabilistic expectation operation, and where it has been assumed that each angle of departure path fades independently, i.e.,

$$E(\alpha_{T,\ell}(t)\alpha^{*}_{T,k}(t))=0 \text{ for } i \neq k. \quad (5)$$

Similarly, the receive covariance matrix may be expressed as

$$R_{h,R}=\sum_{l=1}^{L} E\{|\alpha_{R,l}(t)|^2\}a_R(\theta_l)a_R(\theta_l)^H \quad (6)$$

Equations (4) and (6) have been formulated under the assumption that an equal number of dominant reflectors, at identical locations, exist at the transmit and receive channel frequencies. This constraint will typically be met, since the existence of dominant reflectors of large size increases the likelihood of substantially similar reflection at the slightly different transmit and receive frequencies of each duplex communication channel.

As may be appreciated by comparing equations (4) and (6), the assumed equivalence of the transmit and receive channel covariance matrices is justified if (i) the average strengths $\mathbf{E}\{|\alpha_l(t)|^2\}$ of the transmit and receive paths are equal, and if (ii) the receive and transmit array response vectors $\mathbf{a}_R(\theta_l)$ and $\mathbf{a}_T(\theta_l)$ are substantially the same. For the typical case of a small frequency offset between transmit and receive channels, it has been found that condition (i) is generally met. That is, the transmit and receive channel average path strength is invariant with respect to transmit and receive frequency translation. Condition (ii) may be satisfied if the antenna array(s) used for transmission and reception are substantially insensitive to the frequency difference between the transmit and receive channel bands. In the case of a single antenna array disposed for transmit and receive operation via a diplexer, the requisite frequency insensitivity may be achieved through use of antenna having elements exhibiting substantially the same amplitude and phase response over both the transmit and receive channel bands. Alternately, the frequency difference between the transmit and receive channel bands may be compensated for by appropriately scaling the dimensions of, and spacing between, the antenna elements within separate transmit and receive antenna arrays.

The foregoing makes clear that transmit channel weight vector may be

determined by the transmitter weight vector adaptation module 150 on the basis of a second order statistical characterization of the received array response vector. It is nonetheless to be understood that the compilation of other statistical characterizations of the receive array response vector as a means of determining an optimum transmit beam weight vector is also within the scope of the present invention.

III. Beamforming in Multiple User Environment

In the preceding section it was shown that, within a single user environment, a close approximation of an optimum transmit beam pattern could be effected using the receive array response vector covariance matrix. In the exemplary single user case discussed above, an optimum transmit beam pattern is obtained by simply attempting to maximize power delivered to the mobile user's receiver by the base station antenna array. In this section, a technique is described in which signal power delivered to an intended recipient mobile user by a base station array is maximized, while for other mobile users the base station array simultaneously minimizes the delivered interference power. In what follows the term "interference power" refers to signal energy transmitted by a base station array which is intended for reception by a particular mobile user, but which is also received by one or more other unintended mobile users.

It is noted that the exemplary embodiment described herein illustrates a scheme for forming an adaptive transmission beam for the purpose of reducing cellular frequency re-use intervals, thereby increasing network call traffic capacity. However, it is understood that the signal to interference maximization criteria described below may be equally applied in other contexts. For example, in an alternate embodiment these criteria may enable sharing of frequency channels by more than a single mobile user within a given cell as a means of increasing network call traffic capacity.

In conventional cellular systems of the type which allocate each channel frequency within a cell to a single mobile user, the cells are dimensioned such that base stations using the same frequency set are sufficiently separated to ensure that mutual "co-channel" (i.e., same frequency) interference is kept below an

acceptable level. Unfortunately, this technique for partitioning frequencies among adjacent cells tends not only to reduce traffic capacity per base station, but also reduces trunking efficiency.

It is known that the ratio of the radius of an individual cell (R) to the distance between the centers of co-channel cells (D) determines amount of co-channel interference that a mobile user can expect to experience. It is also known that this ratio (D/R) determines the number of distinct channel sets that are assigned to cells throughout the cellular system. Increasing the value of D/R causes the mobile unit receive less interfering signal power (on average) and requires the cellular system to use a greater number of channel sets (i.e., a larger frequency re-use factor). Since the total number of frequency channels is fixed, increasing the number of channel sets reduces the number of frequency channels available to each cell and results in a reduction in cell capacity. A further capacity penalty arises from considerations of trunking efficiency, which become increasingly significant as the number of channels available to a given cell are reduced.

Accordingly, a trade-off typically exists between the average amount of interference received by a mobile unit within a cellular network, and the number of calls capable of being supported at any given time by each cell in the system. Since the present invention improves the average signal to interference ratio experienced by a mobile user's receiver by the use of adaptive transmit beamforming, the value of D/R for the system may be reduced until the mobile unit's interference threshold is once again reached. This advantageously results in an increase in system capacity due to the reduced D/R ratio. If instead the mobile unit's D/R is not reduced, the mobile unit will instead experience a higher quality connection.

It is further apparent that the present invention may also be employed to increase base station coverage area and/or improve some measure of call quality in lieu of, or in addition to, improving network capacity.

In the exemplary embodiment, an adaptive antenna array is employed at each base station as a means of reducing the interference delivered to undesired users within adjacent cells while simultaneously maximizing the average power to

the desired user. In this way the frequency "re-use" interval of the cellular network is improved by reducing the number of cells needed to be interposed between base stations using the same frequency set. The interference power delivered by the base station array within a given cell to co-channel mobile users in adjacent cells is determined within the covariance estimator 140 by forming an "undesired" covariance matrix for each such user by statistically characterizing (as described in section I) the signal energy received therefrom. This allows formulation of an expression for an optimum transmit beam weight vector matrix $W_{T,OPT}$ as a function of:

(i) the desired covariance matrix characterizing the communications channel between each base station in the network and the "desired" mobile user serviced by each such base station utilizing the same frequency channel, and

(ii) the undesired covariance matrices associated with each base station, wherein each undesired covariance matrix characterizes the signal propagation between a base station and one co-channel mobile user in an adjacent cell.

An exemplary expression for the matrix of optimum transmit beam weight vectors ($W_{T,OPT}$) is set forth below:

$$W_{T,opt}=arg\left\{\max_{W_T}\left[\min_{i}\left(\frac{w_{T_i}^H R_{hTd_i} w_{T_i}}{\sum_{\substack{j=1 \\ j\neq i}}^{d} w_{T_j}^H R_{hTu_{ij}} w_{T_j}}\right)\right]\right\} \tag{7}$$

subject to the constraints of

$$\frac{w_{T_i}^H R_{hTd_i} w_{T_u}}{\sum_{\substack{j=1 \\ j\neq i}}^{d} w_{T_j}^H R_{hTuj} w_{T_j}} \geq SNR_{\min}$$

where

$w_{T,} = [wT1\ w_{T2} \ldots w_{Td}]$ is the optimal transmit beam weight vector matrix, in which w_{Td} corresponds to the optimum transmit weight beam vector of the dth base station antenna array;

R_{hTd_i} is the desired transmit covariance matrix for user i;

$R_{hTd_{i,j}}$ is the undesired transmit covariance matrix j for user i; and

SNR_{min} is the minimum allowable SNR for each mobile user.

The optimization expression of equation (7) is formulated in order to maximize the minimum signal to interference ratio (SNR_{min}) experienced by any given desired mobile user within the network. That is, it is intended that each desired mobile user receives sufficient signal energy to ensure that a minimum signal to interference plus noise ratio ($SINR_{min}$) required for acceptable communications quality is established for each mobile user. When it becomes infeasible for every desired user to experience a SINR greater than $SINR_{min}$, it is expected that the user experiencing the lowest SINR will be assigned to another frequency channel. The optimization contemplated by equation (7) is then performed again with fewer co-channel users.

In embodiments in which means are not provided for communication between the base stations of different cells, the exact interference power transmitted to each desired user by all adjacent cell base stations is unknown to a given base station. However, a given base station is capable of estimating the covariance matrices characterizing signal propagation from the base station to its desired user and the undesired users in adjacent cells. Accordingly, equation (7) may be reformulated as a maximization of the power delivered by each base station to the desired mobile user within its cell, subject to constraints on the amount of interference power which may be delivered to any one of the undesired co-channel users in adjacent cells. By setting an upper limit on the amount of interference power which any given base station is permitted to deliver to an undesired co-channel user in an adjacent cell, and a lower limit on the minimum power received by the desired user, each mobile user is guaranteed to experience an average signal to noise ratio in excess of $SINR_{min}$ in the event that a solution to the optimization problem is found.

This reformulated optimization may be expressed as:

$$w_T = arg\left\{ \max_{w_T} (w_T^H R_{hTd} w_T) \right\} \quad (8)$$

subject to the constraints of,

$$w_T^H R_{hTd} w_T \geq P_{Rmin}$$
$$w_T^H R_{hTu_j} w_T \geq P_{Imax} \quad \forall j$$
$$P_{Tmin} \leq w_T^H w_T \leq P_{Tmax}$$

wherein,

$\mathbf{R}_{hTd}$ is the covariance matrix characterizing the communication channel between the desired user and base station within a given cell,

$\mathbf{R}_{hTu_j}$ is the interference covariance matrix from a given cell to the jth co-channel user within an adjacent cell,

P_{Imax} is the maximum interference power allowed to be delivered by any given base station to any undesired co-channel users within adjacent cells,

P_{Rmin} is the minimum signal power to be received by a desired user in order to ensure that each desired user experience a signal to interference ratio in excess of SNR_{min},

P_{Tmax} is the maximum power capable of being transmitted by a base station, and wherein

P_{Tmin} is the minimum power which must be transmitted given a limited capability by the mobile receiver to reject signal power at adjacent channel frequencies.

Although capable of providing an desirable transmit beam weight vector for use at each base station, the optimization function of equation (8) is relatively computationally intensive in that a covariance matrix is required to be compiled for each undesired co-channel user. In what follows, the computational complexity of the optimization function of equation (8) is reduced by obviating the need for knowledge of the covariance matrix associated with each undesired co-channel user. This is accomplished by formulating an optimization expression

dependent upon the summation of all undesired interference covariance matrices, rather than upon the individual undesired interference covariance matrices. The process of optimizing with respect to the summation of all interference power affords various advantages. For example, the necessary channel covariance estimates can be obtained using only the received signal vector and various ways an estimate of the desired mobile uplink signal. In contrast, individual undesired covariance matrices can generally only be determined if estimates of the undesired interfering signals are generated.

Assuming the various mobile uplink signals to be uncorrelated, the base station received signal vector covariance may be written as

$$R_x = E\{x_R(t)x_R(t)^H\} = P_{s_d} R_{hR_d} + \sum_{i=1}^{N_{int}} P_{s_i} R_{hRu_i} + R_n \quad (9)$$

which allows the approximation,

$$\sum_{i=1}^{N_{int}} P_{s_i} R_{hRu_i} = R_x - P_{s_d} R_{hR_d} - R_n \approx \hat{R}_x - P_{s_d} \hat{R}_{hR_d} \quad (10)$$

where $\hat{\mathbf{R}}_x$ and $\mathbf{R}_{hRd}$ are estimated covariance matrices corresponding to the raw received signal vector, $\mathbf{x_R(t)}$, and the desired user channel vector channel and P_{si} is the power transmitted by the i^{TH} mobile user. The approximation in equation (10) allows formulation of an optimization function which depends upon the summation of the interference covariance matrices associated with a set of undesired co-channel users, rather than a function dependent upon derivation of a separate interference covariance matrix for each undesired co-channel user. More particularly, the simplified optimization function may be expressed as:

$$w_{T,OPT} = arg\left\{ \max_{w_T} (w_T^H R_{hTd} w_T) \right\} \quad (11)$$

subject to the constraints of

$$w_T^H \left[\left\{ \sum_{i=1}^{N_{int}} R_{hTu_i} \right\} + I_M \frac{P_{Imax}}{P_{Tmax}} \right] w_T \leq P_{Imax}$$

where $P_{I,max}$ is the maximum allowable total delivered interference power, $P_{T,max}$ is the maximum allowable transmission power, and where $\mathbf{I}_M$ is an MxM identity matrix. In addition, this simplified optimization function is subject to the feasibility checks of:

$$w_T^H w_T \geq P_{Tmin}$$
$$w_T^H R_{hTd} w_T \geq P_{Rmin}$$

One solution to equation (11) is the scaled, generalized eigenvector associated with the largest generalized eigenvalue of the following matrix pair:

$$(R_{hTd}, \left[\left\{ \sum_{i=1}^{N_{int}} R_{hTu_i} \right\} + I_M \frac{P_{Imax}}{P_{Tmax}} \right]).$$

In an alternate embodiment, the optimum transmit beam pattern weight vector $\{W_T\}$ is selected from a finite set of pre-determined weight vectors giving rise to a corresponding set of predefined transmit beam patterns. In this case the beam pattern may be formed by, for example, selectively assigning fixed amplitude and phase weights to each antenna element via a network of switched RF phased array elements. Rather than finding a closed form eigenvector solution to equation (2), in this embodiment a discrete search is performed for the one of the predefined transmit beam pattern weight vectors providing the most advantageous solution to the optimization problem posed by equation (7), (8) or (11). In a specific implementation, the most advantageous solution is provided by the one of the predetermined transmit beam pattern weight vectors giving rise to

the highest signal to interference ratio.

It is recognized that the random process associated with each vector channel is not strictly stationary. Therefore, the covariance matrix description of the channel can not be considered as time invariant. However, the process components causing variation in the time-averaged covariance estimates tend to vary more slowly than so-called fast fading components of the random channel process. These slowly changing process components include log normal shadowing, base station path propagation angles, and local scatterer propagation angles. While the preceding discussion expresses the covariance channel descriptions as time invariant, it is recognized that the covariance estimate must be viewed as an approximation for time average channel behavior over some finite length time window. Accordingly, an exemplary manner is described below for adapting the channel covariance estimates to the time variation in the slowly changing channel process components. Although many adaptive techniques could be used, one choice involves application of a first order IIR filter to successive estimates of the channel covariance. This may be expressed mathematically as

$$\hat{\mathbf{R}}(k) = \lambda \hat{\mathbf{R}}(k-1) + \mu \hat{\mathbf{R}}_{NEW}(k) \qquad (12)$$

Where $\mathbf{R}(k)$ is the covariance estimate at time index k, $\mathbf{R}_{NEW}(k)$ is the covariance estimate associated with the channel data gathered between time index k-1 and k, and λ and μ are chosen to provide the desired IIR filter response.

FIGS. 4 and 5 provide flowcharts representative of various methods for adaptively determining a transmit weight vector in accordance with the invention. In what follows the term "desired mobile unit" refers to the mobile unit in communication over a given frequency channel with the base station within which is disposed the beamforming network 50. Likewise, the term "undesired mobile unit" refers to a mobile within a different cell engaged in communication, on the given frequency channel, with the base station of the different cell.

Referring now to FIG. 4, there is provided a flowchart summarizing an exemplary procedure for using an optimization function such as equation (11) to determine the transmit weight vector. As an initial step, the beamforming network 50 (FIG. 2) is calibrated in accordance with one of the techniques described below

in Section V. Next, the covariance estimator 140 (FIG. 3) determines an estimated receive channel covariance matrix as described above in Section II.

The transmitter weight vector adaptation module 150 then computes a transmit weight vector using the estimated receive channel covariance matrix. This computation is done in accordance with predefined network agreement criteria inherent within the optimization function evaluated within the weight vector adaptation module 150. In the exemplary case of the optimization function of equation (11), the pertinent transmit criteria is defined as maximization of the ratio of (i) the average power delivered to the desired mobile unit on a given frequency, to (ii) the average total interference delivered to undesired mobile units on the given frequency. If the feasibility checks associated with equation (11) are satisfied for transmission on the given frequency, then the given frequency is deemed satisfactory for communication with the desired mobile unit. If these feasibility checks are not satisfied, a different frequency is evaluated.

In an alternate embodiment, the relevant transmit criteria used in the procedure of FIG. 4 may simply mandate the maximization of the average signal power delivered to the desired mobile unit. This obviates the need for determination of an average receive channel covariance matrix representative of the communication channel to undesired users, and reduces computational complexity. This transmit criteria is believed to be particularly suitable for use in CDMA or frequency-hopped TDMA systems, in which undesired user interference statistics are either unavailable or uninformative.

In the general case, each base station in the cellular network could be constrained to limit transmission to undesired users on the basis of common "network agreement criteria". In an exemplary embodiment such network agreement criteria could comprise placing the following types of constraints upon the power transmitted by each base station:

1) an upper bound on the total power transmitted on a given channel to desired and undesired users,

2) a lower bound on the power received by the desired user,

3) a fixed upper bound on the interference power transmitted to any or all undesired users,

4) an adaptive bound on power transmitted to desired/undesired users dependent upon current traffic channel demand (thereby allowing a compromise to be made between network call capacity and call quality).

5) a lower bound on the total transmitted power

6) any other lower bound on acceptable signal or call quality to the desired user (i.e., average probability of bit error, etc.)

FIG. 5 is a flowchart outlining a general procedure for determining a transmit weight vector by using: (i) transmit criteria in the above-described manner (FIG. 4) to define the objective of an optimization function, and (ii) network agreement criteria to ensure that any optimum weight vector produced in (i) results in transmission satisfying predefined constraints. Again, the first step in the procedure of FIG. 5 involves calibration of the beamforming network 50 (FIG. 2) in accordance with one of the techniques described below in Section V. Next, the covariance estimator 140 (FIG. 3) determines an estimated receive channel covariance matrix as described above in Section II.

The transmitter weight vector adaptation module 150 then computes an optimum transmit weight vector using the estimated receive channel covariance matrix. This computation is done in accordance with predefined network agreement criteria inherent within the optimization function evaluated within the weight vector adaptation module 150. The transmit weight vector solution is then evaluated in light of network agreement criteria of the type listed above to ascertain whether the resultant desired and/or undesired user transmission quality is appropriately bounded. If so, a new estimate is made of the receive channel covariance matrix (which in general will have changed due to movement of desired/undesired mobile units), and the above process is repeated. If the network agreement criteria are not satisfied, a new frequency is selected for at least one of the users and the above process is similarly repeated. If no new frequencies are available, either a call handoff request is sent to the MTSO, or appropriate indication is provided to the calling party. That is, the calling party is informed that communication is incapable of currently being established or maintained with the desired mobile unit, and the call is dropped.

In the general case, the evaluation of transmitted signal power in view of the network agreement criteria will be regularly repeated after communication has been established with the desired mobile unit. When the transmitted signal power begins to encroach upon the constraints set by the network agreement criteria (e.g., desired receiver power nears fixed lower bound), it will typically be desired that communication with the desired user be switched to a new frequency. Such encroachment may be caused by degradation in the quality of the communication channel allocated to the desired mobile unit. For example, channel conditions may deteriorate when the desired user becomes located near the edge of the cell area, while simultaneously becoming aligned between the base station and an undesired user in an adjacent cell.

When deteriorating channel conditions cause the network agreement criteria to become in some way "close" to being violated, a search for a new frequency channel may be commenced. This search process will typically continue until either: (i) signal transmission quality over the current frequency channel as defined by the network agreement criteria improves to a satisfactory extent, or (ii) the desired mobile unit is switched to a new frequency channel over which signal transmission complies with the network agreement criteria. It is a feature of the invention that the evaluation of an alternate frequency for transmission to a mobile unit can be accomplished without the need for the mobile to transmit on the frequency under consideration. Using signals received on the alternate frequency, a receive covariance matrix estimate is generated for the alternate frequency. Since there is not a desired user transmitting on the alternate frequency, the undesired covariance matrix $\mathbf{R}_{alt,u}$ corresponds to the undesired user covariance matrix at the alternate frequency,

$$R_{alt,u} = \sum_{i=1}^{N_{int}} R_{hRu_i} + R_n$$

where N_{int} represents the number of interfering (i.e., undesired) users on the alternate frequency. Again assuming that the covariance matrices are frequency independent for small frequency shifts, the desired covariance matrix estimates

compiled on the previous frequency is equivalent to $\mathbf{R}_{alt,d}$, the desired user covariance matrix on the alternate frequency. Accordingly, the capability of signal transmission on the alternate frequency to comply with the network agreement criteria may be evaluated in the absence of desired user signal measurement on the alternate frequency.

It is anticipated that some hardware resources will be dedicated to updating the covariance matrix estimates on unused frequency channels. In doing so, the base station will be disposed to more rapidly find a suitable new frequency channel for a mobile unit assigned to a deteriorating channel. As discussed above, when mobile units within adjacent cells are located in close proximity, the base stations within the adjacent cells may experience nearly simultaneous channel degradation. That is, the base stations within each cell may simultaneously experience interference on a given frequency channel due to the presence of the undesired co-channel user within the opposing cell. Under these circumstances it is desirable that only one of the two mobile users be reassigned to a new frequency channel, since this action alone will reduce the interference level experienced by each of the two base stations. One way of increasing the likelihood that only a single mobile user is reassigned is to require that a random time interval expire before any such reassignment may occur. Because each interval is random, it is highly unlikely that the two proximately located users will be reassigned contemporaneously. Hence, the co-channel interference experienced by each base station is reduced by allocating a new channel to only one of the proximately located mobile users.

In alternate implementations, searches may be performed substantially contiguously for the most advantageous frequencies over which communication may be maintained with desired mobile units. This is in contrast to the approach previously described, in which a search for a new channel is instigated only upon the transmitted signal power coming sufficiently "close" to a bound set by the network agreement criteria. This alternate approach involves continuously determining the candidate frequency channel satisfying the transmission quality criteria by the greatest margin. The most advantageous candidate channel may then be selected by, for example, ascertaining which of these optimal transmit

weight beam vectors results in signal transmission best satisfying the pertinent network agreement criteria.

The most advantageous candidate frequency channel could instead be defined as the channel having an optimum transmit weight beam vector with which is associated the largest generalized eigenvalue solution of the applicable optimization function (e.g., equation 11). That is, the optimum transmit weight beam vector is determined for each candidate channel, and the largest eigenvalue associated with this set of weight vectors is then ascertained. The frequency channel corresponding to the transmit weight vector associated with this largest eigenvalue is then identified as the most advantageous frequency channel. Other approaches of utilizing an optimization function to identify a candidate frequency channel satisfying the relevant network agreement criteria are also within the scope of the present invention. It is expected that such other approaches may not identify the most advantageous frequency channel in view of the pertinent network agreement criteria, but will perhaps be capable of determining an acceptable channel in a less computationally intensive manner.

When the procedure outlined in FIG. 5 is used to identify a frequency channel to be assigned in response to a call request to/from a desired mobile unit, it is necessary to accumulate statistics associated with the desired mobile unit before initiating evaluation of candidate frequency channels. The initiation of the evaluation process may be expedited by gathering channel statistics using the pilot channel during the paging or call set-up period. Once suitably accurate receive channel statistics (e.g., receive channel covariance matrix estimates) have been accumulated, channel frequency allocation proceeds in the manner outlined in FIG. 5.

IV. Estimating Transmit Channel Covariance Statistics

In accordance with the present invention, any of a number of estimated statistical characterizations of a given receive channel array response vector may be performed as part of the process of generating an optimal transmit beam weight vector. A preferred method of implementing one such statistical characterization, which involves compilation of the aforementioned receive channel covariance

matrix, is described within this section. The method involves statistically characterizing the receive channel associated with the "desired user" to which information is to be transmitted, as well as characterization of the receive channel(s) associated with the "undesired user(s)" that receive interfering signal energy.

This statistical characterization method assumes the availability of a sampled received signal estimate, which is represented as $\hat{s}_R(kT)$, wherein "k" denotes the sample time index and "T" the sample interval. In an exemplary embodiment this signal estimate is derived from the output of the receive antenna array 56 (FIG. 2), and may be further processed to enhance signal estimation accuracy. For example, the signal estimate may be obtained by passing the output of the receive array 56, or of another dedicated antenna array, through a spatial and/or temporal receiver equalizer.

In alternate embodiments the signal estimate $\hat{s}_R(kT)$ is obtained by exploiting a sequence of known training signals which are transmitted from the desired user's mobile unit in order to assist in estimation of the wireless channel properties.

In one embodiment each received signal estimate is cross-correlated with the received data vector $\mathbf{x}_R(kT)$ from the antenna array 56 as a means of forming the instantaneous receive channel array response vector estimate $\tilde{\mathbf{h}}_R(KT)$. The following cross correlation operation defines $\tilde{\mathbf{h}}_R(KT)$:

$$\tilde{h}_R(KT)=\frac{1}{2N_h}\sum_{k=K-N_h}^{K+N_h-1} x_R(kT)\hat{s}_R^*(kT) \qquad (13)$$

$$K = O, 2N_h, 4N_h, 6N_h, \ldots$$

where $2N_h$ denotes the number of received data vector samples used to estimate $\tilde{\mathbf{h}}_R(KT)$. In a preferred implementation the estimation block size is selected such that the time duration ($2N_hT$) of each data block processed during each cross-correlation operation is made to be less than the time scale over which the instantaneous receive channel is expected to vary significantly. In this way an

accurate estimation of instantaneous channel behavior is possible.

Once a set of array response estimates $\tilde{\mathbf{h}}_R(KT)$ have been collected over a given time interval, a receive channel covariance matrix $\mathbf{R}_{hRd}$, may be estimated as follows:

$$\hat{R}_{hRd}(KT) = \lambda \hat{R}_{hRd}((K-2Nh)T) + \mu \tilde{h}_R(KT)\tilde{h}_e^H(KT) \quad (14)$$

Again, the present invention contemplates agreement between such a time-averaged covariance matrix estimation and the true transmit channel short term covariance matrix.

Under certain conditions, the time-averaged covariance matrix estimation may be improved using an estimation filter designed to filter the receive channel response vector estimate $\tilde{\mathbf{h}}_R(KT)$. In accordance with the invention, the estimation filter is designed to correlate time-varying frequency and/or spatial properties of the multipath channel. This approach is believed to present a significant departure from conventional techniques, which generally assume near time-invariance over the desired estimation interval. If $\hat{\mathbf{h}}_R(KT)$ represents the output of the estimation filter in response to the input $\tilde{\mathbf{h}}_R(KT)$, the receive covariance matrix associated with the desired user (i.e., "the desired user covariance matrix") may be expressed as:

$$\hat{R}_{hRd}(KT) = \lambda \hat{R}_{hRd}((K-2N_h)T) + \mu \hat{h}_R(KT)\hat{h}_R^H(KT) \quad (15)$$

The estimation filter may be realized as a linear FIR filter, as a linear IIR filter, as an adaptive filter structure (e.g., a Kalman filter), or as a non-linear filter structure. Moreover, the parameters (e.g., FIR taps or Kalman state-space model) of the estimation filter may be pre-computed based on expected channel time-domain correlation behavior. Alternately, the parameters of the estimation filter may be may be adapted in real-time as a function of measured channel behavior.

Rather than filtering the sequence $\tilde{\mathbf{h}}_R(KT)$ as means of obtaining an improved array response estimate $\hat{\mathbf{h}}_R(KT)$, the estimate of the desired user receive

covariance matrix may first be formulated using only the sequence $\tilde{h}_R(KT)$. The resultant samples $\tilde{R}_{hRd}(KT)$ are then passed through an estimation filter similar to that described above to obtain $\hat{R}_{hRd}(KT)$. In this case, however, the estimation filter parameters are selected to directly optimize $\hat{R}_{hRd}$, rather than to indirectly improve this quantity through estimation filtering of $\hat{h}_R(KT)$.

As discussed above, the formulation of an optimal transmit channel covariance matrix involves not only estimation of a desired user receive covariance matrix $\mathbf{R}_{hRd}$, but also entails estimation of an undesired user receive covariance matrix $\mathbf{R}_{hRu}$. Again, compilation of the undesired user receive covariance matrix involves estimating the interfering signal energy transmitted by mobile users within other cells. One approach to estimation of the undesired user receive covariance matrix $\mathbf{R}_{hRu}$ involves subtraction of a scaled version of the estimated desired user covariance matrix $\mathbf{R}_{hRd}$ from the received signal vector covariance matrix $\mathbf{R}_{xx}$:

$$\sum_{i=1}^{N_{int}} P_{su_i} \hat{R}_{hRui}(NT) = R_{xx}(NT) - P_{s_d} \hat{R}_{hRd}(NT) = \hat{R}_u \tag{16}$$

In accordance with another aspect of the invention, an approach for estimating the undesired user covariance matrix is described which is particularly suitable for employment when relatively short sequences of samples (i.e., sample blocks) are being processed. Specifically, the received signal estimate $\{\hat{\mathbf{h}}(kT)\hat{s}_d(kT)\}$ is subtracted from the received data vector $\{\mathbf{x}(kT)\}$, thereby forming a vector $\{\mathbf{x}_u(kT)\}$ representative of the sum of the undesired received signal power and receiver noise:

$$x_u(kT) = x(kT) - \hat{h}(kT)\hat{s}_d(kT) \tag{17}$$

The undesired user covariance matrix $\hat{\mathbf{R}}_{hRu}$ is then estimated as follows:

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

$$\hat{R}_u(KT)=\lambda\hat{R}_u((K-2N_h)T)+\mu\sum_{k=K-N_h}^{k+n_h-1}x_u(kT)x_u^H(kT) \quad (18)$$

As was mentioned above in connection with description of the desired covariance matrix $\mathbf{R}_{hRd}$, it may at times be desirable to filter samples of the undesired covariance matrix using an estimation filter. Again, such an estimation filter serves to modify the current estimated covariance matrix in response to time-variation in the statistics of the true undesired channel response.

Following determination of the estimated desired and undesired receive channel covariance matrices, the optimal transmit beam weight vector is found by substituting these matrices into equation (11) as follows:

$$\hat{R}_hRd\rightarrow\hat{R}_hTd \quad (19)$$

$$\hat{R}_u\rightarrow\sum_{i=1}^{N_{int}}R_hTu_i$$

The foregoing procedure for optimal transmit beamforming illustrates a particular implementation of the invention, it being understood that other methods for adaptively estimating channel covariance are also within the scope of the invention.

V. Transmit and Receive Channel Calibration

In order to ensure that receive channel statistics are accurately "mapped" to transmit channel statistics which are useful for determining an optimal transmit beam weight vector, the transmit and receive sections of the particular transceiver employed are calibrated. The calibration procedure and apparatus described herein corrects for differences in the amplitude and phase match between the signal paths through the transceiver corresponding to each antenna element of the frequency

channels. This "matching" correction allows receive channel statistics collected for each of the frequency channel to be accurately used within the corresponding transmit channel in the manner described in section IV. Although several specific approaches of a calibration procedure are set forth below, other approaches of correcting for amplitude and phase discrepancies between corresponding transmit and receive channel paths may be apparent to those skilled in the art in view of the teachings herein.

Referring to FIG. 6, a block diagram is provided of an exemplary calibration system as incorporated within the adaptive beamforming network of FIG. 3. The calibration procedure contemplated by the invention involves two operations: (i) calibration of the antenna array 56 and diplexer 58, and (ii) calibration of the remaining electronics within the transmit and receive sections.

Since the antenna array 56 and diplexer 58 (i.e., the array assembly) are comprised of passive components, it is expected that matching (e.g., power matching, impedance matching) between these passive structures and both the transmit and receive and electronics will be relatively invariant over time and temperature. Accordingly, calibration of the matching between the array assembly and the remaining transmit and receive electronics within the adaptive beamforming network may be performed infrequently. As a first step in calibration of the array assembly, the match between the RF receiver 54 and the array assembly is determined for each receive frequency of interest. Similarly, the match between the RF transmitter 52 and the array assembly is also determined for each transmit frequency of interest. These measurements may be conducted at an antenna test range, or at any other appropriate calibration site.

The differences in the measured amplitude and phase match for each corresponding pair of transmit and receive frequencies are stored both within a receiver calibration equalizer & channelizer 250, and within a transmitter calibration equalizer & channel combiner 254. During operation of the adaptive beamforming network, equalization filters within the equalizers 250 and 254 are adjusted so as to compensate for the matching difference at each pair of corresponding transmit and receive frequencies.

Unlike the array assembly, the active components within RF transmitter 52

and RF receiver 54 may exhibit significant amplitude and phase drift as a function of time and temperature. In order to obviate the need for use of expensive, high-precision components in conjunction with compensation circuits as a means of minimizing such amplitude and phase drift, the present invention contemplates utilization of the self-calibration apparatus depicted within FIG. 6. The self-calibration technique described herein involves compensating for differences in amplitude and phase between the different propagation paths within the RF transmitter 52 associated with each antenna element, and likewise for such differences between the different propagation paths within the RF receiver 54. Measurements of the propagation of calibration signals over each path within the RF transmitter 52, and separately within the RF receiver 54, are conducted at each of the N transmit/receive frequency pairs of interest. The measurement results are then employed to compute calibration coefficients used in adjustment of the equalizers 250 and 254.

Referring to the receive section of FIG. 6, a receiver calibration signal injection network 260 is operative to generate calibration signal comprised of all the N RF receive frequencies of interest. This "wideband" calibration excitation may be accomplished either through generation of a plurality of discrete frequency signals, or through generation of a single wideband calibration signal. In either case, the same one or more receiver calibration signals are injected into each of the M signal paths linking each of the M elements of the array 56 to the RF receiver 54. After being downconverted in frequency, digitized, filtered and decimated within the receiver 54, the receiver calibration signals are processed by a receiver calibration coefficient computation circuit 264. In the exemplary embodiment, the computation circuit 264 measures the amplitude and phase difference exhibited by calibration signals of the same frequency after propagation through the receiver 54 on the M different signal paths associated with the antenna elements. A set of filter calibration coefficients are then computed for use in adjustment of either a single wideband equalization filter, or a plurality of narrowband equalization filters, disposed within the receiver calibration equalizer 250.

As mentioned above, calibration information obtained during calibration of

the array assembly is also stored within the calibration equalizer. This calibration information, as well as the coefficients provided by the computation circuit 264, are together used to adjust the equalization filters within the calibration equalizer 250. This adjustment is designed to ensure that for each of the **N** frequency channels, a substantially identical amplitude and phase change occurs as a consequence of propagation through each of the **M** propagation paths of the RF receiver 54.

A similar calibration procedure may be used to compensate for the generally different amplitude and phase characteristics exhibited by each of the **M** signal propagation paths within the RF transmitter 52. In particular, a set of **M** identical wideband digital IF calibration signals are generated within a transmitter calibration signal injection network 274 for application to the **M** signal paths entering the RF transmitter 52. Each of these **M** wideband digital IF calibration signals are then interpolated, filtered, converted to analog signals, and subsequently translated to a higher analog frequency.

At the output of the bank of power amplifiers 164, the amplified calibration signals are coupled to a transmit section calibration receiver comprised of an RF calibration downconverter 280 and an A/D conversion & digital processing module 284. The RF calibration downconverter 280 is operative to translate the frequency of the amplified calibration signals to an intermediate frequency (IF). The resultant set of **M** IF signals are provided to an A/D conversion & digital processing module 284 disposed to digitize, filter, and decimate each IF signal. A transmitter calibration coefficient computation circuit 288 then measures the amplitude and phase difference exhibited by calibration signals of the same frequency carried by the **M** different outputs of the A/D conversion & digital processing module 284 where, again, each of the **M** outputs is associated with one of the **M** signal paths through the RF transmitter.

A set of filter calibration coefficients are then computed within the computation circuit 288 for use in adjustment of the single wideband, or multiple narrowband, equalization filters disposed within the transmitter calibration equalizer and channel combiner 254. These filter calibration coefficients, as well

as the calibration information collected during calibration of the array assembly, are jointly used to adjust the equalization filters within the calibration equalizer & channel combiner 254.

The transmit section calibration receiver will typically also be calibrated in a manner substantially similar to that described above with reference to the RF receiver 54. In order to preserve clarity of representation, the calibration circuitry used in this secondary calibration process is not shown in FIG. 6. Finally, it is noted that the calibration system depicted in FIG. 6 is designed to be equally compatible with an adaptive beamforming network equipped with separate transmit and receive antenna arrays. The implementation of the calibration system within such an adaptive beamforming network is shown in FIG. 7.

FIG. 8 provides a block diagram of a self-calibrated adaptive beamforming network in which the receive section of the beamforming network is advantageously utilized in lieu of a transmit section calibration receiver (FIG. 6). During calibration of the transmit section of the beamforming network, the transmitter signal injection network 284 again applies a wideband calibration signal to each of the **M** inputs to the RF transmitter 52. A transmit calibration switch 302 is operated, during calibration, so as to sequentially couple each one of the **M** calibration outputs of the RF transmitter 52 to a single one of the **M** inputs to the RF receiver 54. In the embodiment of FIG. 8, the bandwidth of the RF receiver 54 encompasses both the transmit and receive channel frequency spectra in order to facilitate processing of the transmit section calibration signals. Based on the content of the calibration signals processed by the RF receiver 54, the transmitter calibration coefficient computation circuit 288 then computes a set of filter calibration coefficients for use in adjustment of the equalization filter(s) disposed within the transmitter calibration equalizer and channel combiner 254.

The transmit calibration switch 302 similarly obviates the need for a receiver calibration signal injection network 260 (FIG. 6). In particular, during calibration of the receive section of the adaptive beamformer, a receive calibration switch 306 is closed so as to allow a receive channel calibration signal generated by one of the **M** paths of the RF transmitter 52 to be applied to the RF receiver 54. Calibration coefficients would then be computed by the receiver calibration

coefficient computation circuit 264 in the manner described above. In this implementation, the bandwidth of the RF transmitter 52 is designed to accommodate the spectra occupied by both the set of transmit channels and the set of receive channels.

As mentioned above, both the calibration equalizer and channelizer 250 and the transmitter calibration equalizer & channel combiner may each include either: (i) a single wideband equalization filter, or (ii) a functionally equivalent set of narrowband equalization filters. Referring to FIG. 9, a block diagram is provided of an implementation of a calibration equalizer and channelizer 250 in which a single wideband calibration equalizer 320 is coupled to each of the **M** outputs of the complex downconverter 112 of the RF receiver 54. During operation of the adaptive beamforming network, the passband characteristics of each wideband calibration equalizer 320 are adjusted on the basis of the results of the previously described calibration procedures. As is indicated by FIG. 9, the equalized output of each of the **M** wideband calibration equalizers 320 is demultiplexed into a set of **N** independent frequency channels by channelizer 324. Within the receive channel weighting network 116 (FIG. 1), a set of **N** space-time equalizers 330 each receive the output produced by the channelizers 324 on a different one of the **N** frequency channels. Each space-time equalizer 330 is disposed to scale signal energy within its assigned frequency channel pursuant to the weighting vector provided the receiver weight vector adaptation network 118, the operation of which was described in sections I and II.

In FIG. 10, a block diagram is provided of an implementation of a transmitter calibration equalizer & channel combiner 250 in which a single transmit wideband calibration equalizer 350 precedes each of the **M** inputs to the complex upconverter 160 of the RF transmitter 52. During operation of the adaptive beamforming network, the passband characteristics of each transmit wideband calibration equalizer 350 are adjusted on the basis of the results of the previously described calibration procedures. As is indicated by FIG. 10, the frequency-multiplexed input of each of the **M** wideband calibration equalizers 350 is provided one of a set of **M** channel combiners 360. Each of the **M** channel combiners 360 receives input on a different one of the **N** frequency channels from

a set of N transmission beamformers 370 within the transmit channel weighting network 158 (FIG. 1). The scaling introduced by the N transmission beamformers 370 is predicated on the composition of the transmit beam weight vector generated by the transmitter weight vector adaptation network 150 (FIG. 1).

FIG. 11 is a block diagram of an implementation of the calibration equalizer and channelizer 250 which, although functionally equivalent to the structure of FIG. 9, utilizes M sets of N narrowband calibration equalizers 390 rather than M wideband equalizers. In addition, in the implementation of FIG. 11 the channelization operation is performed prior to equalization. Accordingly, each of the M channelizers 324 provides output on a different frequency channel to each of the N narrowband calibration equalizers 390 associated therewith.

FIG. 12 depicts a transmitter calibration equalizer & channel combiner 250 functionally identical to that shown in FIG. 10, but within which the equalization function is performed separately for each channel prior to the frequency multiplexing operation. Specifically, a separate set of M narrowband calibration equalizers 410 are seen to be coupled to each transmission beamformer 370. In turn, the N calibration equalizers 410, coupled to a set of the M channel combiners 360, are each operative to produce an equalized signal on each of the N available frequency channels.

VI. Alternate Embodiments

Although the embodiments of the invention presented herein have been described in terms of optimization of the antenna pattern transmitted by a base station antenna array, the teachings of the invention are equally applicable to optimum formation of the mobile unit antenna pattern. That is, the mobile unit antenna pattern is formed such that a desired level of power is transmitted to the one or more base stations with which the mobile unit is in communication, and so that transmission power is minimized to the other base stations within the communication network. Again, an initial step in this antenna pattern optimization procedure involves statistically characterizing the mobile unit receive channel vector. The results of this statistical characterization are then used to determine the beam pattern weight vector which maximizes a predetermined quality

parameter (e.g., signal to noise ratio) of the signal received by the intended base station(s), while minimizing signal transmission to other base stations. At the mobile station, the transmit antenna beam pattern is then generated in accordance with the transmit beam pattern weight vector.

Accordingly, in the following claims the term "central communications station" is intended to refer to either the base station or mobile unit configured to generate an optimized antenna beam pattern in accordance with the invention. When a base station comprises the central communications station, the mobile unit(s) in communication therewith are referred to as "remote communications station(s)". Conversely, when a mobile unit comprises the central communications station, the receiving base station(s) are identified as remote communications station(s).

While the present invention has been described with reference to a few specific embodiments, the description is illustrative of the invention and is not to be construed as limiting the invention. Various modifications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. In a communications system including a central communications station and at least one remote communications station, said central communications station having an antenna array for generating an antenna beam pattern used for transmission of information signals received by said remote communications station, a method for adaptively forming said beam pattern comprising the steps of:

statistically characterizing a receive channel vector, said receive channel vector being representative of a receive communications channel over which signal energy is transmitted from said at least one said remote communications station to said central communications station;

generating a beam pattern weight vector based on results of statistical characterization of said receive channel vector, said beam pattern weight vector being generated in accordance with a predetermined quality measurement of said information signals received by said remote communications station; and

forming said beam pattern using said beam pattern weight vector.

2. The method of claim 1 further including the step of estimating said receive channel vector using one or more time-varying channel estimation filters.

3. The method of claim 1 wherein said step of statistically characterizing further includes the step of compiling an estimated receive channel covariance matrix.

4. The method of claim 3 wherein said step of generating said beam pattern weight vector includes the step of time averaging said estimated receive channel covariance matrix in order to form an estimated transmit channel covariance matrix.

5. The method of claim 4 further including the step of using said estimated transmit channel covariance matrix to form objective and constraint functions from

which said beam pattern weight vector is determined.

6. In a communications system including a central communications station and at least one remote communications station, said central communications station having an antenna array for generating an antenna beam pattern used for transmission of information signals received by said remote communications station, a system for adaptively forming said beam pattern comprising:

means for statistically characterizing a receive channel vector, said receive channel vector being representative of a receive communications channel over which signal energy is transmitted from said at least one remote communications station to said central communications station;

means for generating a beam pattern weight vector based on results of statistical characterization of said receive channel vector, said beam pattern weight vector being generated in accordance with a predetermined quality measurement of said information signals received by said remote communications station; and

a beamforming network for forming said beam pattern using said beam pattern weight vector.

7. The system of claim 6 further including one or more time-varying channel estimation filters for estimating said receive channel vector.

8. The system of claim 6 wherein said means for statistically characterizing further include means for compiling an estimated receive channel covariance matrix.

9. The system of claim 8 wherein said means for generating said beam pattern weight vector includes means for averaging said estimated receive channel covariance matrix in order to form an estimated transmit channel covariance matrix.

10. The system of claim 9 further including means for using said estimated transmit channel covariance matrix to form objective and constraint functions, said

beam pattern weight vector being obtained by solving said objective and constraint functions.

11. In a cellular communications system including a base station and at least one mobile unit, said base station having an antenna array for projecting a transmit antenna beam pattern used for transmission of information signals to said mobile unit, a system for adaptively forming said transmit antenna beam pattern comprising:

a receive channel beamforming network for processing signal energy transmitted by said at least one mobile unit over a receive communications channel to said antenna array, said receive channel beamforming network including means for producing a statistical characterization of a receive channel vector wherein said receive channel vector is representative of said receive communications channel; and

a transmit channel beamforming network for generating a transmit beam pattern weight vector based on said statistical characterization, and for forming said transmit antenna beam pattern using said transmit beam pattern weight vector;

wherein said transmit beam pattern weight vector is generated so as to improve quality of signal reception within said mobile unit.

12. The system of claim 11 further including a diplexer connected between said antenna array and said transmit and receive channel beamforming networks.

13. The system of claim 11 wherein said receive channel beamforming network further includes:

means for generating a receive channel weight vector, and means for scaling signal energy received by antenna elements of said antenna array in accordance with said receive channel weight vector.

14. The system of claim 11 wherein said means for producing a statistical characterization of a receive channel vector further includes means for compiling an estimated receive channel covariance matrix.

15. The system of claim 14 wherein said transmit channel beamforming network includes:

means for averaging said estimated receive channel covariance matrix in order to form an estimated transmit channel covariance matrix, and

means for deriving said transmit beam pattern weight vector from said transmit channel covariance matrix.

16. The system of claim 15 wherein said means for deriving said transmit beam pattern weight vector includes means for determining the principal eigenvector of said transmit channel covariance matrix, said transmit beam pattern weight vector corresponding to said eigenvector of said transmit channel covariance matrix.

17. The system of claim 11 further including calibration means for calibrating said transmit and receive channel networks.

18. The system of claim 17 wherein said calibration means includes:

means for applying a set of test signals to a corresponding set of output ports of elements of said antenna array, and

means for measuring amplitude change and phase shift of each of said test signals arising due to propagation over receive channel paths within said receive channel network.

19. The system of claim 18 wherein said calibration means includes means for equalizing amplitude and phase response through said receive channel paths based on measured phase shift of said test signals.

20. The system of claim 17 wherein said calibration means includes:

means for applying a set of test signals to said transmit channel network, and

means for measuring amplitude change and phase shift of each of said test signals within said set of test signals arising due to propagation over transmit

channel paths within said transmit channel network to a corresponding set of antenna elements of said antenna array.

21. The system of claim 20 wherein said calibration means includes means for equalizing amplitude and phase response through said transmit channel paths based on measured phase shift of said test signals.

22. In a cellular communications system including a base station and at least one mobile unit, said base station having transmit and receive antenna arrays for providing transmit and receive antenna beam patterns, respectively, a system for adaptively forming said transmit antenna beam pattern comprising:

a receive channel beamforming network, operatively coupled to said receive antenna array, said receive channel beamforming network including means for producing a statistical characterization of a receive channel vector wherein said receive channel vector is representative of a receive communications channel over which information is transmitted from said at least one mobile unit; and

a transmit channel beamforming network, operatively coupled to said transmit antenna array, for generating a transmit beam pattern weight vector based on said statistical characterization and for forming said transmit antenna beam pattern using said transmit beam pattern weight vector.

23. The system of claim 22 wherein said means for producing a statistical characterization of a receive channel vector further includes means for compiling an estimated receive channel covariance matrix.

24. The system of claim 23 wherein said transmit channel beamforming network includes:

means for time-averaging said estimated receive channel covariance matrix in order to form an estimated transmit channel covariance matrix, and

means for deriving said transmit beam pattern weight vector from said transmit channel covariance matrix.

25. In a radio frequency communications system including a central communications station having an antenna array, a method for forming a transmit antenna beam pattern comprising the steps of:

adaptively beamforming a signal received from a remote communications unit in order to configure a receiver beam weighting network;

determining an estimated receive channel vector using said signal received from said remote communications unit, said estimated receive channel vector being determined at least partly in accordance with a beamformed signal generated by said receiver beam weighting network; and

transmitting a beamformed signal to said remote communications unit based upon said estimated receive channel vector.

26. The method of claim 25 wherein said step of transmitting further includes the step of averaging said estimated receive channel vector.

27. The method of claim 25 wherein one or more time-varying channel estimation filters are used to determine said estimated receive channel vector.

28. In a radio frequency communications system including a central communications station having an antenna array, a system for adaptively forming a transmit antenna beam pattern comprising:

means for adaptively beamforming a signal received from a communications unit in order to configure a receiver beam weighting network;

means for determining an estimated receive channel vector using said signal received from a communications unit, said estimated receive channel vector being determined at least partly in accordance with a beamformed signal generated by said receiver beam weighting network; and

a transmit beamforming network for transmitting a beamformed signal to said communications unit based upon said estimated receive channel vector.

29. The system of claim 28 wherein said transmit beamforming network includes means for averaging said estimated receive channel vector.

30. The system of claim 28 wherein said means for determining said receive channel vector includes one or more time-varying channel estimation filters.

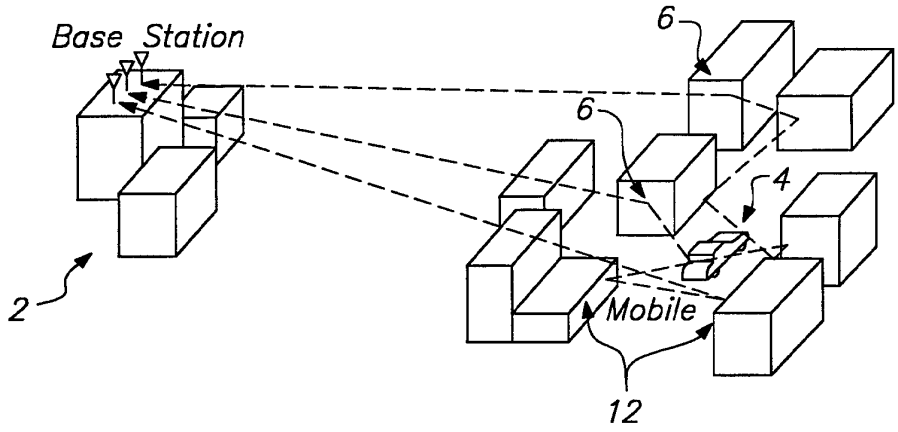
Base Station
6
6
4
2
Mobile
12

FIG. 1

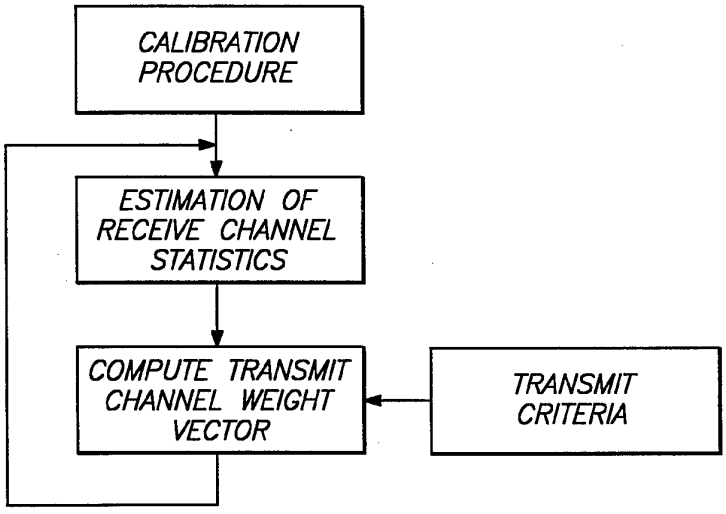
CALIBRATION PROCEDURE
ESTIMATION OF RECEIVE CHANNEL STATISTICS
COMPUTE TRANSMIT CHANNEL WEIGHT VECTOR
TRANSMIT CRITERIA

FIG. 4

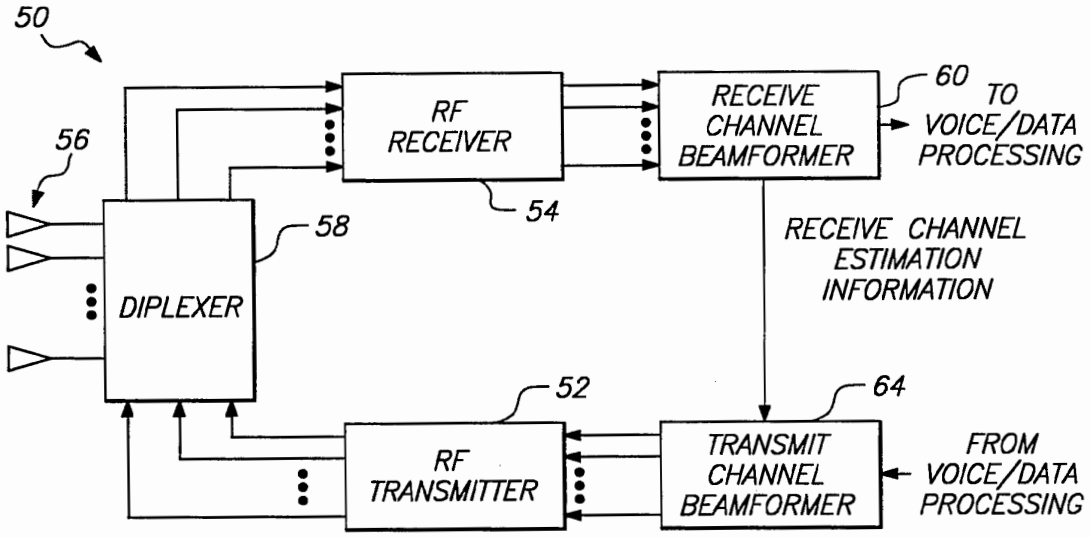
50
56
RF RECEIVER
54
RECEIVE CHANNEL BEAMFORMER
60
TO VOICE/DATA PROCESSING
58
DIPLEXER
RECEIVE CHANNEL ESTIMATION INFORMATION
52
64
RF TRANSMITTER
TRANSMIT CHANNEL BEAMFORMER
FROM VOICE/DATA PROCESSING

FIG. 2A

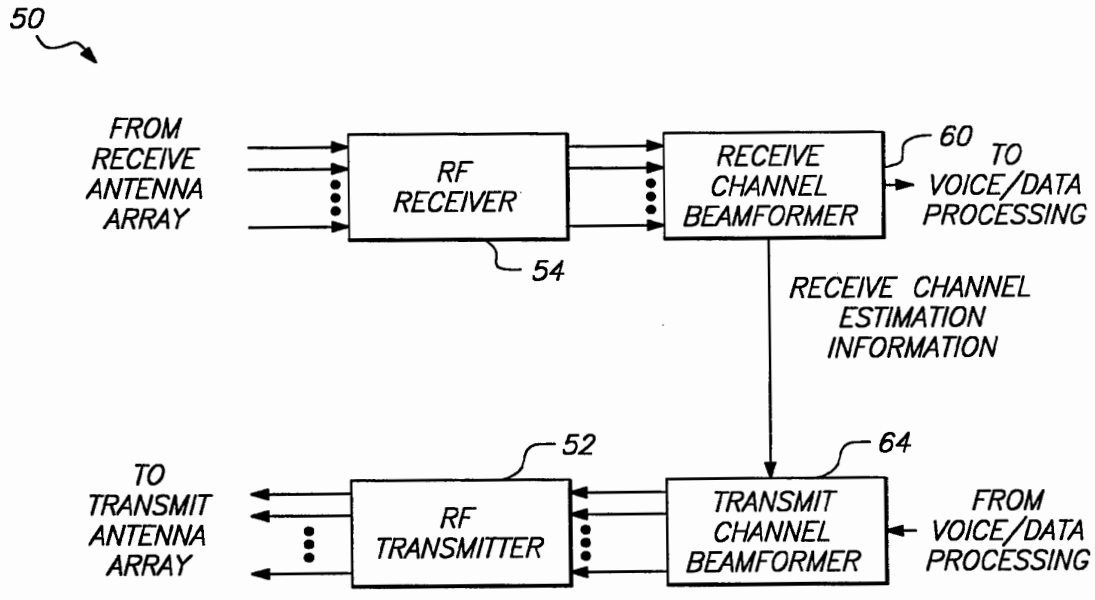
50
FROM RECEIVE ANTENNA ARRAY
RF RECEIVER
54
RECEIVE CHANNEL BEAMFORMER
60
TO VOICE/DATA PROCESSING
RECEIVE CHANNEL ESTIMATION INFORMATION
52
64
TO TRANSMIT ANTENNA ARRAY
RF TRANSMITTER
TRANSMIT CHANNEL BEAMFORMER
FROM VOICE/DATA PROCESSING

FIG. 2B

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FIG. 3

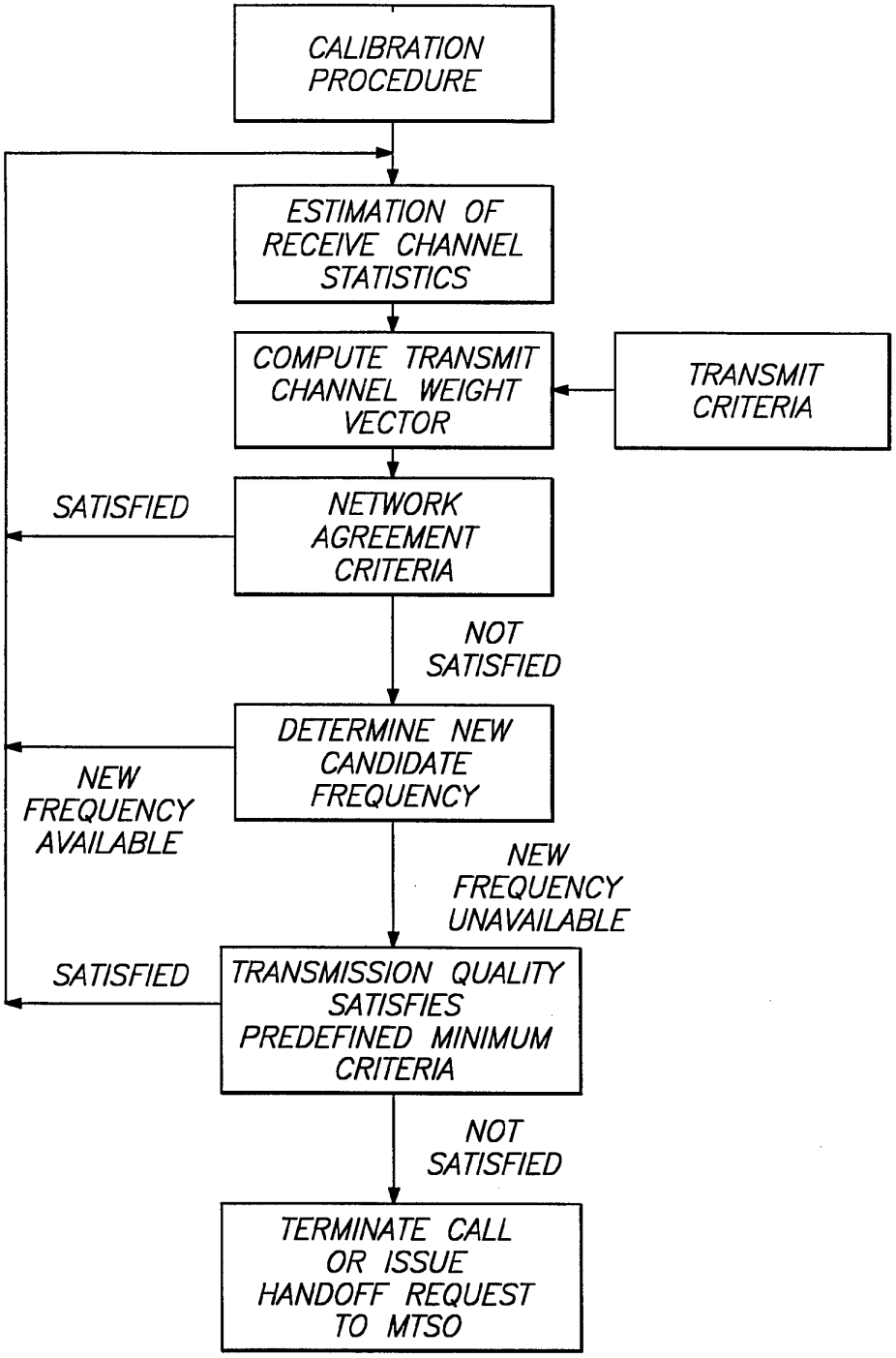
CALIBRATION PROCEDURE
ESTIMATION OF RECEIVE CHANNEL STATISTICS
COMPUTE TRANSMIT CHANNEL WEIGHT VECTOR
TRANSMIT CRITERIA
SATISFIED
NETWORK AGREEMENT CRITERIA
NOT SATISFIED
DETERMINE NEW CANDIDATE FREQUENCY
NEW FREQUENCY AVAILABLE
NEW FREQUENCY UNAVAILABLE
SATISFIED
TRANSMISSION QUALITY SATISFIES PREDEFINED MINIMUM CRITERIA
NOT SATISFIED
TERMINATE CALL OR ISSUE HANDOFF REQUEST TO MTSO

FIG. 5

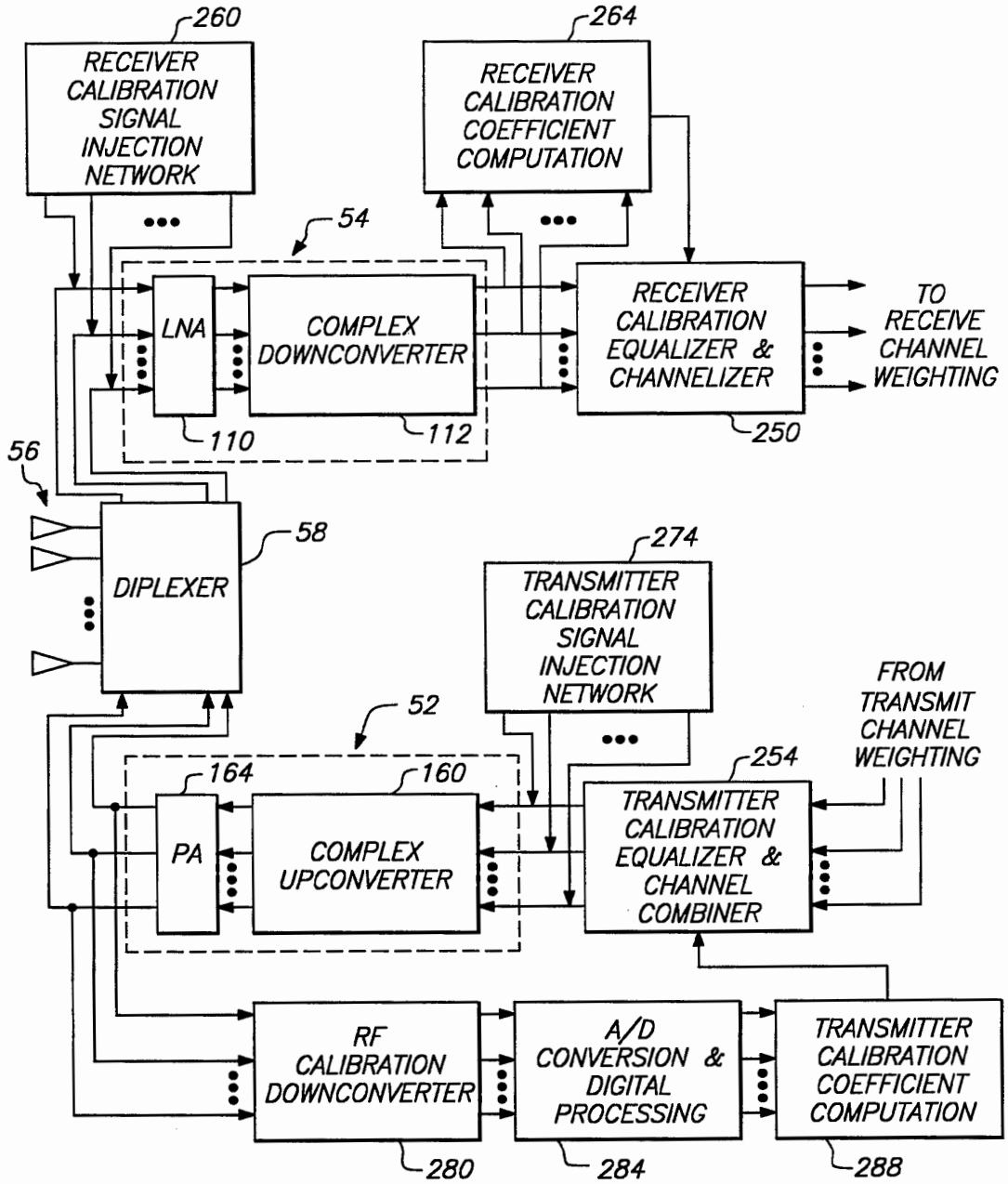
260
RECEIVER CALIBRATION SIGNAL INJECTION NETWORK
264
RECEIVER CALIBRATION COEFFICIENT COMPUTATION
54
LNA
COMPLEX DOWNCONVERTER
RECEIVER CALIBRATION EQUALIZER & CHANNELIZER
TO RECEIVE CHANNEL WEIGHTING
110
112
250
56
DIPLEXER
58
274
TRANSMITTER CALIBRATION SIGNAL INJECTION NETWORK
FROM TRANSMIT CHANNEL WEIGHTING
52
164
160
254
PA
COMPLEX UPCONVERTER
TRANSMITTER CALIBRATION EQUALIZER & CHANNEL COMBINER
RF CALIBRATION DOWNCONVERTER
A/D CONVERSION & DIGITAL PROCESSING
TRANSMITTER CALIBRATION COEFFICIENT COMPUTATION
280
284
288

FIG. 6

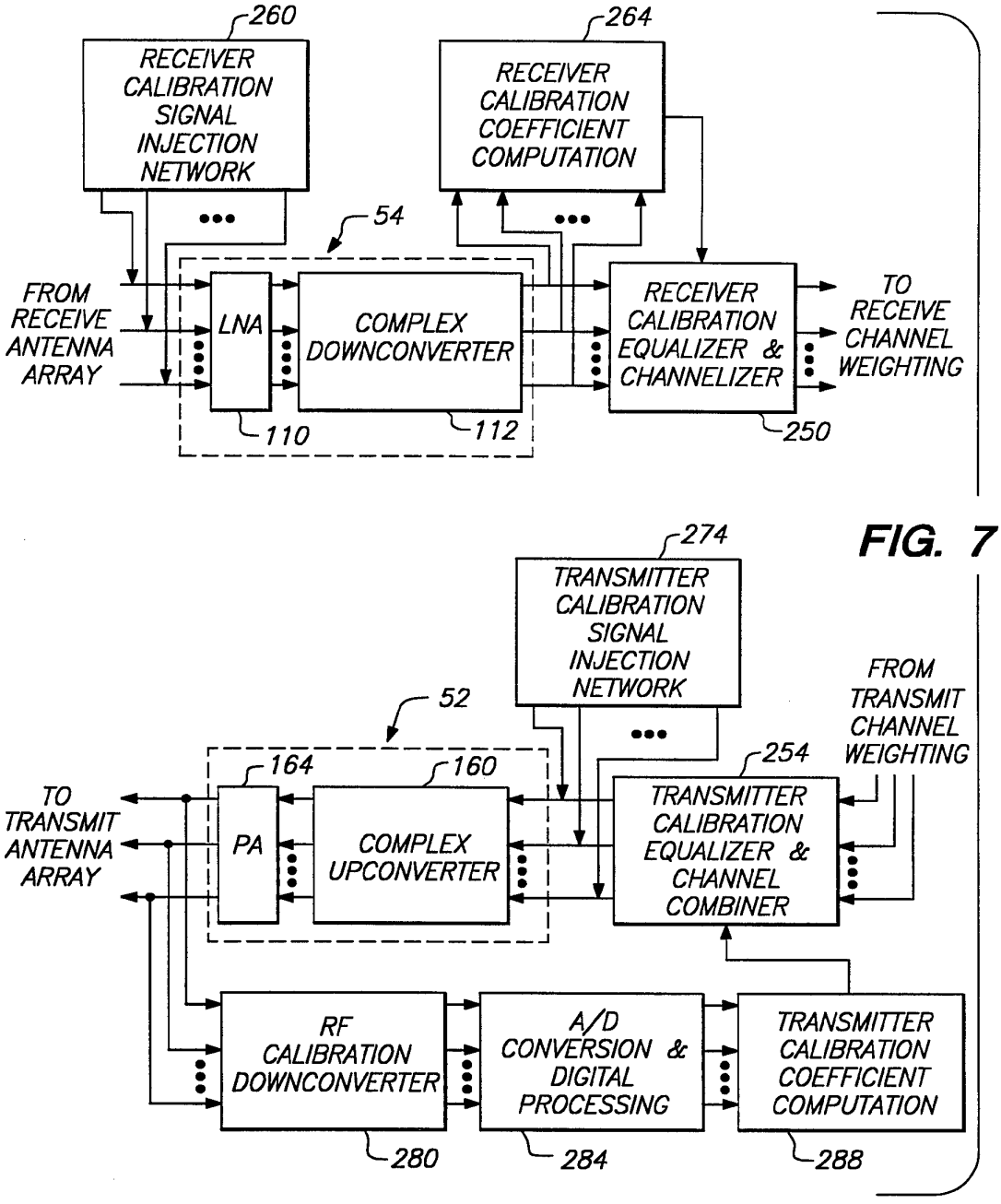
260
RECEIVER CALIBRATION SIGNAL INJECTION NETWORK
264
RECEIVER CALIBRATION COEFFICIENT COMPUTATION
54
FROM RECEIVE ANTENNA ARRAY
LNA
COMPLEX DOWNCONVERTER
RECEIVER CALIBRATION EQUALIZER & CHANNELIZER
TO RECEIVE CHANNEL WEIGHTING
110
112
250
274
TRANSMITTER CALIBRATION SIGNAL INJECTION NETWORK
52
FROM TRANSMIT CHANNEL WEIGHTING
254
164
160
TO TRANSMIT ANTENNA ARRAY
PA
COMPLEX UPCONVERTER
TRANSMITTER CALIBRATION EQUALIZER & CHANNEL COMBINER
RF CALIBRATION DOWNCONVERTER
A/D CONVERSION & DIGITAL PROCESSING
TRANSMITTER CALIBRATION COEFFICIENT COMPUTATION
280
284
288

FIG. 7

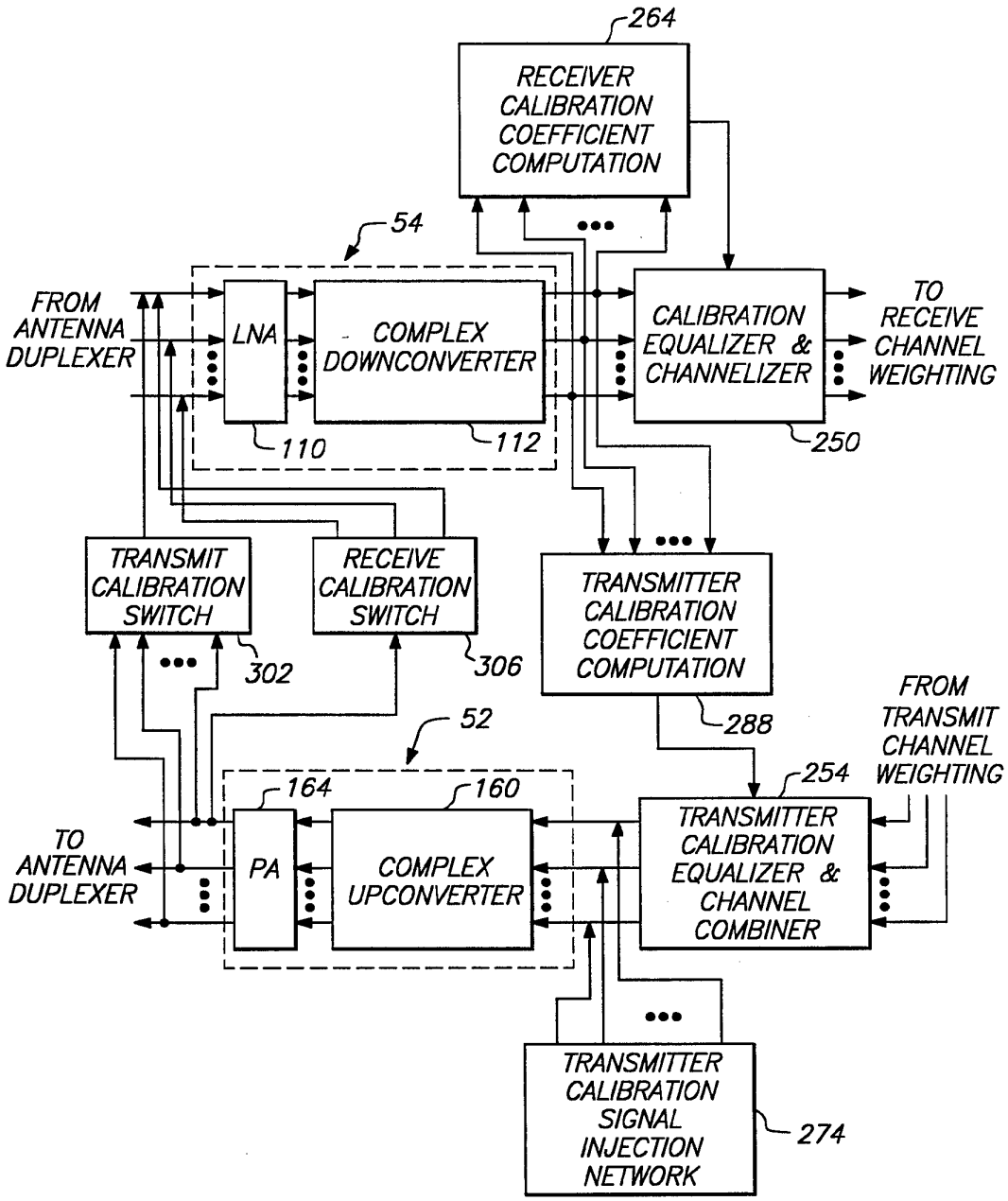
264
RECEIVER CALIBRATION COEFFICIENT COMPUTATION
54
FROM ANTENNA DUPLEXER
LNA
COMPLEX DOWNCONVERTER
CALIBRATION EQUALIZER & CHANNELIZER
TO RECEIVE CHANNEL WEIGHTING
110
112
250
TRANSMIT CALIBRATION SWITCH
RECEIVE CALIBRATION SWITCH
TRANSMITTER CALIBRATION COEFFICIENT COMPUTATION
302
306
288
FROM TRANSMIT CHANNEL WEIGHTING
52
254
164
160
TO ANTENNA DUPLEXER
PA
COMPLEX UPCONVERTER
TRANSMITTER CALIBRATION EQUALIZER & CHANNEL COMBINER
TRANSMITTER CALIBRATION SIGNAL INJECTION NETWORK
274

FIG. 8

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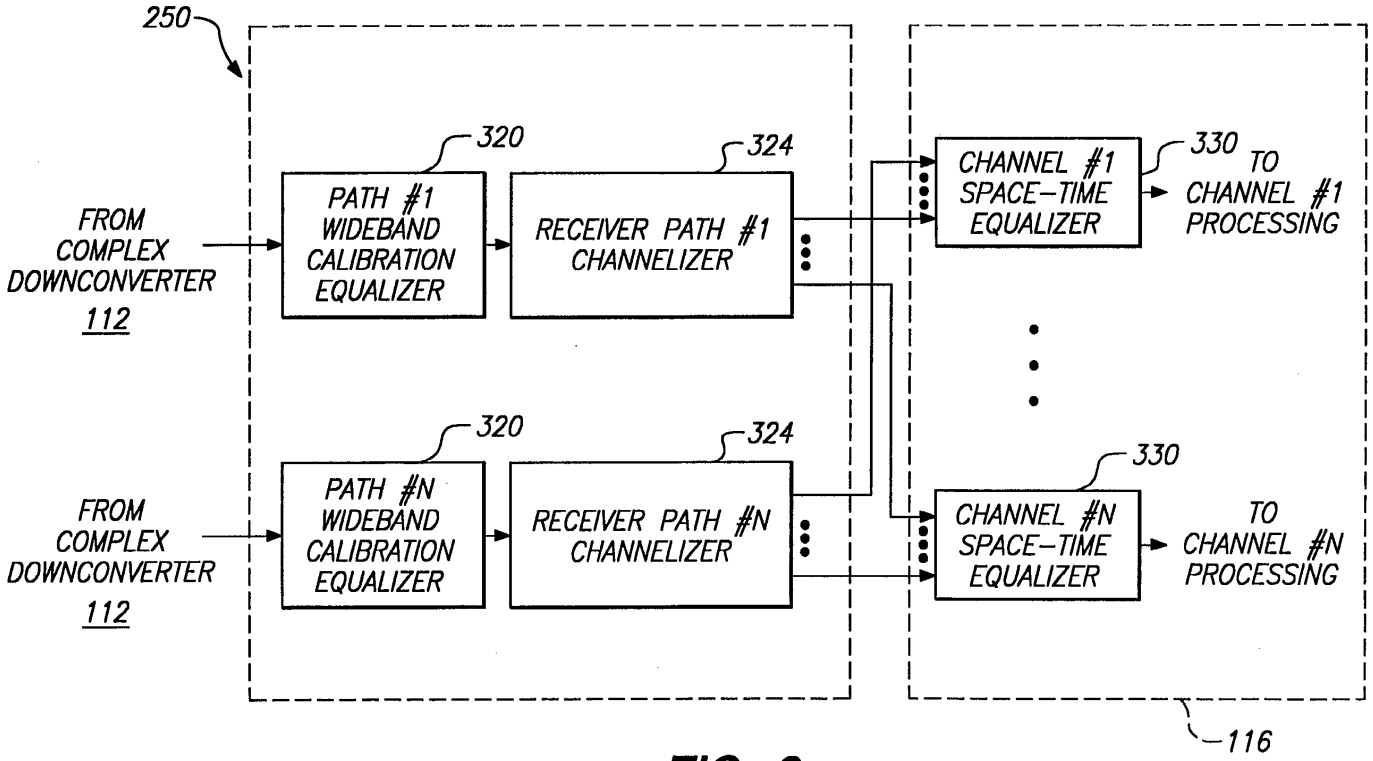

FIG. 9

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

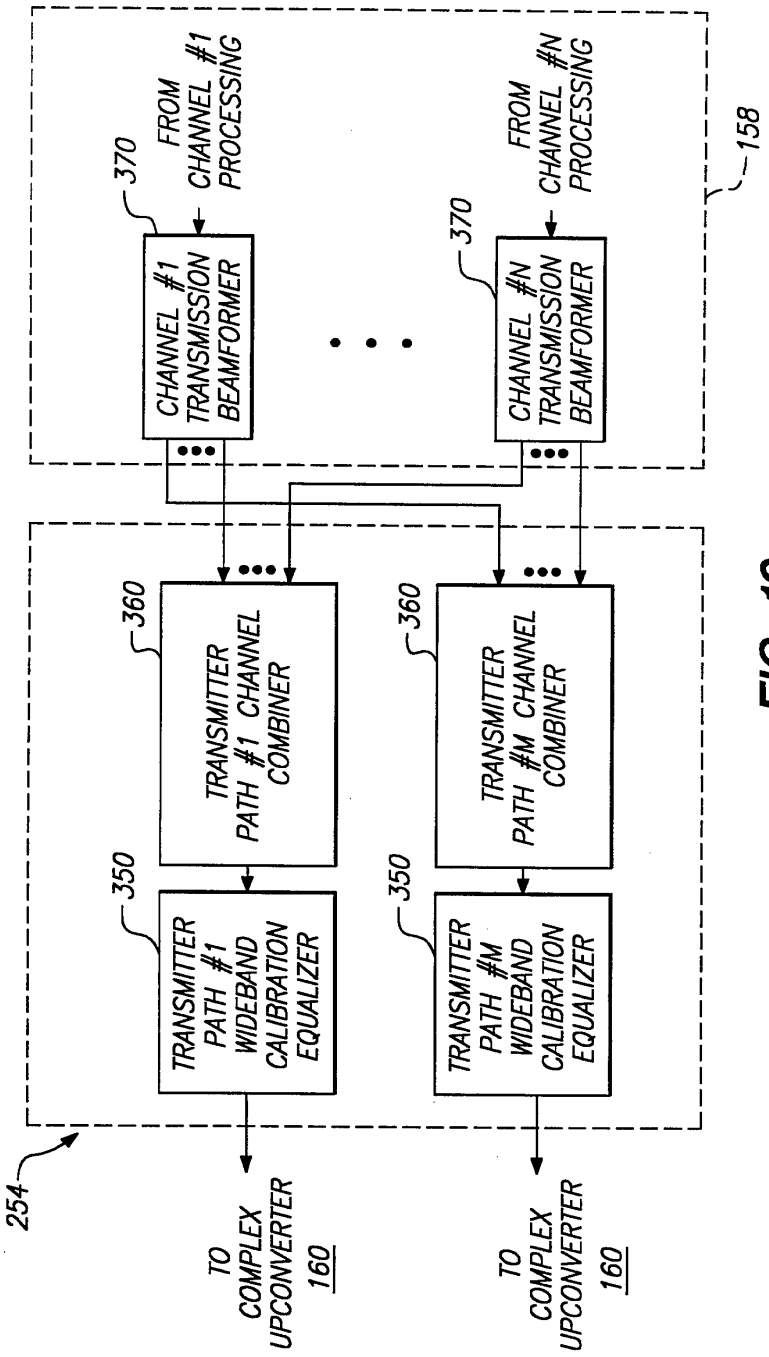

FIG. 10

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148
Exhibit 1002
Page 0732 of 1285

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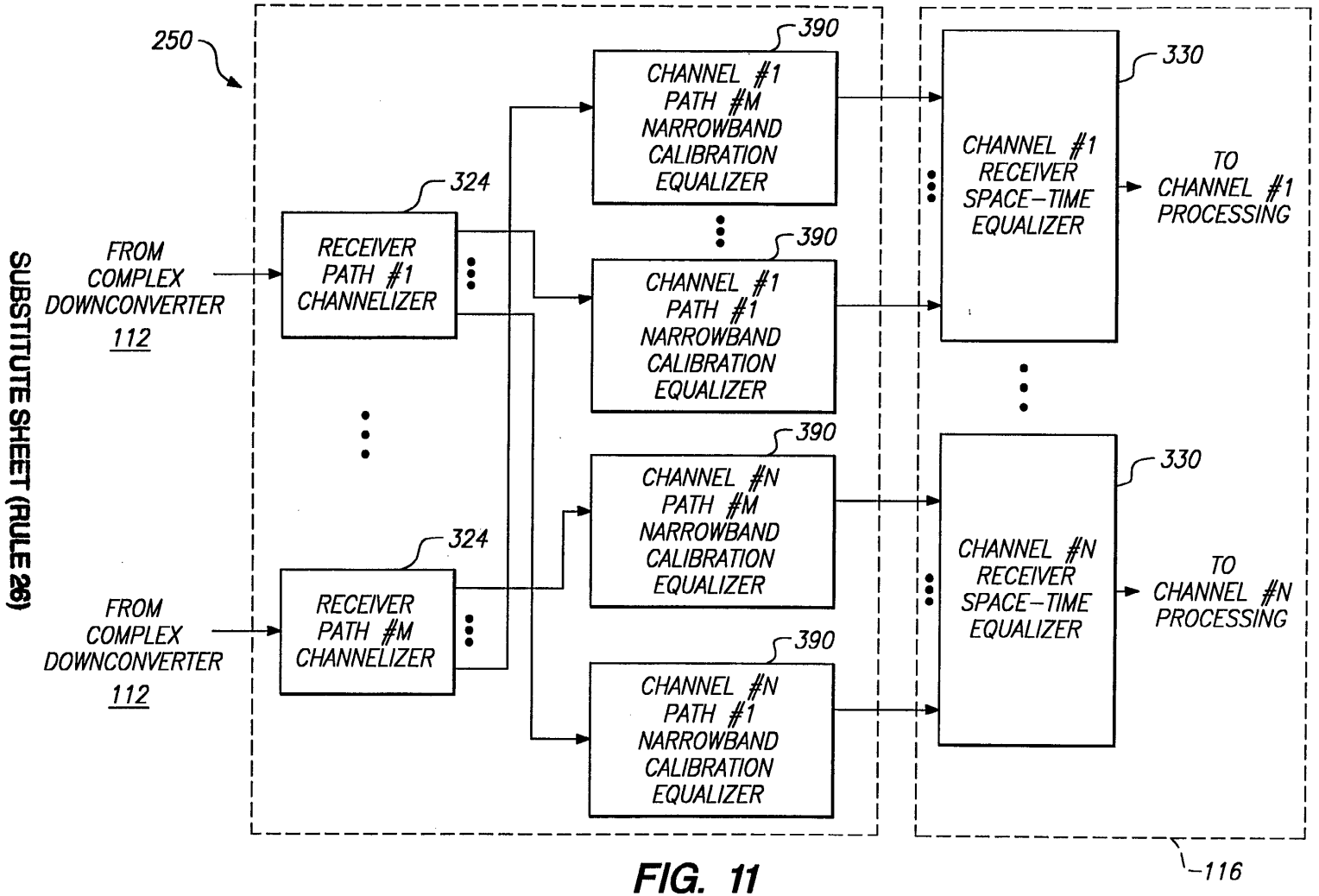

FIG. 11

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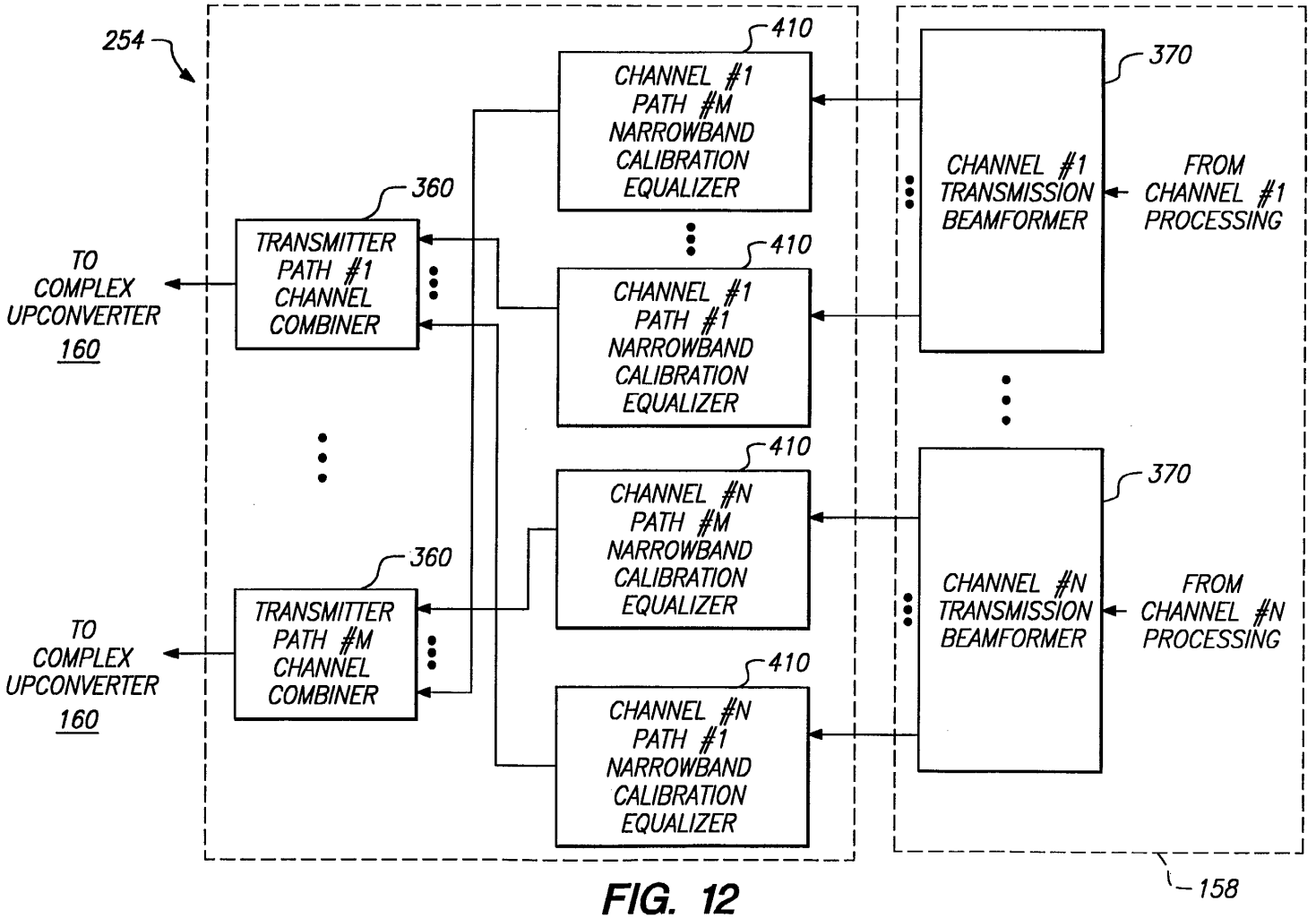

FIG. 12

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

INTERNATIONAL SEARCH REPORT

Inte· ·nal Application No
PCT/US 96/08564

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01Q25/00 H01Q3/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO,A,94 09568 (E-SYSTEMS) 28 April 1994 see abstract; figures 1-6	1,6,11, 22,28
Y	EP,A,0 142 293 (NEC) 22 May 1985 see abstract; claims 1-4; figure 2	1,6,11, 22,28
A	GB,A,2 266 998 (MOTOROLA) 17 November 1993 see abstract; claims 1-17; figures 2-4	1-30
A	US,A,5 260 968 (GARDNER ET AL.) 9 November 1993 see abstract; figures 6-8	1-30
A	EP,A,0 595 247 (ATR OPTICAL AND RADIO COMMUNICATIONS RESEARCH) 4 May 1994 see abstract; figures 1,9,10	1-30

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
13 September 1996	26.09.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Angrabeit, F

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Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
PCT/US 96/08564

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9409568	28-04-94	AU-A-	5354294	09-05-94
EP-A-0142293	22-05-85	JP-B-	6100647	12-12-94
		JP-A-	60088375	18-05-85
		US-A-	4577193	18-03-86
GB-A-2266998	17-11-93	US-A-	5274844	28-12-93
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		FR-A-	2691842	03-12-93
		IT-B-	1262364	19-06-96
		JP-A-	6053727	25-02-94
US-A-5260968	09-11-93	NONE		
EP-A-0595247	04-05-94	JP-A-	6196921	15-07-94
		US-A-	5396256	07-03-95

Form PCT/ISA/210 (patent family annex) (July 1992)

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

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(51) International Patent Classification 6 : H04B 7/26 — A1

(11) International Publication Number: WO 97/33388

(43) International Publication Date: 12 September 1997 (12.09.97)

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(22) International Filing Date: 7 March 1997 (07.03.97)

(30) Priority Data:
08/611,600 8 March 1996 (08.03.96) US

(71) Applicant: WATKINS-JOHNSON COMPANY [US/US]; 3333 Hillview Avenue, Palo Alto, CA 94304-1223 (US).

(72) Inventors: RALEIGH, Gregory, G.; 539 San Juan Avenue, El Granada, CA 94018 (US). POLLACK, Michael, A.; 20196 Northbrook Square, Cupertino, CA 95014 (US).

(74) Agents: TEST, Aldo, J. et al.; Flehr Hohbach Test Albritton & Herbert L.L.P., Suite 3400, 4 Embarcadero Center, San Francisco, CA 94111-4187 (US).

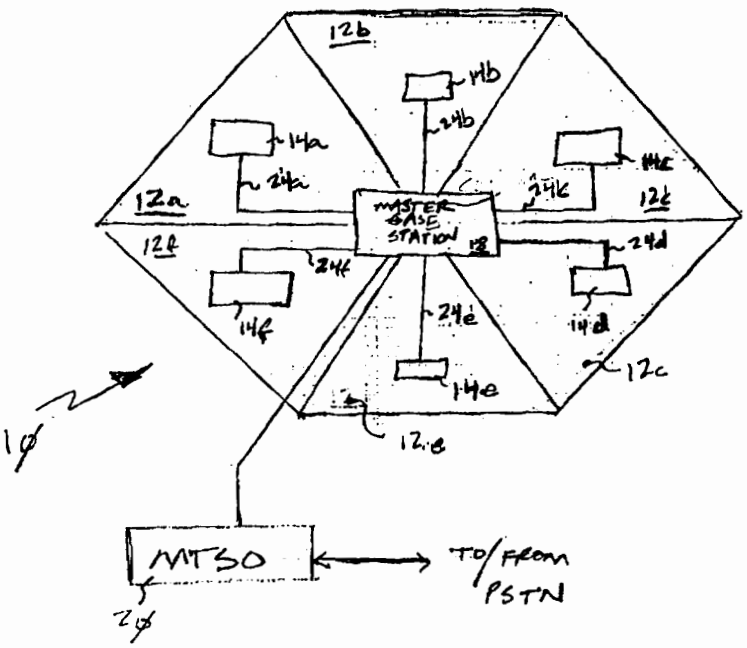
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: DISTRIBUTED MICROCELLULAR COMMUNICATIONS SYSTEM

(57) Abstract

A distributed microcellular communications system (Fig. 1B) comprises a plurality of subcells (12a-12f) arranged within a macrocell(s) (10). The system (Fig. 1B) includes remote site station(s) (14a-14f), each transmits and receives information signals over an assigned set of channels within an associated subcell, includes a wideband RF receiver network wherein signals received from mobile units are converted into reverse link digital information signals. Each remote site station also includes a transceiver for transmitting the reverse link signals to a central base station (18) and receiving forward link digital information signals from the central base station (18). The central base station transmits central signals and forward link digital information signals and processes call information contained in the forward and reverse link digital information signals (24a-24f) within particular cellular protocols. Alternatively, the remote site station (14) further includes a channelizer for channel selection and a set of demodulators.



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Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

DISTRIBUTED MICROCELLULAR COMMUNICATIONS SYSTEM

Field

The present invention relates generally to cellular telephone systems. More particularly, the invention relates to a distributed digital communication system incorporated within cellular telephone systems.

Background

Cellular telephone networks facilitate mobile communications within a given geographic area by dividing the area into contiguous regions, or "cells". Each cell includes a base station, located at a "cell-site", which services mobile units within the cell. In a typical cellular network, each cell is assigned a set of transmission frequencies with which to operate. The sets of frequencies assigned to adjacent cells are different, and are typically not repeated except when cells are separated by a sufficiently large "re-use" interval that interference problems are unlikely to occur.

Within densely populated metropolitan regions, the overall capacity of a cellular system may be limited by the relatively small set of frequencies assigned to each cell. Furthermore, the coverage of the single cell-site base station within each cell may be compromised by fading and blockage of the transmitted signal energy.

One conventional approach to increasing system call carrying capacity involves dividing each original cell within the system into a set of smaller cells. This entails servicing each of the new smaller cells using a conventional base station. Usually, the number of channels at each base station remain unchanged, since the original frequency plan can be applied to a new, scaled-down, cell layout. It follows that since the area covered by each new cell is smaller than the original cell, and since

Exhibit 1002
Page 0739 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

the number of channels available to each base station is the same, the overall system capacity (channels per unit area) is increased. Although this reduction in cell size advantageously increases capacity, an increase in the frequency of calls handed-off between base stations will generally occur. That is, each mobile user may be expected to cross the boundaries of the smaller cells more frequently than the boundaries between the larger original cells.

The handoff process involves switching the mobile unit from its existing operating frequency to a new frequency allocated to the cell into which the mobile unit is entering. The handoff process is generally coordinated by a mobile telephone switching office (MTSO) linked to each cell-site base station, and is initiated by the MTSO in response to a request from a base station. A base station requests hand-off when the quality of a communication channel assigned to a given mobile unit drops below a predefined threshold, which typically indicates that the mobile unit is nearing a boundary between cells. The MTSO queries the base stations surrounding the base station requesting the handoff in order to ascertain which, if any, of the surrounding base stations are capable of establishing communication of suitable quality on a new channel. If the MTSO determines that one of the surrounding base stations is so capable, the MTSO orders the mobile unit to switch to the new channel and passes control to the selected base station. In this way each channel within the cellular system may be used at a plurality of cell sites simultaneously, and the system is thereby enabled to support a number of users exceeding the number of system channels.

Nonetheless, since the capacity of each MTSO to control handoffs and otherwise process calls is limited, efforts have been made to augment system capacity without subdividing existing cells and deploying additional base station equipment. For example, in U.S. Pat. No. 4,932,049 to Lee, there is described a cellular telephone system in which a distributed antenna set configuration is deployed within each cell as a means of dividing the cell into a plurality of zones or sectors. Each cell contains a plurality of antenna sets arranged and configured in an effort to limit propagation of signals substantially to one of the plurality of zones or sectors within the boundaries of the cells. The zones or sectors are substantially less in area than the area of the cell.

In Lee's system all of the antenna sets are coupled to a common set of transmitters and receivers, and a zone switch is used to selectively couple the transmitters and receivers to the antenna units. This selective coupling is coordinated

by a controller located at the cell site, which causes the antenna best able to service a mobile unit on a given channel to be connected to the transmitter/receiver pair associated with the channel. Switching among antenna sets is facilitated by polling the signal strength received at each antenna set from a given mobile unit, and connecting/disconnecting antenna sets accordingly.

In distributed antenna systems of the type described by Lee, transmission on the frequency assigned to a mobile unit is confined to the zone or sector within which is present the mobile unit. As the mobile unit moves into a new zone or sector within the cell, a "soft" handoff occurs whereby transmission to the mobile unit is switched from the antenna set within the previous zone to the antenna set within the new zone -during which time mobile unit continues to transmit/receive on the same frequency channel. Frequency handoff (i.e., "hard" handoff) occurs only upon the mobile unit moving to another cell.

The number of zones or sectors into which each cell serviced by a distributed antenna system may be divided is not limited, but increasing the number of zones does not increase the capacity of the "distributed" cell unless additional channels are assigned to the cell. The assignment of additional channels to a distributed cell is made possible by confining transmission from each antenna set to the surrounding zone, thereby decreasing the frequency re-use interval between neighboring distributed cells. Nonetheless, distributed antenna systems contemplate only soft hand-offs between the zones of a cell, and hence all of the zones must share all of the channels within the channel set assigned to the cell. It follows that increasing the number of zones within each cell does not increase capacity unless the number of channels assigned to the cell is correspondingly increased.

It would thus be desirable to provide a system in which capacity is increased by dividing each cell into a plurality of subcells in a manner not requiring that each subcell use an identical set of channels. The implementation of "intra-cell" hard handoffs between the subcells would make possible such assignment of different channel sets to the subcells. Accordingly, capacity could be increased commensurate with the extent of subdivision of the cell into subcells.

Cellular systems using distributed antenna arrangements, such as the system proposed by Lee, generally require that the antenna set within each zone captures the entire cellular spectrum. The entire analog cellular spectrum, after perhaps being

Exhibit 1002
Page 0741 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

shifted to a different analog frequency band, is transmitted over a wideband communications link to the base station. Another exemplary distributed antenna system of this type is described in European Patent Application No. 0 391 597, published on October 10, 1990, submitted by AT&T. In the AT&T system, optical fiber analog carriers are analog modulated with mobile radio channels throughout the optical fiber network connecting the distributed antenna sites. The entire available set of channels, i.e., the entire allocated cellular band, is transmitted from the base station to the distributed antenna sites, and vice-versa.

Quite obviously, transmission of the entire analog cellular band over a wideband communications link to each distributed antenna site is inefficient in view of the fact that only a fraction of the band is radiated at each antenna site. Likewise, it is inefficient to transmit the entire received spectrum from each remote antenna site back to the base station, given that only a fraction of the frequency channels received at each remote antenna site carry valid information. A system disposed in which only frequency channels actually used by a remote antenna site or the like are transmitted to and from the base station could be expected to advantageously reduce the communication link bandwidth required for such information exchange.

Utilization of an analog communication link may also increase the likelihood that weak signals within the analog cellular spectrum received at each antenna may become lost in the noise of the communications link during propagation to the base station via the analog link. For example, in a cell coverage area of any appreciable radius it is expected that the signals received from mobile units in different parts of the cell may differ in power by as much as 50-75 dB. In the case of optical fiber communication links between the base station and antenna sites, dynamic range is often limited in practice to less than 40 dB. Accordingly, if two signals separated in power by somewhat more than 40 dB (e.g., by 60 dB) were transmitted from the antenna site to the base station over the optical fiber communication link, the base station would be incapable of recovering the weaker signal. While certain analog communication links realized using media other than optical fiber may afford a larger dynamic range, the use of analog techniques to transfer a wideband analog spectrum between to and from remote antenna sites is likely to introduce some form of signal distortion.

Exhibit 1002
Page 0742 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

It would thus be desirable to obviate the need for use of such wideband links by providing a system in which a reduced volume of data is required to pass between the base station and each remote site.

Summary

The present invention provides increased capacity within a cellular communication system by deployment of a network of remote site stations within each standard cell (hereinafter "macrocell") of the cellular system, each remote site station comprising one or more sets of antennas and associated transceiver units. This increased capacity is advantageously achieved without increasing the number of base stations in communication with the cellular system's mobile telephone switching office (MTSO), thereby obviating the need for expensive retrofit or modification of the MTSO when the microcellular system is deployed in a conventional cellular system.

In an exemplary embodiment of the invention, there is provided a distributed microcellular communication system in which a plurality of subcells are arranged within each macrocell. The distributed microcellular communications system includes one or more remote site stations, each of which has a remote radio transceiver for transmitting and receiving information signals over an assigned set of communications channels within an associated subcell.

Each remote site station includes a wideband RF receiver network within which information signals received from mobile units are converted into reverse link digital information signals. Also disposed within each remote site station is a remote communications link transceiver for transmitting the reverse link digital information signals over a communications link to the central base station. The remote communications link transceiver also receives forward link digital information signals from the central base station.

The central base station includes a central communications link transceiver for receiving the reverse link digital information signals delivered over the communications link, and for transmitting the forward link digital information signals. The central base station is disposed to process the call information inherent within the forward and reverse link digital information signals in the manner required by the standard protocols of an existing cellular system (e.g., AMPS, GSM), or as required

Exhibit 1002
Page 0743 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

by other protocols which may be developed in the future. Conventional circuitry is employed to interface the central base station to the MTSO.

In another exemplary embodiment of the present invention, the remote site station further includes a channelizer for selecting a set of the reverse link digital information signals corresponding to the assigned set of communications channels. In the general case the selected set of channels will include far fewer channels than the number of channels in the set assigned to the macrocell in which the remote site station is located. The remote site station may still further include a bank of demodulators for demodulating the set of reverse link digital information signals to produce a set of demodulated reverse link digital information signals. The remote communications link transceiver then transmits the channelized or demodulated reverse link digital information signals to the central base station.

According to another aspect of the invention, a bank of digital modulators are deployed within the transmit section of the remote site station. Each digital modulator is disposed to modulate a carrier signal using one of the forward link digital information signals, with the result that the bank of digital modulators produces a plurality of modulated carrier signals. A bank of digital transmitters are provided for translating the frequency of each of the plurality of modulated carrier signals in order that each said signal occupies an assigned frequency channel within a digitized forward link transmission spectrum. The digitized forward link transmission spectrum is converted to an analog spectrum, upconverted to the RF cellular transmission band, and transmitted from the remote site station.

In accordance with yet another aspect of the invention, reverse link transmissions may be gathered from each mobile unit by a plurality of the remote site stations in order to minimized the likelihood that calls are dropped during the hand-off process. In conventional cellular systems, when a mobile unit approaches a boundary between cells the separation from the base station with which it is communicating approaches a maximum. Consequently, the forward and reverse communication links to and from the mobile unit tend to deteriorate due to increased path loss. In order to prevent deterioration of the communication links to such extent that the call is dropped, it becomes necessary for the cellular system to quickly decide whether a hand-off should occur. The decision of when to undertake the hand-off process is further complicated by the presence of slow fading in the communications channel.

Exhibit 1002
Page 0744 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Such slow fading can corrupt hand-off decisions by affecting the mobile unit signal strength received at hand-off candidate base stations during the polling process.

The present invention overcomes many of the difficulties associated with hard hand-off between remote site stations by monitoring reverse link transmission from a given mobile unit at a plurality of surrounding base stations. Since this allows the strongest signals to be selected for processing, degradation of the quality of the reverse link is minimized when the mobile unit becomes proximate a cell boundary. Similarly, the channel statistics accumulated by the plurality of remote site stations monitoring reverse link transmission from a given mobile unit may be of assistance in selecting the base station(s) in the best position to effectively transmit on the forward link to the mobile unit. By employing macrodiversity techniques to monitor the communication links between a plurality of base stations and a given mobile unit, the present invention facilitates improved communication quality and well-informed hand-off decisions.

The architecture of the distributed microcellular communications system of the invention has also been designed to enable diversity reception at each remote site station. By collecting reverse link signals using two or more antennas deployed at a remote antenna site, Rayleigh (i.e., fast) fading of the communication channel may be mitigated. The signals received from the two or more remote site station antennas are combined at the remote site station, and the resultant diversity signal transmitted back to the central site station over the communications link. This use of diversity combination techniques at the remote site station allows the communication link to the central base station to be of a bandwidth no greater than that required to carry the information to and from a single remote site station antenna element. In contrast, conventional distributed antenna systems typically require that the reverse link signals received by multiple remote antennas each be conveyed to a central base station over the same communication link. Hence, the complexity and expense of conventional systems is increased due to the need for deployment of a wideband communication link between the base station and the multiple remote antennas.

Exhibit 1002
Page 0745 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Brief Description of the Drawings

Additional objects and features of the invention will be more readily apparent from the following detailed description and appended claims when taken in conjunction with the drawings, in which:

Figure 1A is an illustrative representation of a plurality of standard hexagonal macrocells.

Figure 1B is an illustrative representation of a standard hexagonal macrocell which has been partitioned into a set of six subcells.

Figure 1C is an illustrative representation of a standard hexagonal macrocell which has been partitioned into a set of six subcells.

Figure 2 provides a block diagrammatic representation of a central base station linked to a remote site station disposed within a subcell.

Figure 3 shows a block diagram of an exemplary digital filter network suitable for incorporation within the channelizers deployed in the central base station and/or remote site stations.

Figure 4 provides a block diagrammatic representation of an embodiment of the communication system of the invention in which a channelizing function is performed at each remote site station.

Figure 5 depicts the manner in which a remote site station may be configured for diversity reception by including therein more than one separate receive path.

Figure 6 is a block diagram of a distributed communication system of the invention in which both channelizing and modulation/demodulation functions are performed at each remote site station.

Figure 7 is a block diagram of a distributed communication system which is similar to the system of Figure 6, but which is different in that a beamformer function is performed at the remote site station.

Figure 8 is a flowchart representative of an exemplary manner in which calls are processed in accordance with the invention.

Detailed Description

The present invention is designed to be deployed either (i) within an existing cellular system as a means of economically increasing capacity, or (ii) as an independent high-capacity cellular system. The present invention provides a

Exhibit 1002
Page 0746 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

distributed microcellular communications system disposed to operate transparently with respect to the mobile telephone switching office (MTSO) of the existing cellular system. That is, the distributed microcellular system is configured so as to be capable of deployment in the absence of significant modification to the existing cellular system, and is designed to allow increased capacity to be achieved without requiring that enhancements be made to the processing resources elsewhere within the system. As is described below, the inventive microcellular system contemplates that each cell serviced by an existing cellular base station (hereinafter referred to as a "macrocell") be partitioned into a plurality of subcells.

Referring to Figure 1A, there is shown a set of four contiguous macrocells la-ld of a cellular communication system of the present invention. Each macrocell la-ld is partitioned into nine subcells, each of which is assigned one of three channel sets {A,B,C}. In particular, three contiguous subcells within each macrocell la-l are assigned to operate using channel set A, three subcells are assigned for operation upon channel set B, and the remaining three subcells operate upon channel set C. As is described hereinafter, hard hand-off techniques are used to transfer calls between the subcells as a means of facilitating utilization of the three different channel sets {A,B,C} within each subcell. This advantageously allows each macrocell to be partitioned into a large number of subcells while maintaining a high degree of frequency re-use.

Referring now to Figure lB, an illustrative representation is provided of a standard hexagonal macrocell 10 which has been partitioned into a set of six subcells 12a-12f. Since each remote site station 14a-14f is of substantially identical design, only remote site station 14a will be described in greater detail. The six subcells 12a-12f are respectively serviced by a set of six remote site stations 14a-14f, each of which are coupled to a central base station 18. Except to the extent otherwise indicated, central base station 18 comprises a conventional cellular base station disposed to be controlled by an MTSO 20. Base station 18 is linked to the MTSO 20 through a conventional interface line 22 (e.g., a T1 line, line of sight microwave link, or optical fiber). Similarly, the MTSO 20 is interfaced in the usual way with the public switched telephone network (PSTN).

It should be understood that the number of subcells into which each macrocell is divided will be dependent upon the desired overall system capacity. In this regard

Exhibit 1002
Page 0747 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Figure 1C depicts a macrocell 10' which has been partitioned into a set of four subcells 12a'-12d', in which are respectively located remote site stations 14a'-14d'. In Figure 1C, primed reference numerals are used to identify system elements performing substantially similar functions as those elements identified with corresponding reference numerals in Figure 1B. In accordance with the invention, increased capacity to service mobile users is achieved through deployment of a network of remote site stations 14a-14f (Figure 1B) within each macrocell. The increased capacity afforded by the present invention arises from a reduction in the frequency re-use interval between macrocells. By employing hard hand-offs between the groups of subcells within each macrocell operative using different channel sets (see Figure 1A), any desired frequency re-use interval can be achieved.

The remote site stations 14a-14f collectively provide radio coverage to the geographic area encompassed by the macrocell 10, and are respectively in communication with the central base station 18 through communication links 24a-24f. The communication links 24a-24f may be realized using a variety of interconnection technologies (e.g., coaxial cable, optical fiber, or line-of-sight optical or microwave links). As is described in further detail below, in alternate embodiments of the invention the remote site stations 14a-14f are configured to perform signal processing functions of varying degrees of complexity. Accordingly, the nature and quantity of the information carried by the communication links 24a-24f between the central base station 18 and the remote site stations 14a-14f will be dependent upon the particular signal processing operations executed at the remote site stations 14a-14f. Although in the exemplary embodiment of Figure 1B the central base station 18 does not provide radio coverage to a subcell associated therewith, it is understood that the base station may readily be configured with a radio transceiver capable of radio communication with mobile units (not shown) within a surrounding subcell. That is, in alternate embodiments the central base station 18 may be implemented to function as a remote site station while continuing to provide central control to the other remote site stations.

In a first preferred embodiment, each remote site station 14a-14f is equipped with a wideband transceiver network operative to frequency translate cellular band signals to and from digitized intermediate frequency (IF) representations of the cellular band signals. This results in digitized, baseband representations of the cellular "forward" and "reverse" links being carried by the communication links 24a-24f.

Exhibit 1002
Page 0748 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Specifically, the digitized forward link signals are transmitted from the central base station 18 to the remote site stations 14a-14f via the communication links 24a-24f, and the digitized reverse link signals propagate in the opposite direction.

In a second preferred embodiment, each remote site station 14a-14f is provided with a channelizer designed to select only certain of the digitized reverse link signals among the complete set of frequency channels within the cellular band. The particular set of channels selected by the channelizer is specified by the central base station, and includes all channels currently in use within the subcell in which the channelizer is located. In addition, the channelizer may select channels in use in other subcells in order to support other processing or monitoring functions within the central base station. The channel signals selected by the multiplexer are multiplexed into a frequency band smaller than that occupied by the entire digitized reverse link cellular frequency band, and the multiplexed signals transmitted over the communication links 24a-24f to the central base station 18. On the forward link, the central base station 18 multiplexes the signals for the selected channels onto the communication links 24a-24f. Each remote site station 14a-14f demultiplexes the signals sent by the central base station, and passes the demultiplexed signals through a wideband upconversion network for transmission from the remote site station's antenna.

In a third preferred embodiment, each remote site station 14a-14f is not only provided with a channelizer, but also includes a set of demodulators for demodulating each selected reverse link signal to a "digital voice" (e.g., DS0) signal. This allows the digital voice signals to be multiplexed into a narrow frequency band, thereby further reducing the requisite bandwidth of the communication links 24a-24f from each remote site station to the central base station 18. On the forward link, the central base station 18 provides to each remote site station 14a-14f the set of digital voice signals to be broadcast over the channels assigned to the remote site station. After demultiplexing the digital voice signals provided thereto, each remote site station uses the demultiplexed digital voice signals to modulate baseband carrier signals. The modulated baseband carrier signals are then passed through a wideband upconversion network, and transmitted by the remote site station's antenna.

In order to facilitate proper system operation, certain control information is exchanged between the remote site stations and the central base station. This control information is multiplexed with the digital voice signals on the communication links

Exhibit 1002
Page 0749 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

24a-24f. For example, the central base station may multiplex, with the forward link digital voice signals, control information informing a remote site station which RF transmit frequency corresponds to each digital voice signal sent to the remote site station. This facilitates dynamic allocation of frequencies among the subcells comprising a given macrocell, and may be employed to reduce the likelihood of co-channel interference between adjacent subcells. Other features and advantages of the present invention are discussed below in connection with the detailed description provided for each preferred embodiment.

The present invention is disposed to be implemented within any of a number of different types of cellular telephone systems. These include existing analog Advanced Mobile Phone Service (AMPS) cellular networks, as well as various digital multiple access systems: frequency division multiple access (FDMA), code division multiple access (CDMA), and time division multiple access (TDMA). Although the present invention is capable of being incorporated within these and other cellular telephone systems, the exemplary embodiment described hereinafter is directed toward an AMPS implementation consisting of frequency modulated (FM) channels at kHz spacings. Those skilled in the art aware that each AMPS frequency channel can be subdivided into three TDMA digital channels, or alternately that a combination of AMPS and TDMA channels could be supported.

Turning now to Figure 2, a block diagrammatic representation is provided of one embodiment of the central base station 18 and remote site station 14a. Again, each remote site station 14a-14f is assumed to be of substantially identical design, and hence the configuration of only one remote site station 14a is depicted in detail.

The remote site station 14a is seen to include TX and RX antennas 32 and 34 for transmitting and receiving signals (e.g., within the AMPS forward and reverse channel spectra) to and from mobile units (not shown). Those skilled in the art will realized that the TX and RX antennas 32 and 34 could be replaced with a single antenna and diplexer. The signals received by RX antenna 34 are applied to frequency downconverter (DNX) 36. The DNX 36 is operative to translate the reverse channel spectrum of the received signals to a lower frequency range. For example, in an exemplary implementation an AMPS system A reverse channel spectrum from 825-835 MHz containing 333 channels is translated by DNX 36 to the 0.5-10.5 MHz band.

Exhibit 1002
Page 0750 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

The downconverted reverse channel spectrum is sampled by analog to digital converter (ADC) 40 at a sampling rate of at least twice the highest frequency contained within the output of the DNX 36. In the exemplary AMPS System A implementation, this corresponds to a theoretical minimum sampling rate 21 MHz, and in practice 25 MHz might be used. The digital samples (e.g., 12-bits per sample) produced by ADC 40 are provided in the form of a stream of digital words over a parallel data bus to a reverse channel communication link transmitter 44.

The reverse channel communication link transmitter 44 includes a parallel to serial converter operative to convert the 12-bit samples received from the ADC 40 to a serial bit stream. In the exemplary embodiment the serial bit stream from the serial to parallel converter is provided to a reverse link line 48a of communications link 24a. When the reverse link line 48a is realized as an optical fiber, the reverse channel communication link transmitter 44 includes a laser transmitter disposed to be modulated by the data from the ADC 40. The modulated optical output from the laser transmitter is applied to the reverse link line 48a for transmission to a first reverse channel communication link receiver 52a within the central base station 18. The central base station 18 further includes reverse channel communication link receivers 52b-52f for receiving similar modulated optical signals from the remote site stations 14b-14f, respectively.

The remote site station further includes a forward channel communication link receiver 54 operative to receive a forward channel digital data stream from a forward link line 56a of communication link 24a. When the forward link line 56a is realized as an optical fiber, the receiver 54 comprises an electro-optical detection network such as a photo-diode detector. Likewise, a first forward channel communication link transmitter 58a comprised of a laser transmitter may be used to transmit the forward channel digital data stream over the forward link line 56a. Other forward channel communication link transmitters 58b-58f likewise transmit forward channel digital data streams to the remote site stations 14b-14f, respectively.

It is understood that the forward and reverse link lines 48a and 56a of communication link 24a may comprise transmission media other than optical fibers (e.g., coaxial cable), or may be replaced by microwave or other point-to-point links. Accordingly, the specific implementation of the forward and reverse channel

Exhibit 1002
Page 0751 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

communication link transmitters/receivers will be dependent upon the medium of the communications link 24a.

Within the remote site station 14a, the communication link receiver 54 converts the serial data stream received over the communications link 24a to 12-bit digital data samples, and relays the forward channel digital data stream to a digital to analog converter (DAC) 60. In an exemplary embodiment, the forward channel digital data stream comprises a digitized, intermediate frequency (e.g., 0.5 MHz to 10.5 MHz) replica of the forward channel spectrum to be transmitted by the TX antenna 32. The corresponding intermediate frequency analog waveform produced by the DAC 60 is applied to a wideband frequency upconverter (UPX) 64, and is therein translated to the forward channel spectrum of a particular cellular system. For the specific case of AMPS System A, the forward channel spectrum transmitted by TX antenna 32 extends from 870 MHz to 880 MHz.

Referring again to Figure 2, the digitized frequency-downconverted replica of the reverse channel spectrum is provided at an exemplary bit rate of 300 Mbps (12 Msps x 12 bits/sample) by the communication link receiver 52a to a first base station channelizer 66a. The central base station 18 further includes channelizers 66b-66f similarly coupled to the communication link receivers 52b-52f, respectively. The channelizer 66a functions to extract the individual signals corresponding to each frequency channel present within the digitized, frequency-downconverted reverse link channel spectrum provided by the communication link receiver 52a. The extracted frequency channels are divided into separate, parallel data streams, each of which possesses a signal bandwidth consistent with the channel spacing of a particular cellular system (e.g., 30 kHz for AMPS). The sample rate of each extracted channel is sufficiently high to satisfy the Nyquist criterion (e.g., 260 ksps for a 30 kHz AMPS channel), but will typically be appreciably less than the sample rate into the first base station channelizer 66a (e.g., 25 Msps).

The first base station channelizer 66a may be programmed by the base station controller 70 to extract a specific set of desired channels present within the digitized spectrum provided by the communications link receiver 52a. For example, in a specific implementation a frequency re-use factor of four is employed between macrocells, thereby resulting in approximately one-fourth of the available frequency channels being assigned to each macrocell (e.g., 78 channels per macrocell).

Exhibit 1002
Page 0752 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Assuming each macrocell to be divided into four subcells, it follows that each subcell is allocated nineteen voice channels and a shared control channel. This results in each base station channelizer 66 being programmed to extract the twenty channels assigned to the subcell from the digitized reverse-channel spectrum received from the associated remote site station.

It is observed that in the specific embodiment of Figure 2, the RX beamformer 90 associated with a given subcell is provided with information from the channelizers associated with subcells adjacent to the given subcell. This requires that each channelizer extract from the reverse-channel spectrum provided thereto not only the channels assigned to its associated subcell, but also the channels assigned to the subcells adjacent its associated subcell. In alternate embodiments, each channelizer may be programmed to extract all of the channels assigned to a particular macrocell.

Each channelizer 66a-66f includes a separate digital filter network for extracting, from the high-speed (e.g., 25 Msps) data stream provided thereto, each of the channels specified by the base station controller 20. The passband of each digital filter network is commensurate with the channel spacing of the reverse link channels (e.g., 30 kHz), and spans one of the frequency channels within the frequency-downconverted reverse link spectrum (e.g., 0.5-10.5 MHz).

Turning now to Figure 3, a block diagram is provided of an exemplary digital filter network 72 suitable for incorporation within the channelizers 66a-66f. The filter network includes a digital bandpass filter 74 of 30 kHz bandwidth, preferably realized as a finite impulse response (FIR) filter. The filtered output from the digital bandpass filter 74 is then applied to a multiplier 76, within which it is frequency translated to digital baseband via multiplication with a complex sinusoid. The complex sinusoid, which is of a frequency equal to the center frequency of the bandpass filter 74, is generated by a numerically-controlled oscillator 78. As is indicated by Figure 3, a decimator 80 is operative to reduce the exemplary 25 Msps rate of the baseband output of the multiplier 76. The decimator 80 reduces this rate by a predetermined factor, the value (e.g., 300)of which is selected to prevent aliasing by causing the resultant output sample rate (e.g., 83.3 KHz) to become equal to at least twice the exemplary 30 kHz channel bandwidth.

Referring again to Figure 2, a set of N receive (RX) beamformers are each disposed to receive the channelized data stream produced by each channelizer 66a-66f

Exhibit 1002
Page 0753 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

corresponding to one of N reverse-link voice channels. Additionally, RX beamformer 92 is provided the data stream from each channelizer 66a-66f corresponding to an RECC channel, which is a time-division multiplexed control channel. Each RX beamformer 90 is designed to enhance signal quality by using various techniques to weight and combine the data streams from different remote site stations corresponding to the same reverse link channel. For example, in a simplified implementation only the data stream of the highest signal quality is weighted by a factor of " 1", and every other stream is nulled by weighting with a factor of "0". When so configured, the RX beamformer essentially operates to implement "selection diversity" combining selecting only a single reverse-link data stream.

Within each RX beamformer 90 there exist a plurality of signal quality determination circuits, each of which measures the quality of the reverse-link data streams received from one of the channelizers 66a-66f. The results of the signal quality measurements determine the manner in which the streams of the same frequency from the channelizers 66a-66f are weighted by each RX beamformer 90. In the exemplary embodiment the stream of highest quality is weighted by a factor of "1", and the remaining streams of the same frequency by a factor "0". This results in the combination of the weighted reverse-link data streams output by each beamformer 90 comprising the single stream from the subcell best suited to sustain communication with a given mobile unit.

Received signal quality may be determined based upon, for example, total signal power received within the frequency channel in question. However, because the signal power measurement cannot distinguish between power from the desired user and power from interfering users, this technique is best suited for systems within which the expected interfering signal power is expected to be low within all subcells of a macrocell. Other techniques for determining received signal quality can be used as well, including those which rely upon calculation of the SINR at each of the inputs to the beamformer.

The RX beamformers 90 may also be designed such that more than a single reverse-link data stream is assigned a non-zero weighting factor. This results in the output of each RX beamformer comprising a weighted combination of the reverse-link data streams provided thereto. In this implementation the signal weighting and combining performed by the RX beamformers 90 may be viewed as constituting

Exhibit 1002
Page 0754 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

adaptive receive antenna beamforming among the remote site stations. Accordingly, receive beamforming techniques designed for use with co-located antenna arrays may be utilized in the present embodiment to optimize signal reception by the set of remote site stations within a given macrocell. As a specific example, for systems including slow-moving mobile units it is expected that use of a "constant modulus" adaptive beamforming algorithm within the RX beamformers 80 will enhance signal reception in a multipath signal environment.

It has been found that both fast (Rayleigh) fading, as well as slow (log-normal) fading, occurring at remote sites separated by relatively large distances (e.g., > 300 yards) tends to be largely uncorrelated. Thus, combining signals from remote sites in the RX beamformers 90 is expected to be able to diminish the severity of both fast and slow fading. In the preferred embodiment each RX beamformer 90 adapts its signal weighting at a rate which is responsive to fast fading signal components. This may advantageously reduce or even eliminate the need for employment of microdiversity reception techniques at each remote site station as a means of mitigating fast fading.

The inclusion of the RX beamformers 90 within the central base station 18 also aids the base station controller 70 in determining when to request that the MTSO initiate handoff of a mobile unit to another macrocell. By monitoring the signal quality (e.g., average received power level, signal-to-noise ratio, fading depth and/or duration, etc.) of the composite frequency modulated carrier from one RX beamformer 90, the base station controller 70 is able to determine whether the remote site stations are collectively able to produce a useable signal on the frequency channel corresponding to that beamformer. This is so because each remote site station is provided the opportunity to contribute to the composite frequency modulated carrier produced by each RX beamformer 90. It follows that if the quality of the composite signal drops below a minimum quality threshold for a given period of time, the base station controller 70 may conclude that the remote site stations are unable to, either singly or in combination, produce acceptable signal quality using the signal energy received from a given mobile unit. Hence, there is no need to separately "poll" each remote site station prior to requesting the MTSO to initiate handoff of the mobile unit to another macrocell.

The composite frequency modulated carriers from the set of RX beamformers 90 and 92 are provided to a corresponding set of reverse-link demodulators 96 and 97,

Exhibit 1002
Page 0755 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

respectively. Each demodulator 96 extracts a digitized waveform, similar in format to a DSO voice signal, from the composite frequency modulated carrier provided thereto. In an exemplary AMPS embodiment, the demodulated digital waveform produced by each demodulator 96 is comprised of an approximately 8 kHz stream of 8-bit samples. The 8-bit samples primarily comprise digitized voice information but, during periods in which signaling is taking place over the reverse voice channel, the 8-bit samples will also comprise digital signal information. In the exemplary embodiment each reverse voice channel digital message is preceded by a predefined (e.g., 37-bit) dotting sequence, thereby allowing each demodulator 96 to discriminate between voice channel data and digital messages. Digital messages are provided to the controller 70. The demodulated digital waveforms from the demodulator 96 are multiplexed by a T1 multiplexer 100 into a serial bit stream, which is forwarded to the MTSO 20 over a communications link to the MTSO from the base station. The demodulator 97 similarly demodulates the output produced by RX beamformer 92, and provides the resultant baseband control waveform (e.g.,RECC) to a control channel transceiver 98.

The control channel transceiver 98 is disposed to process the forward (FOCC) and reverse (RECC) control channels in accordance with the applicable cellular standard. In particular, the control channel transceiver 98 interprets RECC messages received from remote sites 14a-14f during the processing of calls in the manner contemplated by the applicable cellular standard. The control channel transceiver 98 also generates control messages transmitted by the remote sites 14a-14f over the FOCC.

Referring again to Figure 2, the signal transmission path within the central base station 18 originates at interface demultiplexer 104. The demultiplexer 104 separates the input serial data stream received from the input line 22 into payload (e.g., voice traffic), and control data streams. The control data stream is provided to the controller 70, and the channelized payload data streams are provided to a set of forward link modulators 108. In addition, forward link control channel data is furnished by the control channel transceiver 98 to a control channel modulator 110. Since only digital information is typically transmitted over the control channel, the control channel modulator 110 will generally be adapted to perform only digital modulation.

Exhibit 1002
Page 0756 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

The forward link modulators 108 are disposed to operate in one of two modes. In particular, the modulators 108 modulate a baseband carrier signal using either: (i) voice information from demultiplexer 104, or (ii) control information from controller 70. In an exemplary embodiment the modulators 108 utilize well-known digital signal processing (DSP) techniques to perform this frequency modulation. During the brief periods of message data transmission over a voice channel (e.g., within an AMPS system) is required, the modulation format will temporarily change to binary frequency-shift keyed (FSK) from the nominal FM modulation format. Since each modulator 108 produces an output having a bandwidth approximately equivalent to a single forward link channel (e.g., 30 kHz within AMPS), the sample rate at the output of each modulator 108 is selected to be at least twice the channel bandwidth in order to prevent aliasing (e.g., at least 83.3 ksps).

As is indicated by Figure 2, the modulated output from each modulator 108 and 110 is provided to a corresponding forward link digital transmitter 114. Each digital transmitter 114 upconverts the frequency of one of the modulated sample streams to a unique frequency slot within a predetermined intermediate frequency (IF) band. In an exemplary embodiment, each digital transmitter 114 produces an IF output at a unique frequency within an IF band extending from 0.5 to 10.5 MHz. Since in an exemplary embodiment the sample rate into each digital transmitter 114 is approximately 83.3 ksps, interpolation is required to increase the sample rate to at least 21 MHz in order to avoid aliasing of the IF outputs, with 25 MHZ being chosen for the exemplary embodiment. As discussed below, within the remote site station 14a these IF signals are converted to analog signals and further upconverted to signals within the forward link cellular band. Accordingly, the base station controller 70 is able to allocate the modulated output of each modulator 108 and 110 to a desired channel by specifying the IF frequency slots (e.g., between 0.5 and 10.5 MHz) into which the modulated outputs are to be placed by the digital transmitters 114.

In a simplified embodiment, each TX beamformer 118 functions to select only certain IF frequencies for transmission to each remote site station. That is, the selected frequencies are weighted with a "1", and frequencies not selected for transmission to a given remote site station are weighted with a "0". However, in alternate embodiments the TX beamformers may be configured to cause a given frequency to be transmitted by more than one remote site station. This situation may arise when, for example, the

Exhibit 1002
Page 0757 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

mobile unit assigned to a particular frequency is proximate the boundary between a pair of subcells.

Each TX beamformer 118 provides a 12-bit wide stream of data at an exemplary 25 MHz rate to one of the forward channel communication link transmitters 58a-58f. Each transmitter 58a-58f is coupled to a corresponding remote site station 14a-14f through a forward link line 56a-56f. When the forward link lines 56a-45f are realized as optical fibers, the forward channel communication link transmitters 58a-58f include laser transmitters disposed to be modulated by a serial data stream derived from the 12-bit wide data streams from the TX beamformers 118. The modulated optical output from each laser transmitter is applied to the forward link lines 56a-56f for transmission to the forward channel communication link receivers respectively disposed within the remote site stations 14a-14f.

The base station controller 70 is disposed to regulate communication with the MTSO 20, as well as to oversee operation of each remote site station 14 within the macrocell 10. In this regard the base station controller 70 is designed to "appear" to the MTSO 20 as would the controller of a standard macrocell base station, thereby obviating the need for any significant modification of data processing resources within the MTSO 20. Although appearing in the usual way to the MTSO 20, the base station controller 70 is capable of performing functions (e.g., frequency channel hand-offs between mobile units) heretofore not executed within macrocell base stations. That is, the base station controller 70 is designed to effect a variety of control functions in a manner transparent to the MTSO 20. As a consequence, system capacity may be increased without undertaking expensive augmentation or modification of existing MTSO signal processing resources.

As mentioned above, one function performed by the base station controller 70 relates to the monitoring of the quality of the composite frequency modulated carrier from one or more RX beamformers 90. By monitoring this parameter, the base station controller 70 is able to determine whether the remote site stations are collectively able to produce a useable signal. Hence, the base station controller is able to decide when to request that the MTSO initiate handoff of the mobile unit to another macrocell based on the signal quality produced by the RX beamformers 90.

The base station controller 70 is also configured to orchestrate call hand-offs between the remote site stations 14a-14f so that as the mobile unit moves throughout

Exhibit 1002
Page 0758 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

the macrocell 10 the most suitable remote site station transmits to mobile unit The determination as to which of the remote site stations 14a-14f is the most suitable for transmitting to the mobile unit is made by monitoring the quality of the signal received from the mobile unit at the remote site stations. This function is integrated within each RX beamformer 90, 92 which assesses the quality of the signal on each of its inputs in order to determine the weighting to be applied to those inputs. This information produced in the RX beamformers can be used to determine the weights which are applied within the TX beamformers.

For example, if one of the RX beamformers determines that remote site station 14a is receiving a very strong signal from the mobile unit on its corresponding frequency channel, then the RX beamformer will weight the input from channelizer 66a more heavily than the input from the other channelizers. Knowing that remote site station 14a is receiving a better quality signal from the mobile unit than any of the other remote site stations the controlled chooses to transmit to that mobile unit from remote site station 14a. The TX beamformer 118 connected to communications link interface 58a applies a weight of "1" to its input from the digital transmitter 114 which corresponds the frequency channel in use by the mobile unit. The other TX beamformers weight their inputs from that particular digital transmitter with a "0", effectively preventing transmission from remote site stations 14b-14f.

It is expected that the remote site station 14a-14f identified by the base station controller 70 to be best able of communicating with a given mobile unit may occasionally not be in communication with the mobile unit. Moreover, the identified remote site station 14a-14f may not be currently assigned for operation upon the frequency channel to which the mobile unit is tuned according to the network frequency planning scheme. Under these circumstances, the base station controller 70 may initiate a "hard" hand-off procedure during which the mobile unit is commanded by the remote site station 14a-14f currently in communication therewith to tune to a new frequency channel assigned to the new remote site station 14a-14f. In the case of a TDMA system, the mobile unit is also assigned to given time slot on the new frequency channel.

In the exemplary embodiment these hand-off instructions are provided to the mobile unit via a FOVC data message. The base station controller 70 then (i) commands the appropriate digital transmitter to become tuned to a new frequency, (ii)

Exhibit 1002
Page 0759 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

adjusts one or more TX beamformers as necessary to initiate change transmission from the remote site stations involved in the hand-off, and (iii) informs the MTSO at a convenient later time that a hard hand-off has occurred. It is observed that hard hand-offs between remote site stations 14a-14f are effected in a manner which is transparent to the MTSO. In this way cell capacity may be advantageously increased by deploying additional remote site stations in a manner which does not strain existing processing capability of the MTSO.

As is indicated by Figure 2, the control channel transceiver 98 receives demodulated reverse control channel data (RECC) from the demodulator 96. This information is forwarded to the base station controller 70, which interprets the RECC data in order to process calls in accordance with standard protocols. In addition, the base station controller 70 also generates the control messages transmitted over each forward control channel (FOCC) by the remote site stations 14a-14f. In the exemplary embodiment each remote site station 14a-14f simultaneously transmits identical FOCC information, thereby ensuring that the FOCC information is uniformly disseminated throughout the entire macrocell 10.

Referring to Figure 4, a block diagrammatic representation is provided of an embodiment of the communication system of the invention in which a channelizing function is performed at the remote site station. In Figures 2 and 4, like reference numerals are used to identify those processing elements performing substantially similar functions. Within the remote site station 14a, signals received by the RX antenna 34 are applied to frequency downconverter (DNX) 36 and translated to a lower frequency range. The downconverted reverse channel spectrum is sampled by analog to digital converter (ADC) 40 at a sampling rate of at least twice the highest frequency produced by the DNX 36.

The sampled, frequency-downconverted reverse channel spectrum produced by the ADC 40 is provided to a remote site channelizer 120. The remote site channelizer 120 functions to extract the digitized channel information corresponding to receive channels present within the reverse link cellular frequency spectrum. The extracted channel information is divided into separate, parallel data streams, each of which occupies a bandwidth consistent with the channel spacing of a particular cellular system (e.g., 30 kHz for AMPS). The parallel data streams corresponding to the channels extracted by the channelizer 120 are combined by a remote site multiplexer

Exhibit 1002
Page 0760 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

128 into a serial data stream, which is provided to the reverse channel communication link transmitter 44.

In the exemplary embodiment the remote site channelizer 120 is instructed by the remote site controller 124 as to which channels are to be extracted from the received reverse channel spectrum. The channels specified by the remote site controller 124 for extraction by the channelizer 120 will nearly always include at least those channels assigned to mobile units in the subcell of the remote site station. Additionally, in order to facilitate RX beamforming at the central base station the extracted channels may also comprise those assigned to mobile units in surrounding subcells. Finally, the extracted channels may also correspond to those under evaluation for hand-off either to another macrocell, or to the remote site station within an adjacent subcell.

As is shown in Figure 5, the remote site station 14a may be configured for diversity reception by including therein one or more separate receive paths. In particular, the remote site station 14a may optionally include a second RX antenna 34a, a second DNX 36a, a second ADC 40a and a second remote site channelizer 120a. The outputs of the remote site channelizers 120 and 120a are combined using conventional techniques within a diversity combiner 130, and the resultant set of parallel data streams provided to the multiplexer 128. The remote site configuration of Figure 5 enables "microdiversity" reception over the subcell covered by the remote site station 14a without the necessity of separate transmission, to the central base station, of the reverse link spectrum received by different remote site antennas.

While Figure 5 shows a remote site implementation capable of performing conventional microdiversity using a pair a receive antennas, the concept can be extended to the combination of signals captured by an antenna array with 3 or more antennas. For each additional antenna, by using sophisticated signal processing techniques, a improvement in received signal quality can be realized. The advantage of implementing remote site antenna combining therefore becomes even more dramatic since, if the antenna combining were to be performed at a central site, that would necessitate relaying M (where M is the number of remote site receive antennas) copies of the reverse link spectrum to the central site over the communications link connecting the central site to the remote site station.

Exhibit 1002
Page 0761 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Referring again to Figure 4, a remote site station demultiplexer 134 is disposed to divide the serial TDM data stream produced by the forward communication link receiver 54 into a set of parallel data streams provided to a bank of digital transmitters 114. Each digital transmitter 114 is assigned to one of the frequency channels in use by the remote site station 14a, and the output of each is combined within a digital adder 136 and forwarded to the DAC 60. Distribution of frequency channels among the digital transmitters 114 is effected by the digital transmitter bank 114 pursuant to instructions from the remote site controller 124. The demultiplexer routes channel frequency information, contained within a predetermined time slot on the data stream produced by the forward channel communications link, to the remote site controller 124. The remote site controller then sets each digital transmitter in accordance with the received channel frequency information.

In alternate implementations, information may be transmitted asynchronously over the communication link 56a in a packet format rather than in a time-division multiplexed mode. In this case the data stream from the remote forward channel communication link receiver 54 would be distributed by the demultiplexer 134 on the basis of packet header information or the like, rather than on the basis of time slot assignment.

Directing attention now to the implementation of the central base station 18 of Figure 4, the serial data stream produced by each reverse channel communication link receiver 52a is provided to a different reverse channel demultiplexer 140a-140f. Each demultiplexer 140a-140f demultiplexes the TDM serial stream comprised of the channels assigned to, or monitored by, a corresponding remote site station 14a-14f. The parallel data streams from each demultiplexer 140a-140f are then routed to a bank of RX beamformers 144, each of which is associated with a single receive frequency channel. That is, the data stream from each demultiplexer 140a-140f corresponding to the same frequency receive channel is provided to the same one of the RX beamformers 144.

Each RX beamformer 144 may be designed to use any of a number of available beamforming techniques to weight and combine the data streams provided thereto by the demultiplexers 140a-140f. For example, in a preferred embodiment the complex value of a weighting factor applied to each incident data stream is varied in response

Exhibit 1002
Page 0762 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

to changes in the propagation environment for the frequency channel corresponding to the data stream.

In a "selection diversity" approach to beamforming, the output of each RX beamformer 144 is simply equivalent to the one of its inputs having the highest signal quality. That is, the highest quality input is weighted by a factor of "1", and the remaining inputs weighted by a factor of "0". Alternately, within each RX beamformer inputs provided thereto are weighted commensurately with signal quality and combined. In this implementation, the inputs to the Rx beamformer are adjusted in phase so as to add constructively upon such combination.

The utilization of the RX beamformer 144, is expected to facilitate the process of determining when the controller 70 should issue a hand-off request to the MTSO 20. Specifically, once the signal quality associated with the output of a particular RX beamformer 144 falls below a minimum quality threshold for some predefined interval, the controller 70 initiates the hand-off process with the MTSO 20. Since each RX beamformer 144 is provided with input from each remote site station 14a-14f disposed to receive the frequency channel of interest, there exists no need to separately "poll" each remote site station with respect to signal quality prior to proceeding with the hand-off determination process.

As is indicated by Figure 4, the central base station 18 includes a set of TX beamformers 150a-150f respectively associated with the remote site stations 14a-14f. Each TX beamformer 150a-150f receives modulated baseband signal inputs from N of the modulators 110, where N is the number of frequency channels currently being used by the associated remote site station 14a-14f. Each TX beamformer 150a-150f is also provided with an input corresponding to forward control channel (FOCC) by the control channel transceiver 98. In an exemplary embodiment, information relating to characteristics of the receive channels in use by a given remote site station 14a-14f is used to adjust a weighting vector of the TX beamformer 150a-150f associated with the given station 14a-14f.

The weighting vector of each TX beamformer 150a-150f is adjusted with sufficient regularity to ensure that the average signal power delivered to mobile units within the vicinity of each remote site station 14a-14f exceeds a predefined minimum value. It is observed that it will not typically be desirable to simply maximize the power received by each mobile unit by, for example, transmitting maximum power on

Exhibit 1002
Page 0763 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

every frequency channel from each remote site station 14a-14f. If this approach is taken, there will likely be many instances in which the majority of the signal power received by a mobile unit on an assigned frequency channel is supplied by a given remote site station 14a-14f, but wherein the other remote site stations nonetheless also continue to transmit on the assigned channel. This leads to unnecessary interference power being transmitted to mobile units in other cells also operating upon the assigned frequency channel.

Accordingly, in the preferred embodiment the weighting vectors of the TX beamformers 150a-150f are adjusted such that only those remote site stations 14a-14f disposed to substantially improve the quality of the signal received by a given mobile unit on an assigned frequency channel are allowed to transmit on the assigned channel. It is expected that this will result in one, or perhaps two or three, remote site stations 14a-14f being allowed to transmit upon an assigned frequency channel at any given time. In the case of the forward control channel (FOCC), the weighting vectors of the TX beamformers 150a-150f will generally be set such that each remote site station 14a-14f broadcasts the FOCC with equal strength.

Each beamformer 158a-150f respectively produces N (where N is the number of modulators 110 which are actively producing outputs) parallel data streams consisting of 12 bit samples Each of the N data streams is a weighted baseband modulated channel signal. The parallel data streams destined for each of the remote site stations 14a-14f are multiplexed, along with control information from the controller 70 in one of the associated multiplexers 158a-158f. The multiplexers 158a-158f may be programmed to forego incorporating the data on channels which have been weighted by "O" in the TX beamformers 150a-150f. The resultant serial bit streams are then respectively transmitted by the forward channel communication link transmitters 58a-58f to the remote site stations 14a-14f.

Figure 6 is a block diagram of a distributed communication system in which modulation/demodulation functions, in addition to a channelizing function, are performed at the remote site station. In Figures 4-6, like reference numerals are used to identify those processing elements performing substantially similar functions. Within the remote site station 14a, signals received by the RX antennas 34 applied to frequency downconverter (DNX) 36 and translated to a lower frequency range. The

Exhibit 1002
Page 0764 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

downconverted reverse channel spectrum is sampled by the ADC 40, and the resultant sampled spectrum provided to the remote site channelizers 120.

The 12-bit data samples corresponding to the channels extracted by the channelizer 120 are each provided to a remote site demodulator 180. In the exemplary AMPS embodiment, the demodulated digital waveform produced by each demodulator 180 is comprised of an approximately 8 kHz stream of 8-bit samples. The 8-bit samples primarily comprise digitized voice information, but also represent digital control messages intermittently transmitted by mobile unit for brief periods over reverse link voice channels. Each demodulator 180 is capable of distinguishing between voice and signaling information, and operates to "tag" the signaling information in order that it may be demultiplexed from the voice information within the central base station 18.

The demodulated data streams produced by the demodulator 180 are multiplexed into a composite data stream within a remote site time divisionmultiplexer (TDM) 190. In addition, the remote site TDM 190 also multiplexes signal quality information from a signal quality receiver 194 into the composite data stream.

The signal quality receiver 194 functions to monitor the signal quality (e.g., average received power, or signal-to-noise ratio, or fading depth or duration) of each demodulated data stream produced by the channelizer 120. Signal quality information for each channel currently assigned to, or being monitored by, the remote site station 14a is provided by the receiver 194a in the form of a serial data stream of predetermined format.

In the exemplary AMPS embodiment, the signal quality receiver 194 also monitors the reverse control channel (RECC). An indication of RECC signal quality is provided to the TDM 190 following each access of the RECC by a mobile unit. In order to facilitate call set-up with each mobile unit, the receiver 194 appends header information to each RECC signal quality measurement. The header information specifies the mobile unit responsible for transmitting the RECC over the time period during which the RECC signal quality measurement was performed. Within the central base station 18, the controller 70 uses these RECC signal quality measurements as a basis for assigning remote site(s) 14a-14f in response to call set-up requests from mobile units.

Exhibit 1002
Page 0765 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

The remote site controller 202 is primarily operative to implement instructions issued by the base station controller 70 relating to calls being handled by the remote site station 14a. Included among these instructions are, for example, the RF channel assigned to each call, and the time slot of the reverse link line 48a within which is inserted the demodulated data comprising each call. The remote site controller 202 effects the first of these instructions by commanding the channelizer 120 to extract the RF channels assigned to the remote site station 14a-14f from the digitized reverse channel spectrum. In like manner the TDM 190 is informed of the time slot of the reverse link line 48a allocated to each call being processed by the remote site station 14a.

Referring now to the implementation of the central base station 18 depicted in Figure 6, each time-division multiplexer (TDM) unit 208a-208f receives the voice data stream corresponding to a particular call from the demultiplexer 104. The demultiplexer 104 operates to distribute the time division multiplexed voice data received from the MTSO among the TDM units 208a-208f in response to control information received from the controller 70. Each TDM unit 208a-208f also receives a stream of forward control channel (FOCC) information, as well as control messages 28 generated by the base station controller 70. As is indicated by Figure 6, the three streams of information provided to each TDM unit 208a-208f are multiplexed into a single forward channel data stream and provided to the corresponding forward channel communication link transmitter 58a-58f.

Referring again to the implementation of the remote site station 14a of Figure 6, the forward channel communication link receiver 54 receives the forward channel data stream from the forward channel communication link transmitter 58a and forwards it to a remote site station TDM demultiplexer 218. The TDM demultiplexer 218 extracts the voice/data information corresponding to each call from the appropriate time slot of the received forward channel data stream. The extracted information is then distributed among a bank of digital modulators 222, which function substantially identically to the modulators 110 (Figure 4). The modulated data from the bank of digital modulators 222 is then processed by the digital transmitters 114, as well as by the remaining elements within transmit section of the remote site station 14a, in the manner described previously with reference to Figure 4.

Exhibit 1002
Page 0766 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Figure 7 is a block diagram of a distributed communication system in which modulation/demodulation, channelizing, and beamformer function are performed at the remote site station. Again, like reference numerals are used to identify those processing elements within Figure 7 performing functions substantially identical to those previously described. Within the remote site station 14a, signals received by the RX antennas 34 and 34a are respectively applied to frequency downconverters (DNX) 36 and 36a and translated to a lower frequency range. The downconverted reverse channel spectra are respectively sampled by the ADCs 40 and 40a, and the resultant sampled spectra provided to the remote site channelizers 120 and 120a.

Each channelizer 120 and 120a produces a data stream corresponding to each received frequency channel, and the pair of data streams for each channel are provided by the channelizers 120 and 120a to an associated one of the remote site beamformers 252. In the exemplary embodiment of Figure 7, each beamformer 252 functions to provide either selection diversity or adaptive beamforming. In the former case the beamformer 252 simply weights the highest quality data stream provided thereto by a factor of "1", and weights any other data streams upon the same frequency channel with a factor of "0". When adaptive beamforming is employed, each data stream is weighted in accordance with signal quality and the weighted streams subsequently combined. Similarly, TX beamforming (e.g. adaptive or selection) may be implemented for forward link transmissions. While two antennas are depicted in Figure 7 for reception and transmission respectively, antenna arrays of more than two elements may be used. Also, those skilled in the art will recognize that a single antenna array may be shared for reception and transmission through the use of diplexers.

Figure 8 is a flowchart representative of an exemplary manner in which calls are processed in accordance with the invention. As is indicated by Figure 8, the RECC is monitored for the presence of page responses or access attempts received from mobile units by one or more remote sites (step 402). Upon detection of a page response or access attempt (step 404), the controller 70 informs the MTSO and is assigned an RF channel thereby (step 406). It is then determined if the remote site station best able to establish communication with the mobile unit has been allocated the RF channel assigned by the MTSO (step 408). If so, the above-described call processing hardware (e.g., channelizers, beamformers, digital transmitters) within the

Exhibit 1002
Page 0767 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

central and remote site stations are configured for operation on the assigned RF channel (step 410). If not, the controller 70 assigns a different RF channel to the mobile unit (step 412) and informs the MTSO of the change in channel frequency (step 414).

Once a suitable RF channel has been assigned and the central and remote site stations have been appropriately configured, call set-up instructions are sent to the mobile unit over the FOCC (step 416). In embodiments in which transmit (TX) beamforming capability is provided, the TX beamformers are adjusted so as to maximize the transmit power to the mobile unit (step 418). Call processing then proceeds in accordance with standard protocols (step 420), during which time the quality of the communication link to the mobile unit is monitored (step 422). This link quality monitoring may be performed within the mobile unit in some cellular standards, in which case signal quality information would be provided by the mobile unit to the remote site station(s) in communication therewith. Alternately, the remote site station(s) are configured with a signal quality receiver 194 (Figures 6 and 7) designed to monitor a given quality metric (e.g., signal to noise ratio). If TX and/or RX beamforming techniques prove incapable of maintaining the requisite signal quality, a hand-off request is issued to the MTSO (step 424) and control of the call is subsequently released in the usual way (step 426).

While the present invention has been described with reference to a few specific embodiments, the description is illustrative of the invention and is not to be construed as limiting the invention. Various modifications may occur to those skilled in the art while remaining within the spirit and scope of the invention as defined by the appended claims.

Exhibit 1002
Page 0768 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

WHAT IS CLAIMED IS:

1. In a cellular system including a plurality of contiguous cells, a distributed microcellular communications systems disposed within one of said cells, said distributed microcellular communications system comprising:

a remote site station having a remote radio transceiver for transmitting and receiving information signals over an assigned set of communications channels within a first subcell within said one of said cells, said remote site station further including:

means for converting information signals received by said transceiver to reverse link digital information signals, and

a remote communications link transceiver for transmitting said reverse link digital information signals and for receiving forward link digital information signals; and

a central base station having a central communications link transceiver for receiving said reverse link digital information signals and for transmitting said forward link digital information signals.

2. The distributed microcellular communications system of claim 1 further including control means for allocating selected ones of a set of communications channels available to said one cell to said assigned set of communications channels.

3. The distributed microcellular communications system of claim 1 wherein said central base station further includes a central radio transceiver for transmitting and receiving information signals within a second subcell of said one cell, said communications system further including control means allocating selected ones of a set of communications channels available to said one cell to said assigned set of communications channels and for allocating remaining ones of said communications channels available to said one cell for use by said central radio transceiver.

4. The distributed microcellular communications system of claim 1 wherein said remote site station further includes channelizer means for selecting ones of said reverse link digital information signals corresponding to said assigned set of communications channels, said remote communications link transceiver transmitting

Exhibit 1002
Page 0769 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

only said ones of said reverse link digital information signals corresponding to said assigned set of communications channels.

5. The distributed microcellular communications system of claim 4 wherein said remote site station further includes a multiplexer, interposed between said channelizer means and said remote communications link transceiver, for multiplexing said ones of said reverse link digital information signals corresponding to said assigned set of communications channels into a reverse link serial data stream.

6. The distributed microcellular communications system of claim 4 wherein said channelizer means further includes means for selecting other ones of said reverse link digital information signals, said remote site station further including a signal quality monitoring module for monitoring signal quality of said communications channels corresponding to said other ones of said reverse link digital information signals.

7. The distributed microcellular communications system of claim 1 wherein said remote site station further includes:

channelizer means for selecting a set of said reverse link digital information signals corresponding to said assigned set of communications channels, and

demodulator means for demodulating said set of said reverse link digital information signals to produce a set of demodulated reverse link digital information signals, said remote communications link transceiver including means for transmitting said demodulated reverse link digital information signals.

8. The distributed microcellular communications system of claim 1 wherein said remote site station further includes:

digital modulator means for modulating a carrier signal with said forward link digital information signals, thereby producing a plurality of modulated carrier signals, and

digital transmitter means for translating frequency of said plurality of modulated carrier signals in order that each of said signals occupy an assigned frequency channel within a digitized forward link transmission spectrum.

Exhibit 1002
Page 0770 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

9. The distributed microcellular communications system of claim 8 wherein digital transmitter means includes:

a plurality of digital transmitters, each of said digital transmitters being disposed to modulate one of said carrier signals with one of said forward link digital information signals,

a digital to analog converter, and

a digital summer interposed between said digital to analog converter and said plurality of digital transmitters.

10. The distributed microcellular communications system of claim 8 wherein said remote site station further includes wideband transmitter means for translating frequency of said modulated carrier signals into a frequency-shifted forward link transmission spectrum.

11. In a cellular system including at least a first cell having a cell-site, a distributed microcellular communications system comprising:

a central base station, located at said cell-site, having a central communications link transmitter for transmitting forward link digital information signals, each of said forward link digital information signals being produced by modulating a digitized carrier signal; and

a remote site station, said remote site station having at least:

a remote communications link receiver for receiving said forward link digital information signals,

means for converting said forward link digital information signals into frequency-shifted forward link analog information signals, and

a remote radio transmitter for transmitting said frequency-shifted forward link analog information signals within a first subcell of said first cell.

12. The distributed microcellular communications system of claim 11 wherein said remote site station further includes:

Exhibit 1002
Page 0771 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

a wideband receiver for receiving reverse link information signals and for converting frequency of said reverse link information signals into a frequency-shifted reverse link spectrum so as to produce frequency-shifted reverse link information signals,

an analog to digital converter for converting said frequency-shifted reverse link information signals into reverse link digital information signals, and

a remote communications link transmitter for transmitting said reverse link digital information signals.

13. In a cellular system including at least a first cell having a cell-site, a distributed microcellular communications system comprising:

a remote site station including:

a wideband receiver for receiving reverse link information signals from users within a first subcell of said first cell, and for converting frequency of said reverse link information signals into a frequency-shifted reverse link spectrum so as to produce frequency-shifted reverse link information signals,

an analog to digital converter for converting said frequency-shifted reverse link information signals into reverse link digital information signals,

a channelizer for selecting ones of said reverse link digital information signals corresponding to channel frequencies assigned to said remote site station, and

a remote communications link transmitter for transmitting said reverse link digital information signals; and

a central base station, located at said cell-site, having a central communications link receiver for receiving said reverse link digital information signals.

14. The distributed microcellular communications system of claim 13 wherein said central base station further includes a central radio transceiver for transmitting and receiving information signals within a second subcell of said first cell, said communications system further including control means allocating selected ones of an available set of communications channels to said channel frequencies assigned to said remote site station and for allocating remaining ones of said available set of communications channels for use by said central radio transceiver.

Exhibit 1002
Page 0772 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

15. The distributed microcellular communications system of claim 1 wherein said means for converting information signals received by said transceiver to reverse link digital information signals includes:

a wideband receiver for translating frequency of said information signals received by said transceiver to a frequency-shifted reverse channel spectrum, and

an analog to digital converter coupled to said wideband receiver.

16. In a cellular system including a plurality of contiguous cells, a method for providing distributed microcellular communication within one cell of said cells, said method comprising the steps of:

at a remote site station located within said one cell:

transmitting and receiving information signals over an assigned set of communications channels within a first subcell of said one cell,

converting information signals received by said remote site station from users within said first subcell into reverse link digital information signals,

transmitting said reverse link digital information signals; and

at a central base station located at a cell-site of said first cell:

receiving said reverse link digital information signals.

17. The method of claim 16 wherein said step of converting includes the steps of:

translating frequency of said information signals received by said remote site station into a frequency-shifted reverse link spectrum so as to provide frequency-shifted reverse link information signals, and

converting said frequency-shifted reverse link information signals into said reverse link digital information signals.

18. The method of claim 17 further including the steps of:

at said central base station, transmitting forward link digital information signals; and

at said remote site station:

receiving said forward link digital information signals,

converting said forward link digital information signals into frequency-shifted forward link digital information signals, and

Exhibit 1002
Page 0773 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

converting said frequency-shifted forward link digital information signals into analog forward link information signals within a forward link transmission spectrum.

19. In a cellular system including a plurality of contiguous cells, a distributed microcellular communications systems disposed within one of said cells, said distributed microcellular communications system comprising:

a plurality of remote site stations respectively disposed within a plurality of subcells of said one cell, each of said plurality of remote site stations having a remote radio transceiver for transmitting and receiving information signals over an assigned set of communications channels, each of said remote site stations further including means for converting information signals received by said remote radio transceiver included therein to reverse link digital information signals for transmission by a remote station communications link transmitter; and

a central base station having a central communications link receiver for receiving said reverse link digital information signals from said plurality of remote site stations.

20. The distributed microcellular communications system of claim 19 further including means for allocating communication channels from an available set of communication channels to each said assigned set of communication channels, thereby permitting establishment of a desired channel capacity within each of said subcells.

21. The distributed microcellular communications system of claim 19 wherein said central base station further includes central communications link transmitter means for transmitting a plurality of forward link digital information signals to said plurality of remote site stations.

22. The distributed microcellular communications system of claim 7 wherein said remote site station further includes a plurality of beamformers disposed to receive said set of reverse link digital information signals, said demodulator means including a corresponding plurality of digital demodulator coupled to said plurality of beamformers.

Exhibit 1002
Page 0774 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

23. The distributed microcellular communications system of claim 11 wherein said cell-site station further includes beamforming means for providing said forward link digital information signals to said communications link transmitter.

24. In a cellular system including a plurality of contiguous cells, a distributed microcellular communications system disposed within one of said cells, said distributed microcellular communications system comprising:

a plurality of remote site stations respectively situated in a like plurality of subcells within said one of said cells, each of said plurality of remote site stations having a remote radio transceiver for transmitting and receiving information signals over an assigned set of communications channels, each of said remote site stations further including:

means for converting information signals received by said transceiver to reverse link digital information signals, and

a remote communications link transceiver for transmitting said reverse link digital information signals and for receiving forward link digital information signals; and

a central base station having a central communications link transceiver for receiving said reverse link digital information signals from each of said plurality of remote site stations, and for selectively transmitting said forward link digital information signals to each of said plurality of remote site stations.

25. The distributed microcellular communications system of claim 1 wherein said remote site station further includes a diversity remote radio receiver for receiving information signals over said assigned set of communications channels within said first subcell, said remote site station further including a diversity combiner for combining said information signals received by said diversity remote radio receiver with said information signals received by said remote radio transceiver.

Exhibit 1002
Page 0775 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

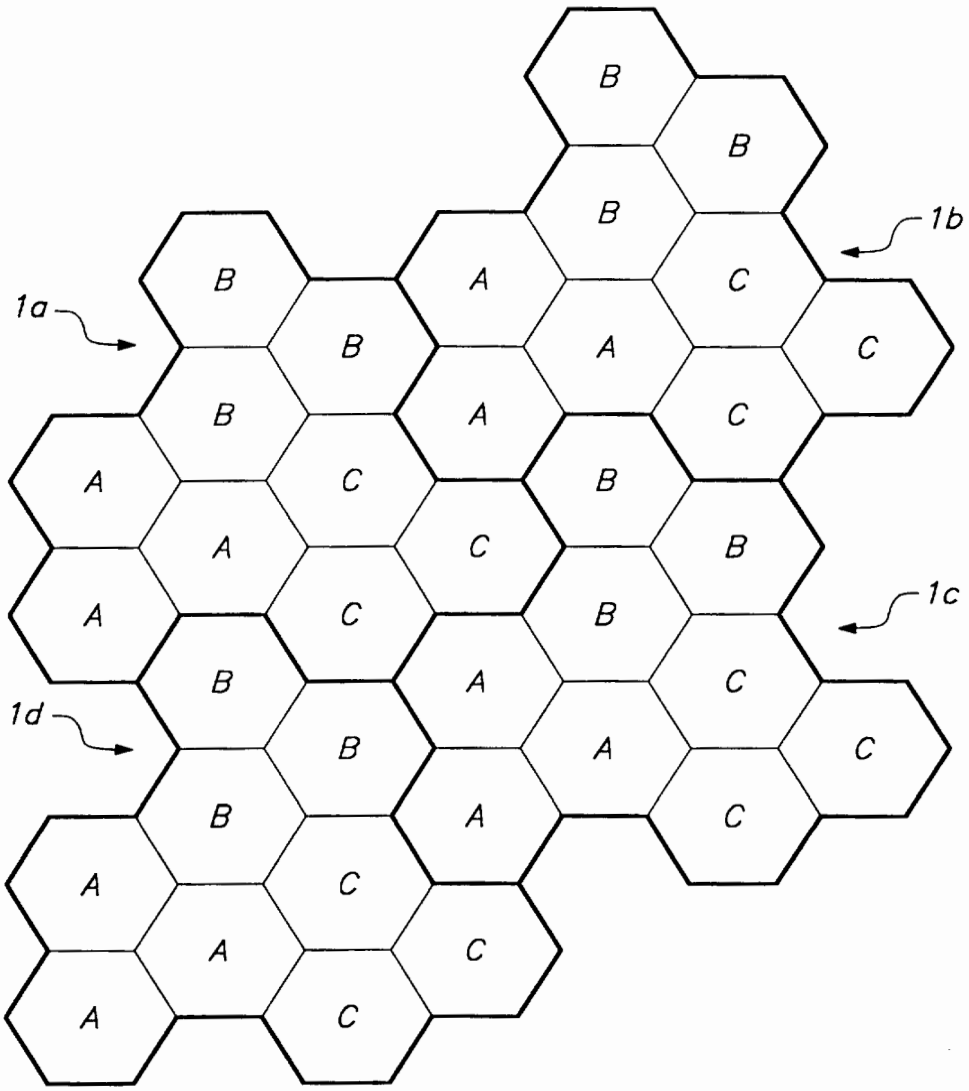

FIG. 1A

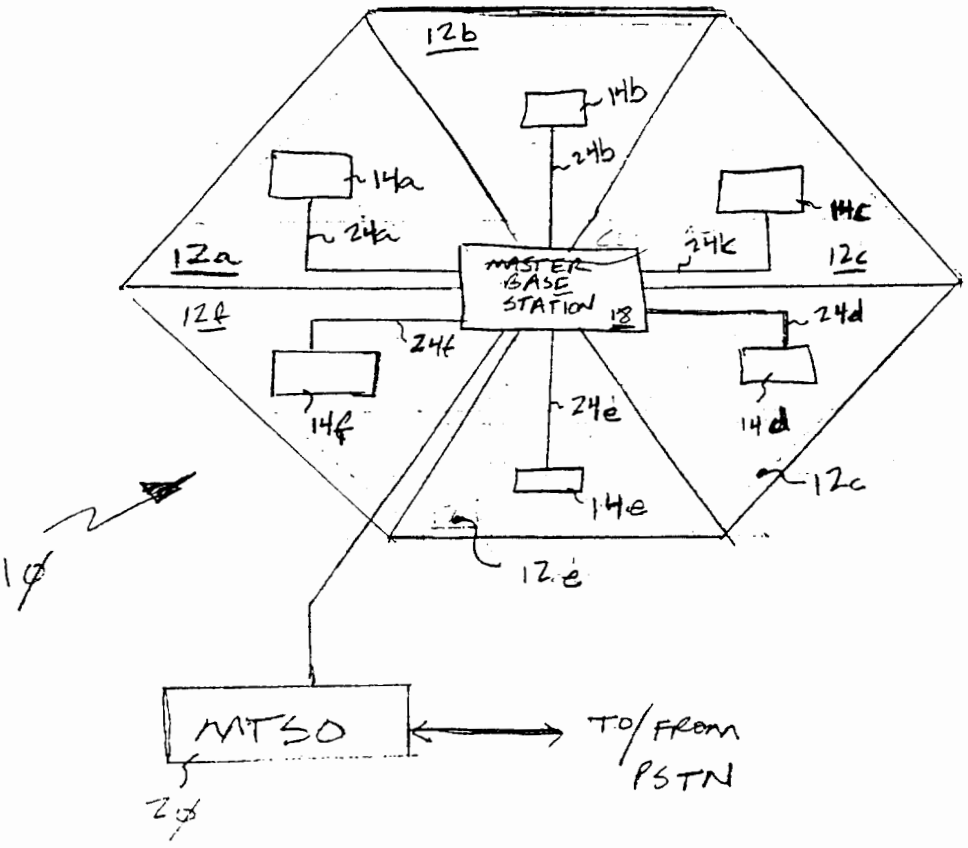
12b
14b
24b
14a
24a
14c
24c
12a
12c
MASTER BASE STATION 18
12f
24d
24f
14f
24e
14d
14e
12c
12e
10
MTSO
TO/FROM PSTN
20

FIG. 1B

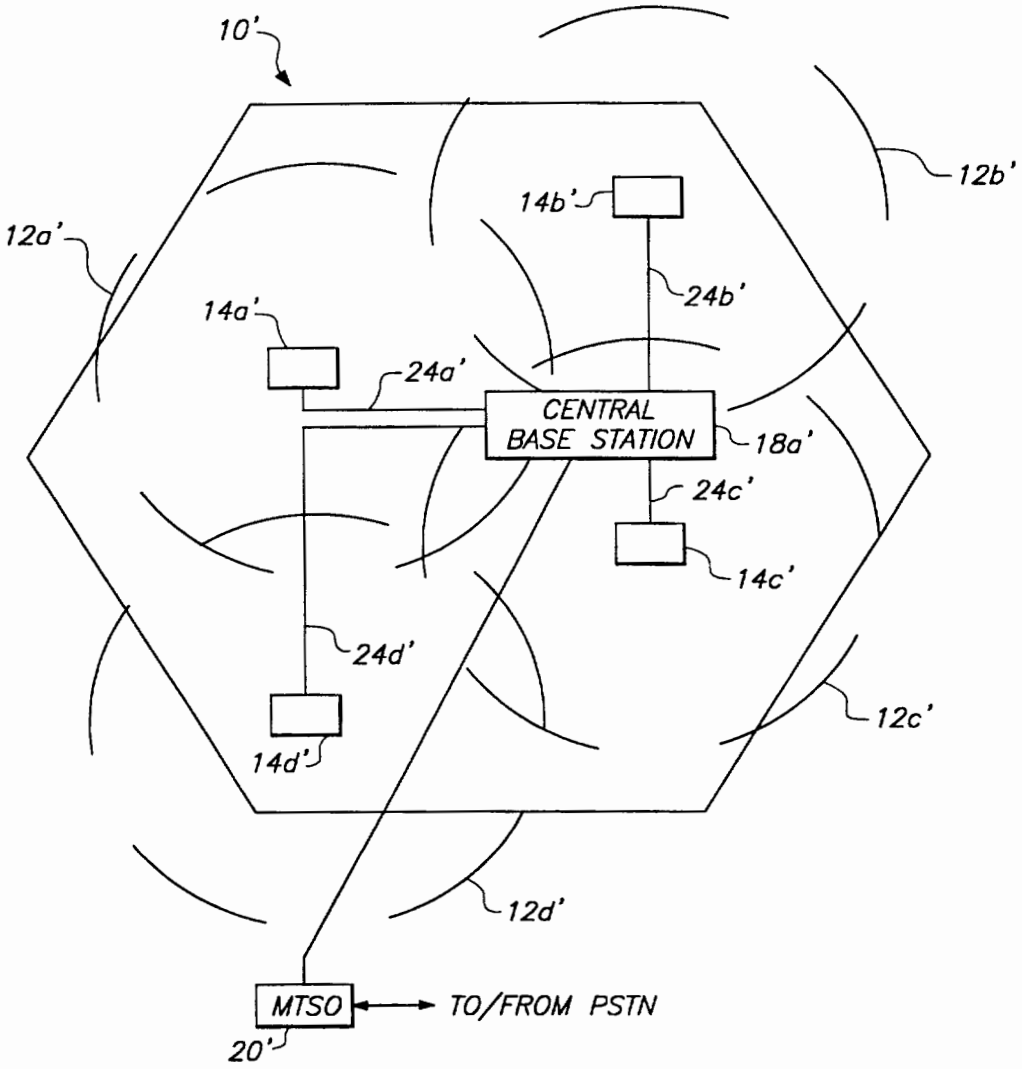

FIG. 1C

Exhibit 1002
Page 0778 of 1285

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

SUBSTITUTE SHEET (RULE 26)

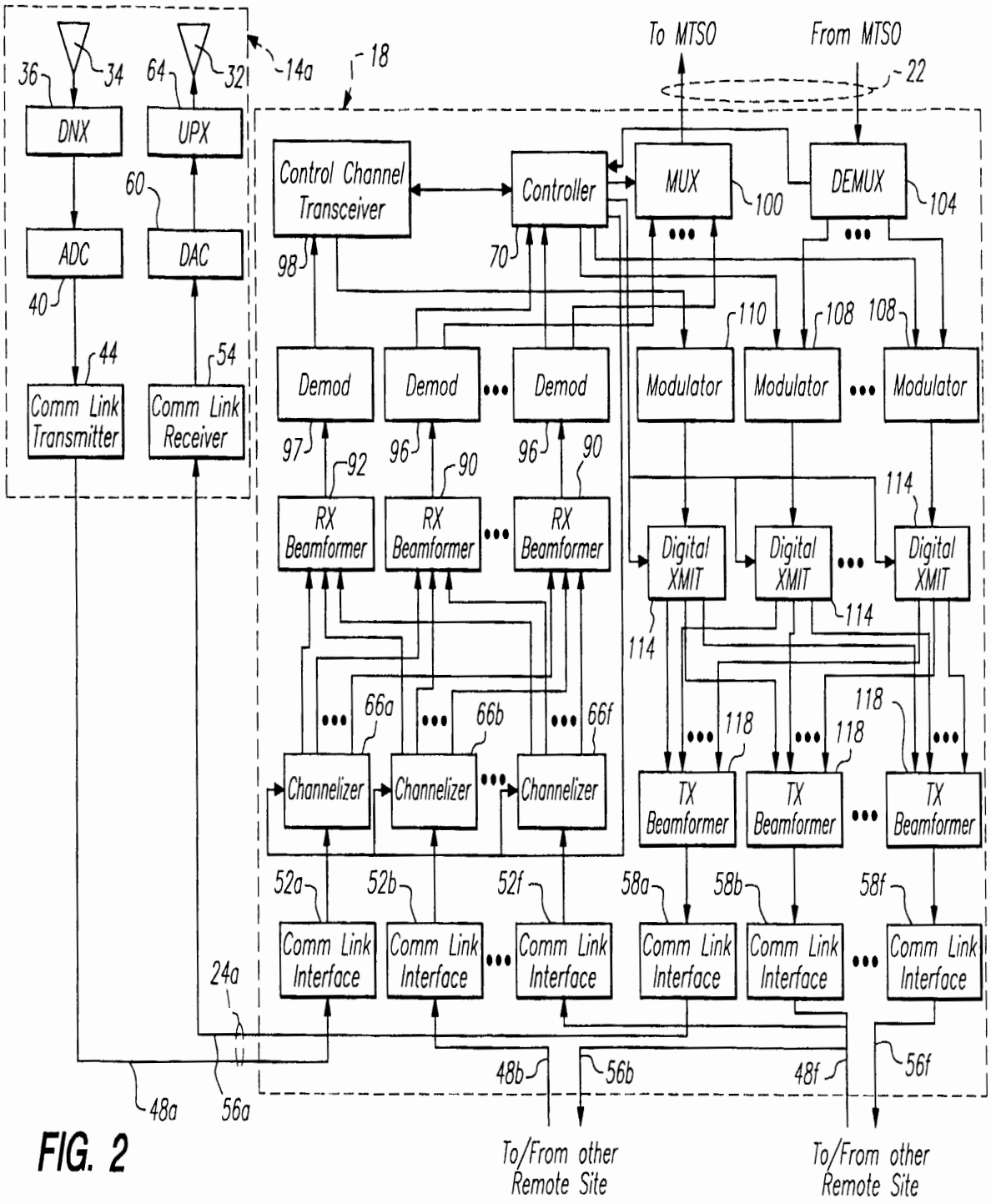

FIG. 2

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

TUNING INFORMATION FROM CONTROLLER 70
72
FROM RECEIVER 52
25 Msps
DIGITAL BANDPASS FILTER
74
76
DECIMATOR
80
83.3 ksps
NCO
78
TUNING INPUT FROM CONTROLLER 70

FIG. 3

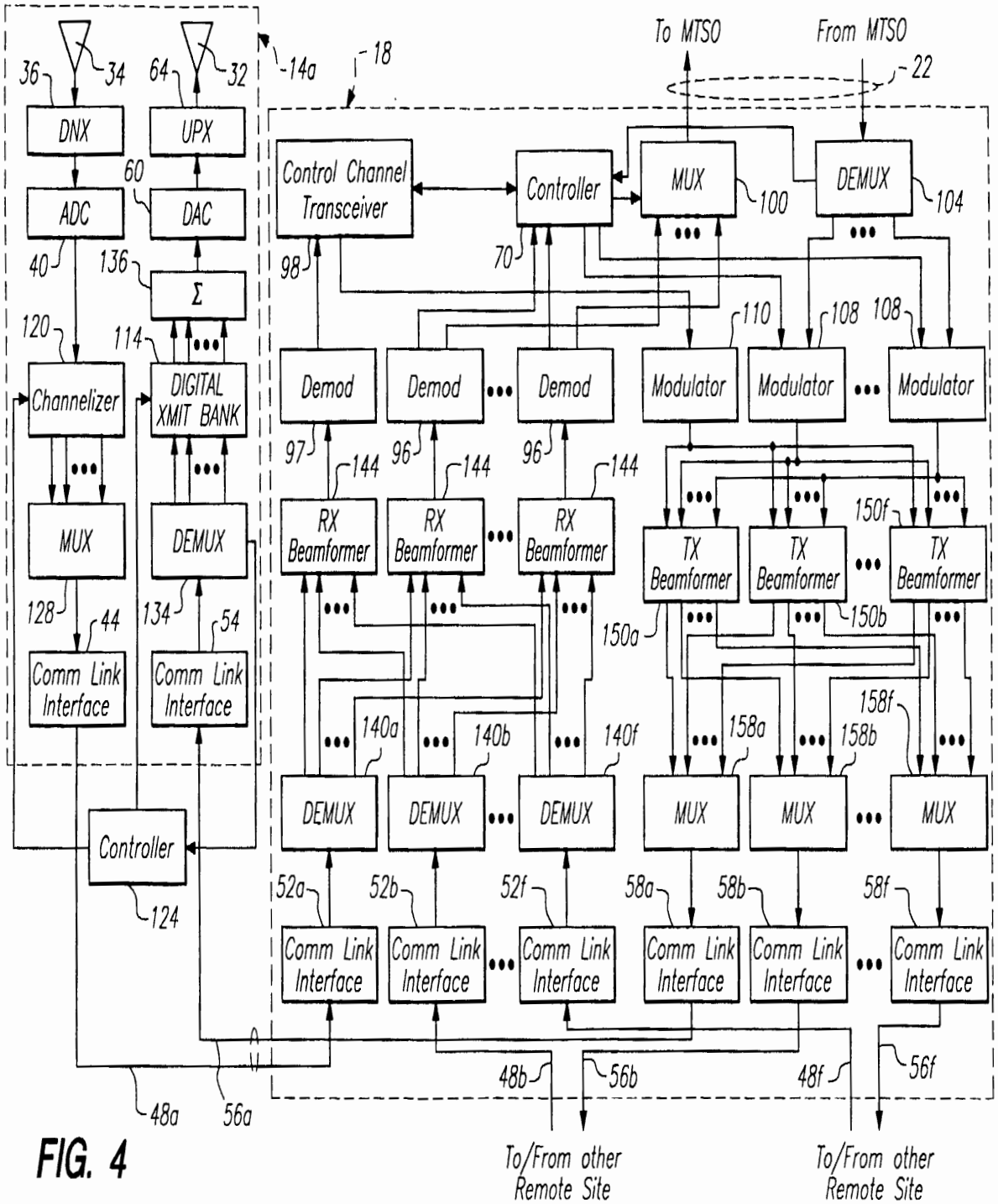
To MTSO
From MTSO
22
18
14a
36
34
64
32
DNX
UPX
60
ADC
DAC
40
136
Σ
120
114
Channelizer
DIGITAL XMIT BANK
MUX
DEMUX
128
44
134
54
Comm Link Interface
Comm Link Interface
Controller
124
48a
56a
Control Channel Transceiver
Controller
MUX
100
DEMUX
104
98
70
110
108
108
Demod
Demod
Demod
Modulator
Modulator
Modulator
97
96
96
144
144
144
RX Beamformer
RX Beamformer
RX Beamformer
150f
TX Beamformer
TX Beamformer
TX Beamformer
150a
150b
140a
140b
140f
158f
158a
158b
DEMUX
DEMUX
DEMUX
MUX
MUX
MUX
52a
52b
52f
58a
58b
58f
Comm Link Interface
Comm Link Interface
Comm Link Interface
Comm Link Interface
Comm Link Interface
Comm Link Interface
48b
56b
48f
56f
To/From other Remote Site
To/From other Remote Site

FIG. 4

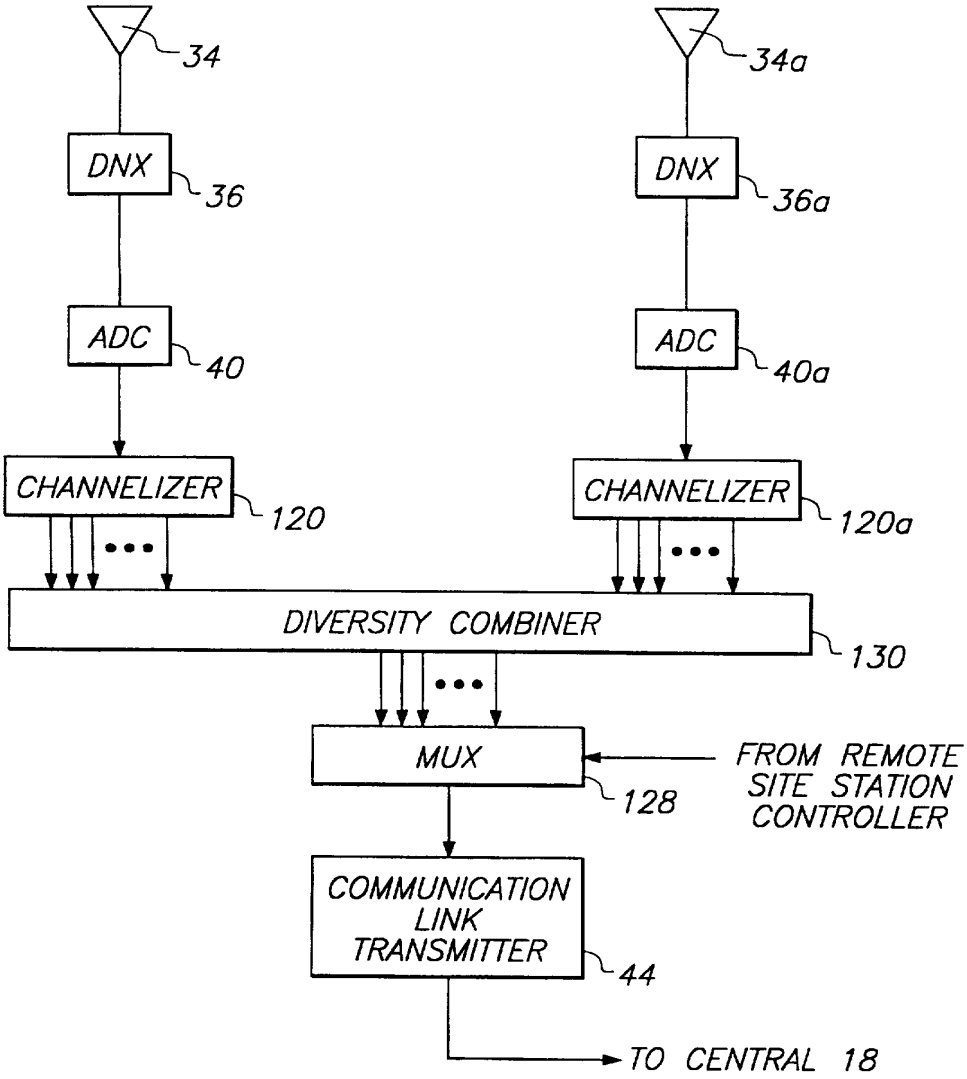
34
34a
DNX
36
DNX
36a
ADC
40
ADC
40a
CHANNELIZER
120
CHANNELIZER
120a
DIVERSITY COMBINER
130
MUX
128
FROM REMOTE SITE STATION CONTROLLER
COMMUNICATION LINK TRANSMITTER
44
TO CENTRAL 18

FIG. 5

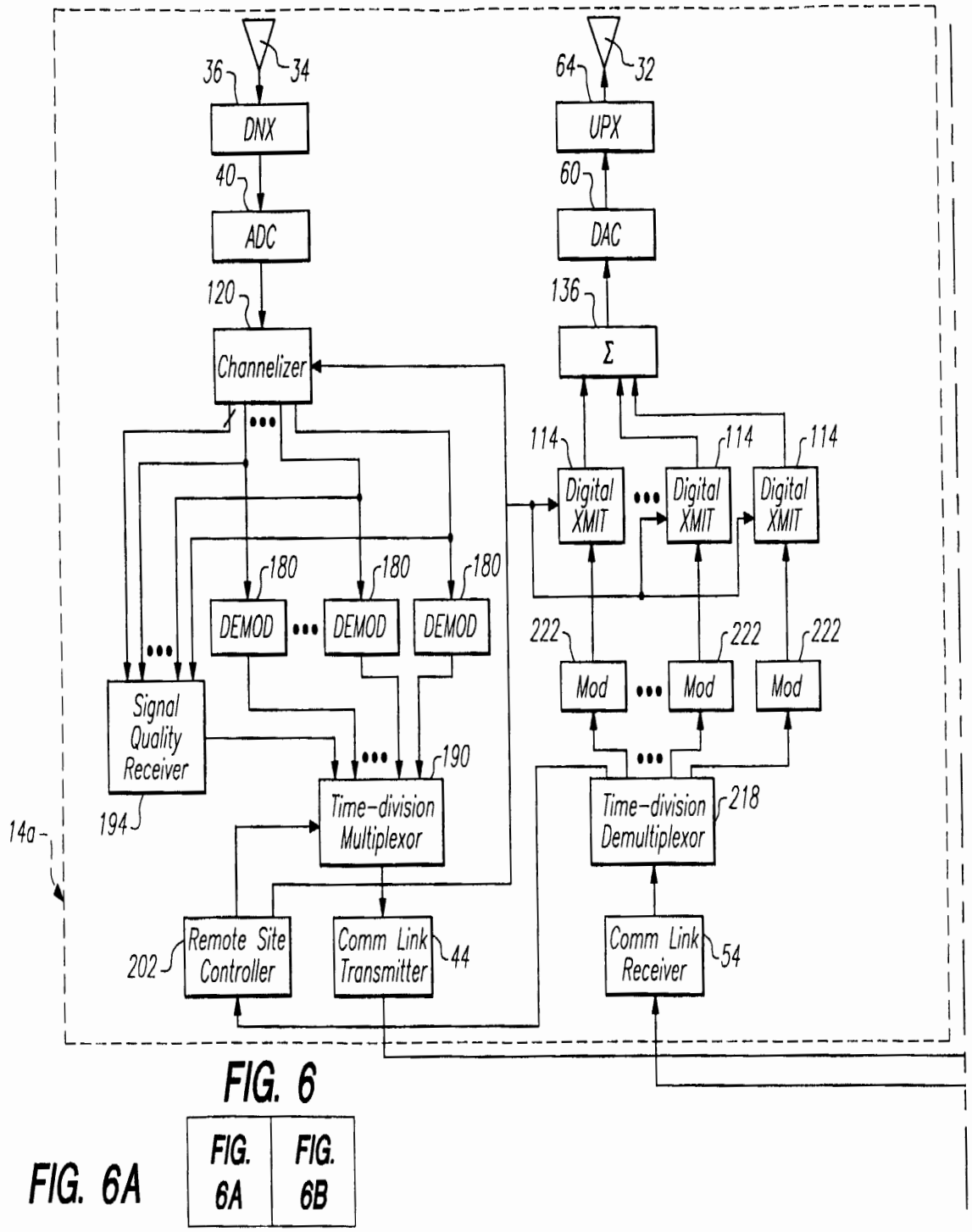

FIG. 6

FIG. 6A

FIG. 6A	FIG. 6B

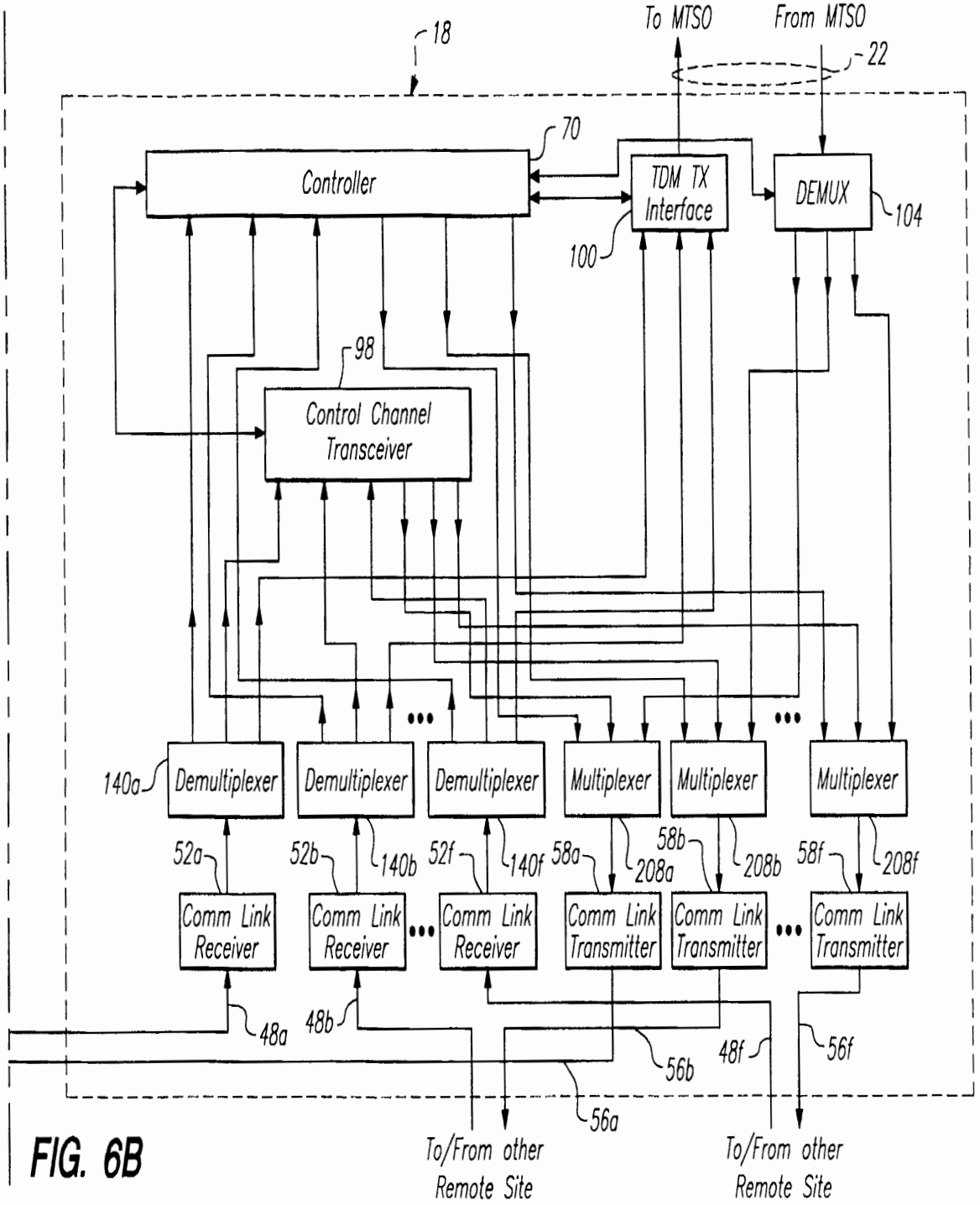
18
To MTSO
From MTSO
22
70
Controller
TDM TX Interface
DEMUX
104
100
98
Control Channel Transceiver
140a
Demultiplexer
Demultiplexer
Demultiplexer
Multiplexer
Multiplexer
Multiplexer
52a
52b
140b
52f
140f
58a
208a
58b
208b
58f
208f
Comm Link Receiver
Comm Link Receiver
Comm Link Receiver
Comm Link Transmitter
Comm Link Transmitter
Comm Link Transmitter
48a
48b
48f
56f
56b
56a
To/From other Remote Site
To/From other Remote Site

FIG. 6B

SUBSTITUTE SHEET (RULE 26)

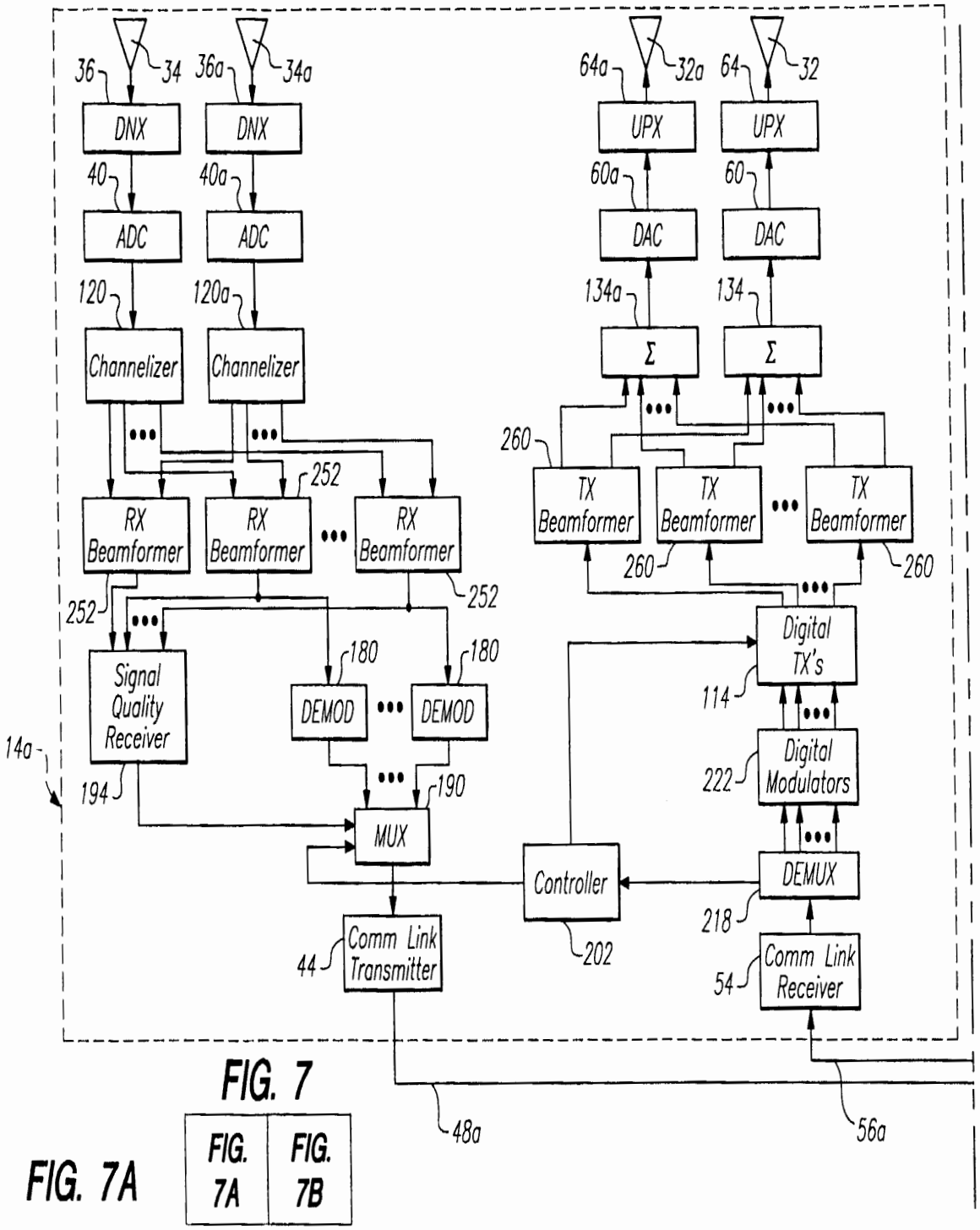

FIG. 7

FIG. 7A

FIG. 7A	FIG. 7B

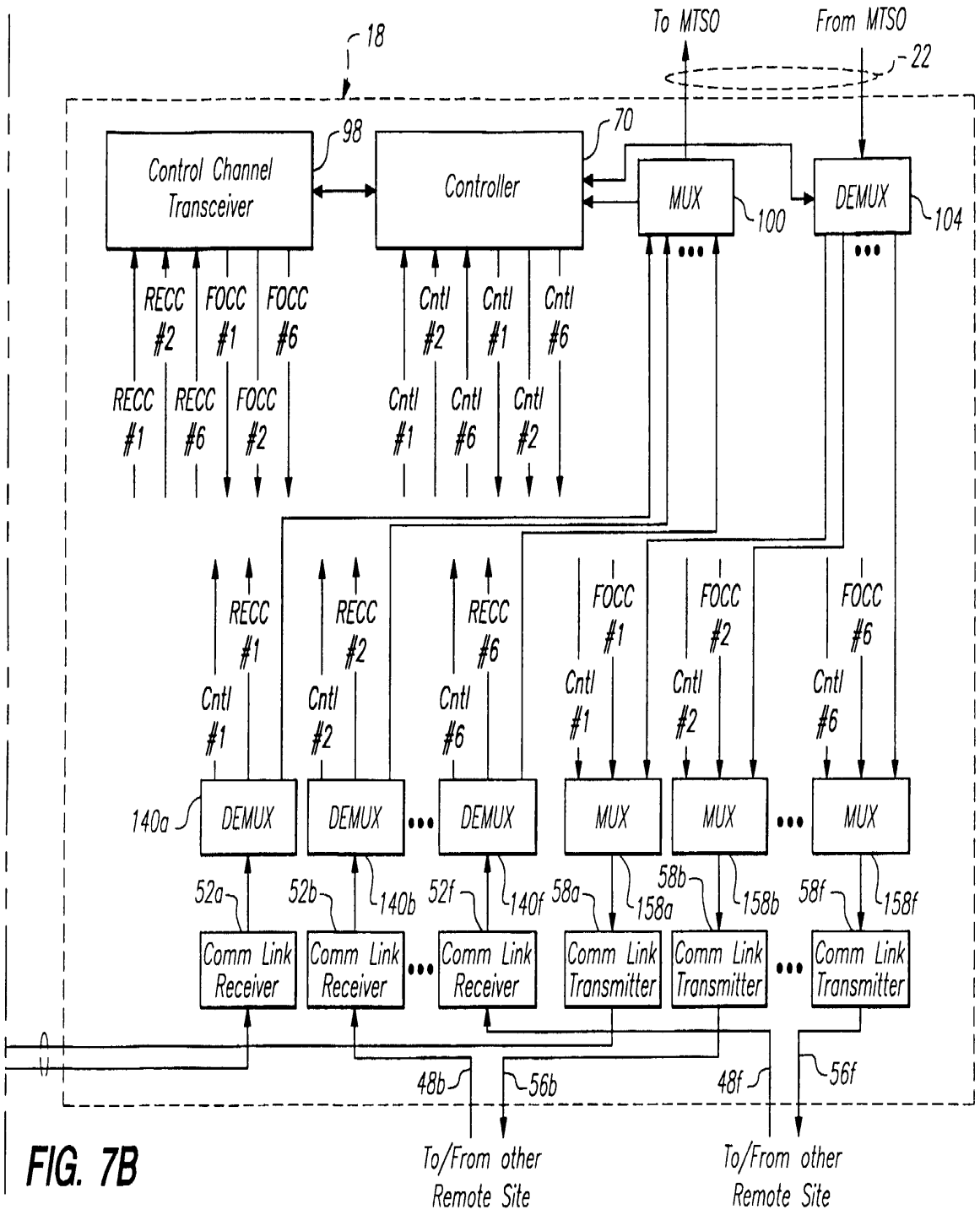
18
To MTSO
From MTSO
22
98
70
Control Channel Transceiver
Controller
MUX
100
DEMUX
104
RECC #2
FOCC #1
FOCC #6
Cntl #2
Cntl #1
Cntl #6
RECC #1
RECC #6
FOCC #2
Cntl #1
Cntl #6
Cntl #2
RECC #1
RECC #2
RECC #6
FOCC #1
FOCC #2
FOCC #6
Cntl #1
Cntl #2
Cntl #6
Cntl #1
Cntl #2
Cntl #6
140a
DEMUX
DEMUX
DEMUX
MUX
MUX
MUX
52a
52b
140b
52f
140f
58a
158a
58b
158b
58f
158f
Comm Link Receiver
Comm Link Receiver
Comm Link Receiver
Comm Link Transmitter
Comm Link Transmitter
Comm Link Transmitter
48b
56b
48f
56f
To/From other Remote Site
To/From other Remote Site

FIG. 7B

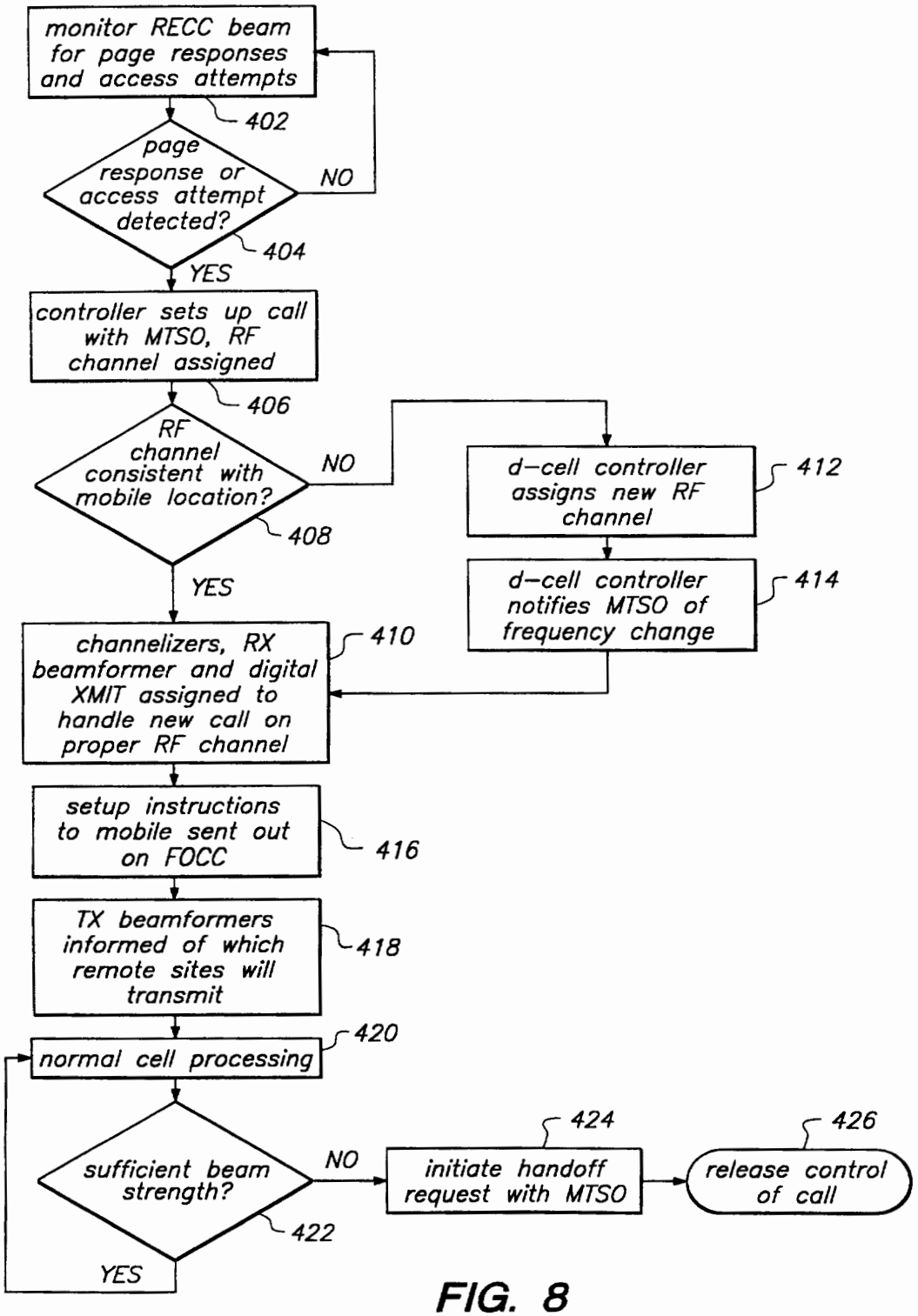
monitor RECC beam for page responses and access attempts
402
page response or access attempt detected?
NO
404
YES
controller sets up call with MTSO, RF channel assigned
406
RF channel consistent with mobile location?
NO
408
YES
d-cell controller assigns new RF channel
412
d-cell controller notifies MTSO of frequency change
414
channelizers, RX beamformer and digital XMIT assigned to handle new call on proper RF channel
410
setup instructions to mobile sent out on FOCC
416
TX beamformers informed of which remote sites will transmit
418
normal cell processing
420
sufficient beam strength?
NO
422
YES
424
initiate handoff request with MTSO
426
release control of call

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/03629

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04B 7/26
US CL :455/33.1

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/33.1, 33.2, 33.3, 33.4, 39, 49.1, 53.1, 54.1, 57.1, 73, 80

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS IMAGE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,448,753 A (AHL et al) 05 September 1995, fig. 21; col. 1, lines 21-25, 28-32; col. 3, lines 10-16, 25-32, 43-68; col. 4, lines 36-44.	1-25
A	US 5,463,671 A (MARSH et al) 31 October 1995, fig. 1; col. 1, lines 30-67 through col. 4, lines 1-7.	1-25
Y	US 5,481,546 A (DINKINS) 02 January 1996, figs. 2, 6A-6B; col. 1, lines 15-23; col. 2, lines 55-61; col. 3, lines 2-11, 56-67; col. 5, lines 43-60; col. 6, lines 17-40; col. 8, lines 38-61; col. 9, lines 5-15, 48-67.	1-25

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
17 JUNE 1997	29 JUL 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer TOMMY CHIN Telephone No. (703) 305-4715

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/03629

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y, P	US 5,555,260 A (RINNBACK et al) 10 September 1996, col. 1, lines 20-50; col. 3, lines 23-40; col. 4, lines 28-45; col. 5, lines 26-46; col. 8, lines 55-65; col. 9, lines 57 through col. 10, lines 1-15.	1-25
A, P	US 5,542,107 A (KAY) 30 July 1996, col. 1, lines 14-23; col. 4, lines 39-58; col. 6, lines 10-16.	1-25
Y	US 5,333,178 A (NORELL) 26 July 1994, col. 1, lines 16-26, 36-37, 43-45; col. 2, lines 8-19, 44-63; col. 3, lines 16-28.	1-25

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [6] : **H04B 1/38, H04M 1/00**	**A1**	**(11) International Publication Number:** **WO 98/09381** **(43) International Publication Date:** 5 March 1998 (05.03.98)

(21) International Application Number: PCT/US97/15363

(22) International Filing Date: 29 August 1997 (29.08.97)

(30) Priority Data:

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60/025,228	29 August 1996 (29.08.96)	US

(71) Applicant: THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY [US/US]; Suite 350, 900 Welch Road, Palo Alto, CA 94304 (US).

(72) Inventors: RALEIGH, Gregory, G.; 539 San Juan Avenue, El Granada, CA 94018 (US). CIOFFI, John, M.; 14298 Saddle Mountain Drive, Los Altos Hills, CA 94022 (US).

(74) Agent: McFARLANE, Thomas, J.; 426 Lowell Avenue, Palo Alto, CA 94301 (US).

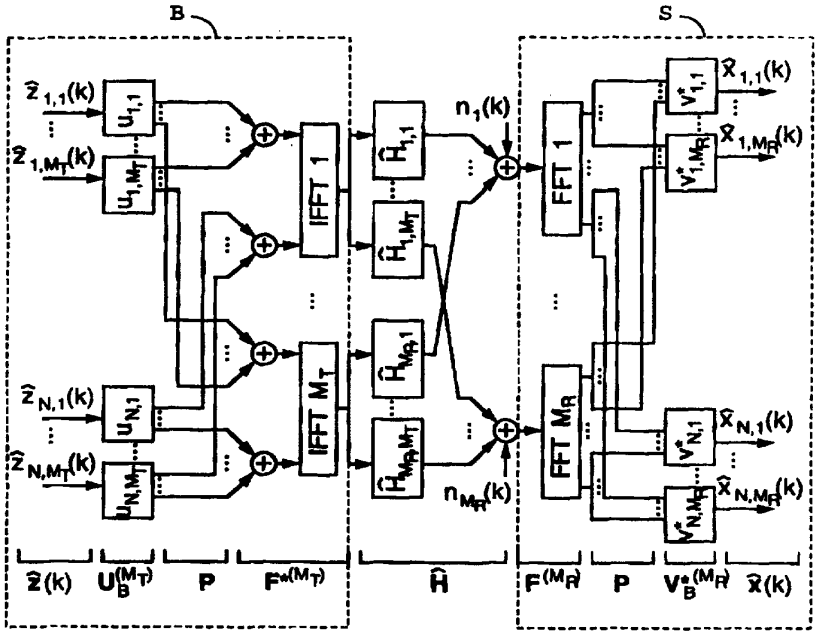
(81) Designated States: CA, JP, MX, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: HIGH CAPACITY WIRELESS COMMUNICATION USING SPATIAL SUBCHANNELS

(57) Abstract

In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix H couples an adaptive array of Mt antenna elements (1-Mt) at the base station (B) with an adaptive array Mr antenna elements (1-Mr) at the subscriber unit (S). The method comprises the step of determining from the channel matrix H a number L of independent spatio-temporal subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have Mt complex valued components and are selected to transmit distinct signal information in parallel over the independent subchannels, thereby providing increased communication capacity between the base and the subscriber. The sequence of transmitted signal vectors is transmitted from the base station array (1-Mt), and a sequence of received signal vectors is received at the subscriber array (1-Mr) and are decoded to yield the original information signals. Specific spatio-temporal coding techniques are described that increase system performance.



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AU	Australia	**GA**	Gabon	**LV**	Latvia	**SZ**	Swaziland
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BF	Burkina Faso	**GR**	Greece			**TR**	Turkey
BG	Bulgaria	**HU**	Hungary	**ML**	Mali	**TT**	Trinidad and Tobago
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CA	Canada	**IT**	Italy	**MX**	Mexico	**UZ**	Uzbekistan
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CZ	Czech Republic	**LC**	Saint Lucia	**RU**	Russian Federation		
DE	Germany	**LI**	Liechtenstein	**SD**	Sudan		
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High Capacity Wireless Communication Using Spatial Subchannels

RELATED APPLICATIONS

This application claims priority from U.S. provisional applications 60/025,227 and 60/025,228, both filed 08/29/96. Both applications are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to digital wireless communication systems. More particularly, it relates to using antenna arrays by both a base station and a subscriber to significantly increase the capacity of wireless communication systems.

BACKGROUND OF THE INVENTION

Due to the increasing demand for wireless communication, it has become necessary to develop techniques for more efficiently using the allocated frequency bands, i.e. increasing the capacity to communicate information within a limited available bandwidth. This increased capacity can be used to enhance system performance by increasing the number of information channels, by increasing the channel information rates and/or by increasing the channel reliability.

FIG. 1 shows a conventional low capacity wireless communication system. Information is transmitted from a base station B to subscribers $S_1, \ldots, S_9$ by broadcasting omnidirectional signals on one of several predetermined frequency channels. Similarly, the subscribers transmit information back to the base station by broadcasting similar signals on one of the frequency channels. In this system, multiple users independently access the system through the

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

division of the frequency band into distinct subband frequency channels. This technique is known as frequency division multiple access (FDMA).

A standard technique used by commercial wireless phone systems to increasing capacity is to divide the service region into spatial cells, as shown in FIG. 2. Instead of using just one base station to serve all users in the region, a collection of base stations $B_1, \ldots, B_7$ are used to independently service separate spatial cells. In such a cellular system, multiple users can reuse the same frequency channel without interfering with each other, provided they access the system from different spatial cells. The cellular concept, therefore, is a simple type of spatial division multiple access (SDMA).

In the case of digital communication, additional techniques can be used to increase capacity. A few well known examples are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA allows several users to share a single frequency channel by assigning their data to distinct time slots. CDMA is normally a spread-spectrum technique that does not limit individual signals to narrow frequency channels but spreads them throughout the frequency spectrum of the entire band. Signals sharing the band are distinguished by assigning them different orthogonal digital code sequences. These techniques use digital coding to make more efficient use of the available spectrum.

Wireless systems may also use combinations of the above techniques to increase capacity, e.g. FDMA/CDMA and TDMA/CDMA. Although these and other known techniques increase the capacity of wireless communication systems, there is still a need to further increase system performance. Recently, considerable attention has focused on ways to increasing capacity by further exploiting the spatial domain.

One well-known SDMA technique is to provide the base station with a set of independently controlled directional antennas, thereby dividing the cell into separate sectors, each controlled by a separate antenna. As a result, the frequency reuse in the system can be increased and/or cochannel interference can be reduced. Instead of independently controlled directional antennas, this technique can also be implemented with a coherently controlled antenna array, as shown in FIG. 3. Using a signal processor to control the relative phases of the signals applied to the antenna elements, predetermined beams can be formed in the directions of the separate sectors. Similar signal processing can be used to selectively receive signals only from within the distinct sectors.

In an environment containing a significant number of reflectors (such as buildings), a signal will often follow multiple paths. Because multipath reflections alter the signal directions, the cell space experiences angular mixing and can not be sharply divided into distinct sectors. Multipath can therefore cause cochannel interference between sectors, reducing the benefit of sectoring the cell. In addition, because the separate parts of such a multipath signal can arrive with different phases that destructively interfere, multipath can result in unpredictable signal fading.

In order to avoid the above problems with multipath, more sophisticated SDMA techniques have been proposed. For example, U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al. disclose wireless communication systems that increase performance by exploiting the spatial domain. In the downlink, the base station determines the spatial channel of each subscriber and uses this channel information to adaptively control its antenna array to form customized beams, as shown in FIG. 4A. These beams transmit an information

signal x over multiple paths so that the signal x arrives to the subscriber with maximum strength. The beams can also be selected to direct nulls to other subscribers so that cochannel interference is reduced. In the uplink, as shown in FIG. 4B, the base station uses the channel information to spatially filter the received signals so that the transmitted signal x' is received with maximum sensitivity and distinguished from the signals transmitted by other subscribers. In this approach the same information signal follows several paths, providing increased spatial redundancy.

In the uplink, there are well known signal processing techniques for estimating the spatial channel from the signals received at the base station antenna array, e.g. by using *a priori* spatial or temporal structures present in the signal, or by blind adaptive estimation. If the uplink and downlink frequencies are the same, then the spatial channel for the downlink is directly related to the spatial channel for the uplink, and the base can use the known uplink channel information to perform transmit beamforming in the downlink. Because the spatial channel is frequency dependent and the uplink and downlink frequencies are often different, the base does not always have sufficient information to derive the downlink spatial channel information. One technique for obtaining downlink channel information is for the subscriber to periodically transmit test signals to the base on the downlink frequency rather than the uplink frequency. Another technique is for the base to transmit test signals and for the subscriber to feedback channel information to the base. If the spatial channel is quickly changing due to the relative movement of the base, the subscriber and/or reflectors in the environment, then the spatial channel must be updated frequently, placing a heavy demand on the system. One method to reduce the required feedback rates is to track only the subspace spanned by the time-averaged channel vector, rather than the instantaneous channel vector. Even with this

reduction, however, the required feedback rates are still a large fraction of the signal information rate.

Although these adaptive beamforming techniques require substantial signal processing and/or large feedback rates to determine the spatial channel in real time, these techniques have the advantage that they can navigate the complex spatial environment and avoid, to some extent, the problems introduced by multipath reflections. As a result, an increase in performance is enjoyed by adaptive antenna array systems, due to their use of the spatial dimension. Note, however, that while the base station antenna array can make efficient use of the spatial dimension by selectively directing the downlink signal to the subscriber S, the uplink signal in these systems is spatially inefficient. Typically, the subscriber is equipped with only a single antenna that radiates signal energy in all directions, potentially causing cochannel interference. These communication systems, therefore, do not make optimal use of the spatial dimension to increase capacity.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a communication system that significantly increases the capacity and performance of wireless communication systems by taking maximum advantage of the spatial domain. Another object of the invention is to provide computationally efficient coding techniques that make optimal use of the spatial dimensions of the channel. These and other objects and advantages will become apparent from the following description and associated drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a method of digital wireless communication that takes maximal advantage of spatial channel dimensions between a base station and a subscriber unit to increase system capacity and performance.

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

Surprisingly, the techniques of the present invention provide an increased information capacity in multipath environments. In contrast, known techniques suffer in the presence of multipath and do not exploit multipath to directly increase system capacity. In brief, the present invention teaches a method of wireless communication using antenna arrays at both the base and subscriber units to transmit distinct information signals over different spatial channels in parallel, thereby multiplying the capacity between the base and the subscriber. The present invention also teaches specific spatio-temporal coding techniques that make optimal use of these additional spatial subchannels.

Generally, the present invention provides a method of digital wireless communication between a base station and a subscriber unit, where a spatial channel characterized by a channel matrix **H** couples an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit. The method comprises the step of determining from the channel matrix **H** a number L of independent spatial subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have M_T complex valued components and are selected to distribute distinct signal information over the independent spatial subchannels. The sequence of transmitted signal vectors is transmitted from the array of M_T antenna elements at the base station, and a sequence of received signal vectors is received at the array of M_R antenna elements at the subscriber unit. The received signal vectors have M_R complex valued components. These received signal vectors are decoded to yield the information signals.

In another aspect, the invention provides a method that comprises computing from a set of K original information signals a spatio-temporal coded signal in accordance with a channel matrix **H**. The channel matrix **H** represents the spatio-temporal characteristics of the information link between a

base station array of M_T antenna elements and a subscriber unit array of M_R antenna elements. Signal processing techniques are used to decompose **H** into K parallel spatio-temporal subchannels that can independently carry information signals between the base and subscriber units. After transmitting the spatio-temporal coded signal over the channel, it is decoded into a set of K received information signals that correspond to the K original information signals. In a preferred embodiment, the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are derived from a decomposition of **H** into independent modes, and a set of K corresponding receive sequences. For example, the K spatio-temporal transmission sequences may be multiples of right singular vectors of **H**, and the receive sequences may be a matched set of K spatio-temporal filter sequences that are left singular vectors of **H**.

If L is the number of multipath components between the base station and the subscriber unit, then the number K of parallel spatio-temporal channels is not more than $(N+\nu) \times M_R$, not more than $N \times M_T$, and not more than $N \times L$, where $(N+\nu)$ is a maximum number of nonzero output samples transmitted for a block of N symbols. In a preferred embodiment, the original information signals comprise K blocks of N symbols, and the channel matrix **H** comprises $M_T \times M_R$ blocks of $N \times (N+\nu)$ channel matrices $\mathbf{H}_{ij}$.

In some applications of the present invention, the channel state information (CSI) may not be completely known, or may be expensive to compute. Accordingly, the present invention also provides a method for facilitating the efficient computation of the K received information signals from the transmitted spatio-temporal coded signal by adding cyclic prefixes to the coded signal prior to transmission.

Exhibit 1002
Page 0798 of 1285
Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

DESCRIPTION OF THE FIGURES

FIG. 1 shows a low capacity wireless communication system well known in the prior art.

FIG. 2 illustrates a known technique of spatially dividing a service region into cells in order to increase system capacity.

FIG. 3 illustrates the use of beamforming with an antenna array to divide a cell into angular sectors, as is known in the art.

FIGS. 4A and 4B illustrate state-of-the-art techniques using adaptive antenna arrays for downlink and uplink beamforming, respectively.

FIGS. 5A and 5B show the parallel transmission of distinct information signals using spatial subchannels in downlink and uplink, respectively, as taught by the present invention.

FIGS. 6A and 6B are physical and schematic representations, respectively, of a communication channel for a system with multiple transmitting antennas and multiple receiving antennas, according to the present invention.

FIG. 7 is a block diagram of the system architecture for communicating information over a multiple-input-multiple-output spatial channel according to the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

As discussed above in relation to FIGS. 4A and 4B, prior art wireless systems employing an adaptive antenna array at the

Ubiquiti Inc. v. XR. Comm.
IPR2024-00148

base station are multiple-input-single-output (MISO) systems, i.e. the channel from the base to the subscriber is characterized by multiple inputs at the transmitting antenna array and a single output at the receiving subscriber antenna. Because these MISO systems can exploit some of the spatial channel, they have an increased capacity as compared to single-input-single-output (SISO) systems that are discussed above in relation to FIGS. 1 and 2. It should be noted that although the MISO systems disclosed in the prior art provide an increase in overall system capacity by spatially isolating separate subscribers from each other, these systems do not provide an increase in the capacity of information transmitted from the base to a single subscriber, or vice versa. As shown in FIGS. 4A and 4B, only one information signal is transmitted between the base and subscriber in both downlink and uplink of a MISO system. Even in the case where the subscriber is provided with an antenna array, the prior art suggests only that this capability would further reduce cochannel interference. Although the overall system capacity could be increased, this would not increase the capacity between the base and a single subscriber.

The present invention, in contrast, is a multiple-input-multiple-output (MIMO) wireless communication system that is distinguished by the fact that it increases the capacity of both uplink and downlink transmissions between a base and a subscriber through a novel use of additional spatial channel dimensions. The present inventors have recognized the possibility of exploiting multiple parallel spatial subchannels between a base station and a subscriber, thereby making use of additional spatial dimensions to increase the capacity of wireless communication. Surprisingly, this technique provides an increased information capacity and performance in multipath environments, a result that is in striking contrast with conventional wisdom.