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PTO/SB/16 (2-96)

Approved for use through 01/31/98 OMB 0651-0037

Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

jc916 U.S. PTO
60/243808
10/27/00

Docket Number		907.0015USP	Type a plus sign (+) inside this box ->	+
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TITLE OF INVENTION (280 characters max)				
SYNCHRONOUS DS-CDMA SYSTEM AND METHOD EMPLOYING SDMA AND OTHER ENHANCEMENTS				
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ENCLOSED APPLICATION PARTS (check all that apply)				
☒ Specification		Number of Pages	[17]	☐ Small Entity Statement
☒ Drawing(s)		Number of Sheets	[2]	☐ Other (specify) [APPENDIXES A-H (total 51 pages)]
]				
METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT (check one)				
☒ A check or money order is enclosed to cover the filing fees.			FILING FEE AMOUNT (\$)	\$150.00
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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.☐ Yes, the name of the U.S. Government agency and the Government contract number are:

SIGNATURE

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REGISTRATION NO. [32,493]
(if appropriate)

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s): Thomas R. Giallorenzi et al.
Serial No.: Not Yet Assigned
Filed: October 27, 2000
For: SYNCHRONOUS DS-CDMA SYSTEM AND METHOD
EMPLOYING SDMA AND OTHER ENHANCEMENTS
Attorney Docket No.: 907.0015USP

PROVISIONAL PATENT APPLICATION TRANSMITTAL

Assistant Commissioner for Patents
Box Provisional Patent Application
Washington, D.C. 20231

We enclose for filing under 37 C.F.R. §1.53(c);

XXX Provisional Application Cover Sheet;

XXX 17 sheets of Specification (15 pages of Specification; 1 page of Claims; 1 page Abstract);

XXX 2 sheets of drawings; and

XXX Appendix A (6pps.), Appendix B (3 pps.), Appendix C (4 pps.), Appendix D (9 pps.), Appendix E (7 pps.), Appendix F (7pps.), Appendix G (2 pps.) Appendix H (13 pps.) Total: 51 pages of Appendices

_____ An assignment of the invention to: _____, including the \$40.00 recordation fee and Assignment Recordation Form Cover Sheet;

The Filing Fee is calculated below.

CLAIMS AS FILED				
(1) For	(2) Number Filed	(3) Number Extra	(4) Rate	(5) Basic Fee \$150.00
TOTAL FILING FEE			\$150.00	
1/2 FILING FEE FOR SMALL ENTITY			\$N/A	

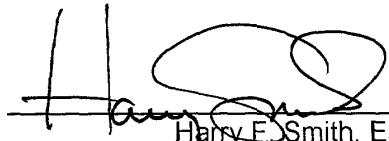
_____ Verified Statement of Small Entity Status is enclosed.

XXX A firm check in the amount of \$ **150.00** to cover the filing fee is enclosed.

XXX The Commissioner is hereby authorized to charge any additional fees under 37 C.F.R. §§1.16 and 1.17 which may be required with this communication or during the entire pendency of the application, or credit any overpayment, to **Deposit Account No. 01-0467**. A duplicate copy of this Form is enclosed.

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October 27, 2000
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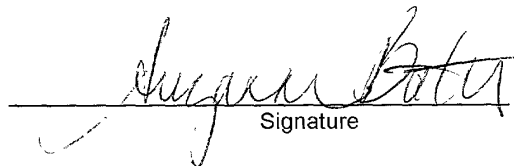


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Date

EXPRESS MAIL NO.: EL 688 069 191 US

L-3 Communications Corporation Docket Nos.:

SL-054, SL-055, SL-056, SL-057, SL-064, SL-068, SL -069

Ohlandt, Greeley, Ruggiero & Perle, L.L.P. Docket No.:

5 907.0015 USP

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**SYNCHRONOUS DS-CDMA SYSTEM AND METHOD EMPLOYING SDMA
AND OTHER ENHANCEMENTS**

FIELD OF THE INVENTION:

This invention relates generally to wireless communications systems and methods, and relates in particular to Code Division Multiple Access (CDMA) systems.

20

BACKGROUND OF THE INVENTION:

Synchronous CDMA systems and methods are becoming more widespread. A number of factors influence the overall efficiency and usability of such a system, including transmit and receive antenna structures and PN code assignment and other factors.

SUMMARY OF THE INVENTION

25

This invention provides enhanced operation of a Synchronous CDMA system through the use of Space Division Multiple Access (SDMA), as well as improved code assignment and selection techniques, with or without chip repetition to produce a flexible bandwidth..

BRIEF DESCRIPTION OF THE DRAWINGS

The above set forth and other features of the invention are made more apparent in the ensuing Detailed Description of the Invention when read in conjunction with the attached Drawings, wherein:

- 5 Fig. 1 is simplified block diagram of a wireless access reference model that pertains to the teachings of this invention;

Fig. 2 is block diagram of a physical (PHY) system reference model showing a major data flow path;

- 10 Fig. 3 shows an Error Control Coding (ECC) and scrambling technique for single CDMA channel;

Fig. 4 is a Table illustrating exemplary parameters for a 3.5MHz RF channelization;

Fig. 5 is a Table depicting an aggregate capacity and modulation factors versus modulation type and array size;

DETAILED DESCRIPTION OF THE INVENTION

- 15 Disclosed herein is a physical (PHY) system intended for IEEE 802.16.3 and related standards, although those having skill in the art should realize that various aspects of these teachings have wider applicability.

- 20 The technique is based on a hybrid synchronous DS-CDMA (S-CDMA) and FDMA scheme using quadrature amplitude modulation (QAM) and trellis coding. For a general background and benefits of S-CDMA with trellis-coded QAM one may refer to R. De Gaudenzi, C. Elia and R. Viola, "Bandlimited Quasi-Synchronous CDMA: A Novel Satellite Access Technique for Mobile and Personal Communication Systems," IEEE Journal on Selected Areas in Communications, Vol. 10, No. 2, February 1992, pp. 328-343, and to R. De Gaudenzi and F. Giannetti, "Analysis and Performance Evaluation of
- 25 Synchronous Trellis-Coded CDMA for Satellite Applications," IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995, pp. 1400-1409.

The ensuing description focuses on a frequency division duplexing (FDD) mode. While

a time division duplexing (TDD) mode is also within the scope of these teachings, the TDD mode is not discussed further.

What follows is an overview of the PHY teachings in accordance with this invention.

5 The system provides synchronous direct-sequence code division multiple access (DS-CDMA) for both upstream and downstream transmissions. The system further provides spread RF channel bandwidths from 1.75-7 MHz, depending on target frequency band, and a constant chip rate from 1-6 Mcps (Million chips per second) within each RF sub-channel with common I-Q spreading. The chip rate depends on channelization of interest (e.g. 3.5 MHz or 6 MHz). The system features orthogonal, variable-length spreading
10 codes using Walsh-Hadamard designs with spread factors (SF) of 1, 2, 4, 8, 16, 32, 64 and 128 chips/symbol being supported, and also features unique spreading code sets for adjacent, same-frequency cells/sectors. Upstream and downstream power control and upstream link timing control are provided, as are single CDMA channel data rates from 32 kbps up to 16 Mbps depending on SF (spreading factor) and chip rate. In the preferred system S-CDMA channel aggregation is provided for the highest data rates.
15

Furthermore, in the presently preferred embodiment FDMA is employed for large bandwidth allocations with S-CDMA in each FDMA sub-channel, and S-CDMA/FDMA channel aggregation is used for the higher data rates. Code, frequency and/or time division multiplexing is employed for both upstream and downstream transmissions.
20 Frequency division duplex (FDD) or time division duplex (TDD) can be employed, although as stated above the TDD mode of operation is not described further. The system features coherent QPSK and 16-QAM modulation with optional support for 64-QAM. End-to-end raised-cosine Nyquist pulse shape filtering is employed, as is adaptive coding, using high-rate punctured, convolutional coding (K=7) and/or Turbo coding (rates of 4/5, 5/6 and 7/8 are typical). Data randomization using spreading code
25 sequences is employed, as is linear equalization in the downstream with possible transmit pre-equalization for the upstream. Also featured is the use of space division multiple access (SDMA) using adaptive beam-forming antenna arrays (1 to 16 elements possible) at the base station.

30 Fig. 1 shows the wireless access reference model per the IEEE 802.16.3 FRD (see IEEE 802.16.3-00/02r4, "Functional Requirements for the 802.16.3 Interoperability Standard."). Within this model, the PHY technique in accordance with these teachings provides access between one or more subscriber stations (SS) 10 and base stations 11

to support the user equipment 12 and core network 14 interface requirements. An optional repeater 16 may be deployed.

In Fig. 2, the PHY reference model is shown. This reference model is useful in discussing the various aspects of the PHY technique. As is apparent, the SS 10 and BS
5 transmission and reception equipment may be symmetrical.

The PHY interfaces with the Media Access Control (MAC) layer, carrying MAC packets and enabling MAC functions based on Quality of Service (QoS) requirements and Service Level Agreements (SLAs). As a S-CDMA system, the PHY interacts with the MAC for purposes of power and timing control. Both power and timing control
10 originate from the BS 11, with feedback from the SS 10 needed for forward link power control. The PHY also interacts with the MAC for link adaptation (e.g. bandwidth allocation and SLAs), allowing adaptation of modulation formats, coding, data multiplexing, etc.

With regard to frequency bands and RF channel bandwidths, the primary frequency
15 bands of interest for the PHY include the ETSI frequency bands from 1-3 GHz and 3-11 GHz as described in ETSI EN 301 055, Fixed Radio Systems; Point-to-multipoint equipment; Direct Sequence Code Division Multiple Access (DS-CDMA); Point-to-point digital radio in frequency bands in the range 1 GHz to 3 GHz, and in ETSI EN 301 124, Transmission and Multiplexing (TM); Digital Radio Relay Systems (DRRS);
20 Direct Sequence Code Division Multiple Access (DS-CDMA) point-to-multipoint DRRS in frequency bands in the range 3 GHz to 11 GHz, as well as with the MMDS/MDS (digital TV) frequency bands. In ETSI EN 301 124, the radio specifications for DS-CDMA systems in the fixed frequency bands around 1.5, 2.2, 2.4 and 2.6 GHz are given, allowing channelizations of 3.5, 7, 10.5 and 14 MHz. Here, the
25 Frequency Division Duplex (FDD) separation is specific to the center frequency and ranges from 54 to 175 MHz. In ETSI EN 301 124, Transmission and Multiplexing (TM); Digital Radio Relay Systems (DRRS); Direct Sequence Code Division Multiple Access (DS-CDMA) point-to-multipoint DRRS in frequency bands in the range 3 GHz to 11 GHz, the radio characteristics of DS-CDMA systems with fixed frequency bands
30 centered around 3.5, 3.7 and 10.2 GHz are specified, allowing channelizations of 3.5, 7, 14, 5, 10 and 15 MHz. Here, FDD separation is frequency band dependant and ranges from 50 to 200 MHz. Also of interest to these teachings the MMDS/ITSF frequency bands between 2.5 and 2.7 GHz with 6 MHz channelizations.

With regard to multiple access, duplexing and multiplexing, the teachings herein provide a frequency division duplex (FDD) PHY using a hybrid S-CDMA/FDMA multiple access scheme with SDMA for increased spectral efficiency. In this approach, a FDMA sub-channel has an RF channel bandwidth from 1.75 to 7 MHz. The choice of FDMA sub-channel RF channel bandwidth is dependent on the frequency band of interest, with 3.5 MHz and 6 MHz being typical per the IEEE 802.16.3 FRD. Within each FDMA sub-channel, S-CDMA is used with those users transmitting in the upstream and downstream using a constant chipping rate from 1 to 6 Mcips/second. While TDD could be used in a single RF sub-channel, this discussion is focused on the FDD mode of operation. Here, FDMA sub-channel(s) are used in the downstream while at least one FDMA sub-channel is required for the upstream. The approach is flexible to asymmetric data traffic, allowing more downstream FDMA sub-channels than upstream FDMA sub-channels when traffic patterns and frequency allocation warrant. Based on existing frequency bands, typical upstream/downstream FDMA channel separation range from 50 to 200 MHz.

Turning now to the Synchronous DS-CDMA (S-CDMA) aspects of these teachings, within each FDMA sub-channel, S-CDMA is used in both the up and downstream. The chipping rate is constant for all SS with rates ranging from 1 to 6 Mcips/second depending on the FDMA RF channel bandwidth. Common I-Q spreading is performed using orthogonal, variable-length spreading codes based on Walsh-Hadamard designs with spread factors ranging from 1 up to 128 chips per symbol, see E. Dinan and G. Jabbari, "Spreading Codes for Direct Sequence CDMA and Wideband CDMA Cellular Networks," IEEE Communications Magazine, September 1998, pp. 48-54. For multi-cell deployments with low frequency reuse, unique spreading code sets are used in adjacent cells to minimize interference.

It should be noted that as aspect of these teachings is a symmetric waveform within each FDMA sub-channel, where both the upstream and downstream utilize the same chipping rate (and RF channel bandwidth), spreading code sets, modulation, channel coding, pulse shape filtering, etc.

Referring now to Code and Time Division Multiplexing and channel aggregation, with a hybrid S-CDMA/FDMA system it is possible to multiplex data over codes and frequency sub-channels. Furthermore, for a given code or frequency channel, time division multiplexing could also be employed. In the preferred approach, the following multiplexing scheme is employed:

For the downstream transmission with a single FDMA sub-channel, the channel bandwidth (i.e. capacity measured in bits/second) is partitioned into a single TDM pipe and multiple CDM pipes. The TDM pipe may be created via the aggregation of multiple S-CDMA channels. The purpose of this partition is based on the desire to provide Quality of Service (QoS). Within the bandwidth partition, the TDM pipe would be used for best effort service (BES) and for some assured forwarding (AF) traffic. The CDM channels would be used for expedited forwarding (EF) services, such as VoIP connections or other stream applications, where the data rate of the CDM channel is matched to the bandwidth requirement of the service.

Of course, the downlink could be configured as a single TDM pipe. Here, time slot assignment may be employed for bandwidth reservation, with typical slot sizes ranging from 4–16 ms in length. While a pure TDM downlink is possible in this approach, it is preferred instead to employ a mixed TDM/CDM approach. This is so because long packets can induce jitter into EF services in a pure TDM link. Having CDMA channels (single or aggregated) dedicated to a single EF service (or user) reduces jitter without the need for packet fragmentation and reassembly. Furthermore, these essentially “circuit-switched” CDM channels would enable better support of legacy circuit-switched voice communications equipment and public switched telephone networks.

For the upstream, the preferred embodiment employs a similar partition of TDM/CMD channels. The TDM channel(s) would be used for random access, using a slotted-Aloha protocol. In keeping with a symmetric waveform, recommended burst lengths are on the order of the slot times for the downlink, ranging from 4-16 ms. Multi-slot bursts are possible. The BS 11 monitors bursts from the SS 10 and allocates CDMA channels to SSs upon recognition of impending bandwidth requirements or based on service level agreements (SLAs). As an example, a BS 11 recognizing the initiation of a VoIP connection could move the transmission to a dedicated CDMA channel with a channel bandwidth of 32 kbps.

When multiple FDMA sub-channels are present in the up or downstream, similar partitioning could be used. Here, extra bandwidth exists meaning more channel aggregation is possible. With a single TDM channel, data would be multiplexed across CDMA codes and across frequency sub-channels.

With regard now to Space Division Multiple Access (SDMA) extensions, a further aspect of this multiple access scheme involves the use of SDMA using adaptive

beamforming antennas. Reference can be made to J. Liberti and T. Rappaport, Smart Antennas for Wireless CDMA, Prentice-Hall PTR, Upper Saddle River, NJ, 1997, for details of beamforming with CDMA systems.

5 In accordance with the teachings herein there is provided an adaptive antenna array at the BS 11, with fixed beam SS antennas. In this approach, S-CDMA/FDMA channels can be directed at individual SSs. The isolation provided by the beamforming allows the CDMA spreading codes to be reused within the same cell, greatly increasing spectral efficiency. Beamforming is best suited to CDM rather than TDM channels. In the downstream, TDM would employ beamforming on a per slot or burst basis, increasing
10 complexity. In the upstream, beamforming would be difficult since the BS would need to anticipate transmission from the SS in order to form the beams appropriately. In either case, reuse of CDMA spreading codes in a TDM-only environment would be difficult. With CDM, however, the BS 11 could allocate bandwidth (i.e. CDMA channels) to SS 10 based on need or on SLAs. Once allocated, the BS 11 would form
15 a beam to the SS 10 to maximize signal-to-interference ratios. Once formed, the BS 11 could allocate the same CDMA channel to other SSs in the cell. It is theoretically possible for the spectral efficiency of the cell to scale linearly with the number of antennas in the BS array.

SDMA greatly favors the approach of “fast circuit-switching” over pure, TDM packet-switching in a CDMA environment. By “fast circuit-switching”, what is implied is a packet-services that is handled using dedicated connections, which are allocated and terminated based on bandwidth requirements and/or SLAs. An important consideration when providing effective packet-services using this approach lies in the ability of the BS
20 11 to rapidly determine bandwidth needs and the allocate and terminate connections rapidly. With fast channel allocation and termination, SDMA combined with the low frequency reuse offered by S-CDMA is the best option in terms of spectral efficiency for FWA applications.

A discussion is now made of waveform specifications. The waveform includes the channel coding, scrambling, modulation, pulse shaping and equalization functions of the
30 air interface. Also included are waveform control functions, including power and timing control. In the presently preferred PHY, each CDMA channel (i.e. spreading code) uses a common waveform, with the spreading factor dictating the rate of the channel.

With regard to Error Control Coding (ECC), the error control coding is preferably high-

rate and adaptive. High rate codes are used to maximize the spectral efficiency of BWA systems using S-CDMA systems that are code-limited. In code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. Adaptive coding is preferred in order to improve performance in multipath fading environments. For the coding options, the baseline code is a punctured, convolutional code (CC). The constituent code is the industry standard, rate 1/2, constraint length 7 code with generator $(133/171)_8$. Puncturing is used to increase the rate of the code, with rates of 3/4, 4/5, 5/6 or 7/8 supported using optimum free distance puncturing patterns. The puncturing rate of the code may be adaptive to mitigate fading conditions. For decoding, a Viterbi decoder is preferred. Reference in this regard can be made again to the above-noted publication R. De Gaudenzi and F. Gianneti, "Analysis and Performance Evaluation of Synchronous Trellis-Coded CDMA for Satellite Applications," IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995, pp. 1400-1409, for an analysis of trellis-coded S-CDMA.

Turbo coding, including block turbo codes and traditional parallel and serial concatenated convolutional codes, are preferably supported as an option at the rates suggested above.

Each CDMA channel is preferably coded independently. Independent coding of CDMA channels furthers the symmetry of the upstream and downstream waveform and enables a similar time-slot structure on each CDMA channel. The upstream and downstream waveform symmetry aids in cost reduction, as the SS and BS baseband hardware can be identical. The independent coding of each S-CDMA/FDMA channel is an important distinction between this approach and other multi-carrier CDMA schemes.

Randomization is implemented on the coded bit stream. Rather than using a traditional randomizing circuit, it is preferred to use randomizing codes derived from the spreading sequences used by the transmitting station. Using the spreading codes allows different randomizing sequences to be used by different users, providing more robust randomization and eliminating problems with inter-user correlated data due to periodic sequences transmitted (e.g. preambles). Since the receiving station has knowledge of the spreading codes, de-randomization is trivial. Randomization may be disabled on a per channel or per symbol basis. Fig. 3 shows the preferred channel coding and scrambling method for a single CDMA channel.

With regard to modulation, both coherent QPSK and square 16-QAM modulation

formats are supported, with optional support for square 64-QAM. Using a binary channel coding technique, Gray-mapping is used for constellation bit-labeling to achieve optimum decoded performance. This combined coding and modulation scheme allows simple Viterbi decoding hardware designed for binary codes to be used. Differential
5 detection for all modulation formats may be supported as an option. Depending on the channel coding, waveform spectral efficiencies from 1 to 6 information bits/symbol are realized.

The modulation format utilized is preferably adaptive based on the channel conditions and bandwidth requirements. Both up and downstream links are achievable using QPSK
10 waveform provided adequate SNR. In environments with higher SNR, up and downstream links may utilize 16-QAM and /or 64-QAM modulation formats for increased capacity and spectral efficiency. The allowable modulation format depends on the channel conditions and the channel coding being employed on the link.

End-to-end raised-cosine Nyquist pulse shaping is applied using a minimum roll-off
15 factor of 0.25. Pulse shape filtering is designed to meet relevant spectral masks, mitigate inter-symbol interference (ISI) and adjacent FDMA channel interference.

To mitigate multipath fading, a linear equalizer is preferred for the downstream. Equalizer training may be done using a preamble, with decision-direction used following initial training. With S-CDMA, equalizing the aggregate signal in the downlink
20 effectively equalizes all CDMA channels. Multipath delay spread of less than 3 μ s is expected for Non-Line Of Sight (NLOS) deployments using narrow-beam (10-20°) subscriber station 10 antennas (see, for example, J. Porter and J. Thweat, "Microwave Propagation Characteristics in the MMDS Frequency Band," Proceedings of IEEE International Conf. On Communications (ICC) 2000, New Orleans, LA, USA, June
25 2000, and V. Erceg, et al, "A Model for the Multipath Delay Profile of Fixed Wireless Channels," IEEE Journal on Selected Areas in Communications (JSAC), Vol. 17, No. 3, March 1999, pp. 399-410.

The low delay spread allows simple, linear equalizers with 8-16 taps that effectively equalize most channels. For the upstream, pre-equalization may be used as an option,
30 but requires feedback from the subscriber station 10 due to frequency division duplexing.

Timing control is required for S-CDMA. In the downstream, timing control is trivial.

However, in the upstream timing control is controlled by the BS 11. Timing-control results in reduced in-cell interference levels. While infinite in-cell signal to interference ratios are theoretically possible, timing errors and reduction in code-orthogonality from pulse shape filtering allows realistic signal to in-cell interference ratios from 30-40 dB.

5 In asynchronous DS-CDMA (A-CDMA) systems, higher in-cell interference levels exist, less out-of-cell interference can be tolerated and higher frequency reuse is needed to mitigate out-of-cell interference(see, for example, T. Rappaport, Wireless Communications: Principles and Practice, Prentice-Hall PTR, Upper Saddle River, NJ, 1996, pp. 425-431. The ability of timing-control to limit in-cell interference is an

10 important aspect of achieving a frequency reuse of one in a S-CDMA system.

Power control is also required for S-CDMA systems. Power control acts to mitigate in-cell and out-of-cell interference while also ensuring appropriate signal levels at the SS 10 or the BS 11 to meet bit error rate (BER) requirements. For a SS 10 close to the BS 11, less transmitted power is required, while for a distant SS 10, more transmit power is required in both the up and downstream. As with timing control, power control is an

15 important aspect of achieving a frequency reuse of one.

Turning now to a discussion of capacity, spectral efficiency and data rates, for a single, spread FDMA channel, the presently preferred S-CDMA waveform is capable of providing channel bandwidths from 1 to 16 Mbps. Using variable-length spreading codes, each CDMA channel can be configured to operate from 32 kbps (SF=128) to 16 Mbps (SF=1), with rates depending on the modulation, coding and RF channel bandwidths. With S-CDMA channel aggregation, high data rates are possible without requiring a SF of one. In general, the use of S-CDMA along with the presently preferred interference mitigation techniques enable the system to be code-limited. Note, mobile

20 cellular A-CDMA systems are always interference-limited, resulting in lower spectral efficiency. Recall also that in code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. In a code-limited environment, the communications channel bandwidth of the system is equal to the communications channel bandwidth of the waveform, assuming a SF of one. In the

25 Table shown in Fig. 4 sample parameters are shown for a hypothetical system using different coded modulation schemes and assuming a code-limited DS-CDMA environment. The Table of Fig. 4 illustrates potential performance assuming a single 3.5 MHz channel in both the upstream and downstream. The numbers reported apply to both upstream and downstream, meaning that upwards of 24 Mbps full duplex is

30 possible (12 Mbps upstream and 12 Mbps downstream). With additional FDMA RF

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channels or large RF channels [e.g. 6 MHz], additional communication bandwidth is possible with the same modulation factors from the Table. As an example, allocation of 14 MHz could be serviced using 4 FDMA RF channels with the parameters described in the Table of Fig. 4. At 14 MHz, peak data rates to a SS 10 up to 48 Mbps are achievable, with per CDMA channel data rates scaling up from 32 kbps. The channel aggregation method in accordance with these teachings is very flexible in servicing symmetric versus asymmetric traffic, as well as for providing reserved bandwidth for QoS and SLA support.

With regard to multi-cell performance, to this point both the capacity and spectral efficiency have been discussed in the context of a single, isolated cell. In a multi-cell deployment, S-CDMA enables a true frequency reuse of one. With S-CDMA, there is no need for frequency planning, and spectral efficiency is maximized. With a frequency reuse of one, the total system spectral efficiency is equal to the modulation factor of a given cell. Comparing S-CDMA to a single carrier TDMA approach, with a typical frequency reuse of 4, TDMA systems must achieve much higher modulation factors in order to compete in terms of overall system spectral efficiency. Assuming no sectorization and a frequency reuse of one, S-CDMA systems can achieve system spectral efficiencies from 1 to 6 bps/Hz, with improvements being possible with SDMA.

While frequency reuse of one is theoretically possible for DS-CDMA, the true allowable reuse of a specific deployment is dependent on the propagation environment (path loss) and user distribution. For mobile cellular systems, it has been shown that realistic reuse factors range from 0.3 up to 0.7 for A-CDMA: factors that are still much higher than for TDMA systems. In a S-CDMA system, in-cell interference is mitigated by the orthogonal nature of the S-CDMA, implying that the dominant interference results from adjacent cells. For the fixed environments using S-CDMA, true frequency reuse of one can be achieved for most deployments using directional SS antennas and up and downstream power control to mitigate levels of adjacent cell interference. In a S-CDMA environment, true frequency reuse of one implies that a cell is code-limited, even in the presence of adjacent cell interference.

For sectorized deployments with S-CDMA, a frequency reuse of two is required to mitigate the interference contributed by users on sector boundaries. In light of this reuse issue, it is preferred to use SDMA with adaptive beamforming rather than sectorization to improve cell capacity.

Since spectral efficiency translates directly into cost, the possibility of a frequency reuse of one is an important consideration.

- 5 The use of SDMA in conjunction with S-CDMA offers the ability to dramatically increase system capacity and spectral efficiency. SDMA uses an antenna array at the BS 11 to spatially isolate same code SSs 10 in the cell. The number of times that a code may be reused within the same cell is dependent upon the number of antenna elements in the array, the array geometry, the distribution of users in the cell, the stability of the channel, and the available processing power. Theoretically, in the absence of noise, with an M element antenna array it is possible to reuse each code sequence M times, thereby increasing system capacity by a factor of M . In practice, the code reuse is slightly less than M due to implementation loss, frequency selective multipath fading, and receiver noise. Regardless, significant capacity gains are achievable with SDMA. With appropriate array geometry and careful grouping of users sharing CDMA codes, it is possible to achieve a code reuse of $0.9M$ or better.
- 10
- 15 In an actual deployment the number of antenna elements is limited by the available processing power, the physical tower constraints, and system cost (e.g. the number of additional RF front ends (RFFE's)). Selected array sizes vary depending upon the required capacity of the given cell on a cell-by-cell basis. The Table shown in Fig. 5 illustrates the achievable aggregate capacity and modulation factor with typical array sizes, assuming a code reuse equal to the number of antenna elements. The aggregate capacity is defined as the total data rate of the BS 11. Modulation factors exceeding 56 bps/Hz are achievable with 64 QAM and a sixteen-element antenna array. It should be noted that while SDMA increases the capacity of cell, it does not increase the peak data rate to a given SS 10.
- 20
- 25 The PHY system disclosed herein is very flexible. Using narrowband S-CDMA channels, the PHY system can adapt to frequency allocation, easily handling non-contiguous frequency allocations. The data multiplexing scheme allows great flexibility in servicing traffic asymmetry and support of traffic patterns created by higher-layer protocols such as TCP.
- 30 Deployments using the disclosed PHY are very scalable. When traffic demands increase, new frequency allocation can be used. This involves adding additional FDMA channels, which may or may not be contiguous with the original allocation. Without additional frequency allocation, cell capacity can be increased using an adaptive antenna

array and SDMA.

The high spectral efficiency of the disclosed waveform leads to cost benefits. High spectral efficiency implies less frequency bandwidth is required to provide a certain amount of capacity.

- 5 Using a symmetric waveform (same in the upstream and downstream), is a cost saving feature, allowing the use of common baseband hardware in the SS 10 and the BS 11. The use of CDMA technology also aids in cost reduction, as some CDMA technology developed for mobile cellular applications may be applicable to gain economies of scale.

- 10 As a spread spectrum signal, the proposed waveform offers inherent robustness to interference sources. Interference sources are reduced by the spreading factor, which ranges from 1 to 128 (interference suppression of 0 to 21 dB.) At the SS 10, equalization further suppresses narrowband jammers by adaptively placing spectral nulls at the jammer frequency. Additional robustness to interference is achieved by the directionality of the SS antennas, since off-boresight interference sources are attenuated
15 by the antenna pattern in the corresponding direction. At the BS 11, the antenna array used to implement SDMA offers the additional benefit of adaptively steering nulls towards unwanted interference sources.

- 20 The presently proposed waveform exhibits several properties that make it robust to channel impairments. The use of spread spectrum makes the waveform robust to frequency selective fading channels through the inherent suppression of inter-chip interference. Further suppression of inter-chip interference is provided by equalization at the SS 10. The waveform is also robust to flat fading channel impairments. The adaptive channel coding provides several dB of coding gain. The antenna array used to implement SDMA also functions as a diversity combiner. Assuming independent fading
25 on each antenna element, diversity gains of M are achieved, where M is equal to the number of antenna elements in the array. Finally, since the S-CDMA system is code-limited rather than interference limited the system may run with a large amount of fade margin. Even without equalization or diversity, fade margins on the order of 10 dB are possible. Therefore, multipath fades of 10 dB or less do not increase the BER beyond
30 the required level.

The adaptive modulation also provides some robustness to radio impairments. For receivers with larger phase noise, the QPSK modulation offers more tolerance to

receiver phase noise and filter group delay. The adaptive equalizer at the SS 10 reduces the impact of linear radio impairments. Finally, the use of clipping to reduce the peak-to-average power ratio of the transmitter signal helps to avoid amplifier saturation, for a given average power output.

- 5 An important distinction between the presently preferred embodiment and a number of other CDMA approaches is the use of a synchronous upstream, which allows the frequency reuse of one. Due to some similarity with mobile cellular standards, cost savings are possible using existing, low-cost CDMA components and test equipment.

10 The presently preferred PHY is quite different from cable modem and xDSL industry standards, as well as existing IEEE 802.11 standards. However, with a spreading factor of one chip/symbol, the PHY supports a single-carrier QAM waveform similar to DOCSIS 1.1 and IEEE 802.16.1 draft PHY (see "Data-Over-Cable Service Interface Specifications: Radio Frequency Interface Specification", SP-RF1v1.1-I05-000714, and IEEE 802.16.1-00/01r4, "Air Interface for Fixed Broadband Wireless Access Systems",
15 September 2000.

The presently preferred PHY technique provides an optimum choice for IEEE 802.16.3 and for other applications. An important aspect of the PHY is its spectral efficiency, as this translates directly to cost measured in cost per line or cost per carried bit for FWA systems. With a frequency reuse of one and efficient support of SDMA for increased
20 spectral efficiency, the combination of S-CDMA with FDMA is an optimum technology for the fixed wireless access market.

Benefits of the presently preferred PHY system include:

High spectral efficiency (1-6 bps/Hz system-wide), even without SDMA;

25 Compatibility with smart antennas (SDMA), with system-wide spectral efficiency exceeding 20 bps/Hz possible; and

A frequency reuse of one possible (increased spectral efficiency and no frequency planning).

The use of S-CDMA provides robustness to channel impairments (e.g. multipath

Also provided is bandwidth flexibility and efficiency support of QoS requirements, flexibility to support any frequency allocation using a combination of narrowband S-CDMA combined with FDMA, while adaptive coding and modulation yield robustness to channel impairments and traffic asymmetries.

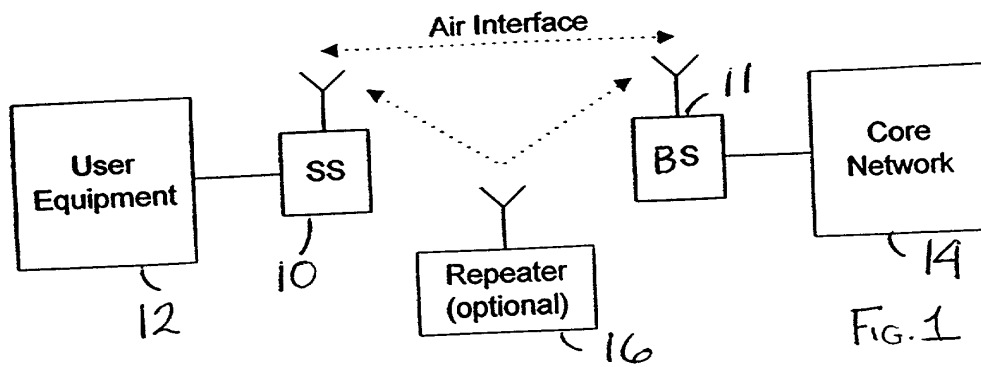
Having thus described the overall PHY system, reference may now be had to the attached Appendices A, B, C, D, E, F and G, each of which is incorporated by reference herein in its entirety, for providing further disclosure regarding various presently preferred embodiments of this invention.

While the invention has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that changes in form and details may be made therein without departing from the scope and spirit of the invention.

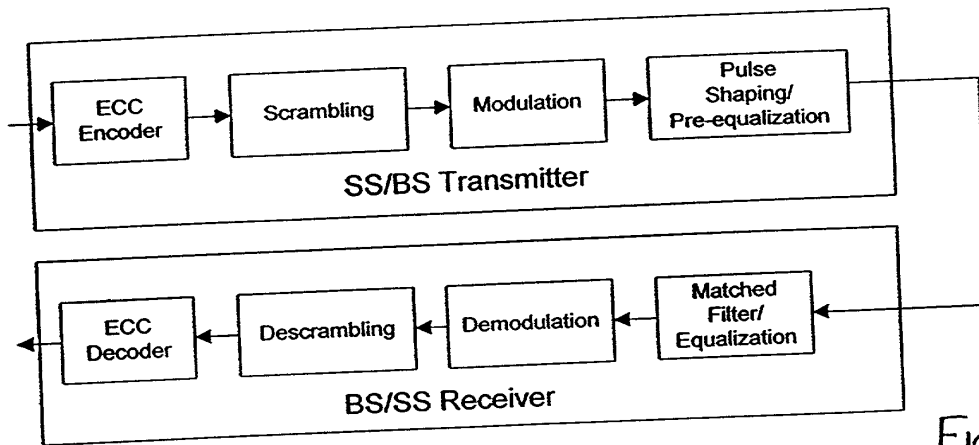
ABSTRACT OF THE DISCLOSURE

A synchronous CDMA communication system operates with adaptive SDMA and enhanced PN code assignment and chip transmission capabilities. This invention provides enhanced operation of a Synchronous CDMA system through the use of Space Division Multiple Access (SDMA), as well as improved code assignment and selection techniques, with or without chip repetition to produce a flexible bandwidth..

Variable	Mean		SD		t		p	
	Control	Case	Control	Case	Control	Case	Control	Case
Age	24.5	24.5	1.5	1.5	0.0	0.0	1.0	1.0
Gender	10	10	0	0	0.0	0.0	1.0	1.0
Education	12	12	0	0	0.0	0.0	1.0	1.0
Occupation	10	10	0	0	0.0	0.0	1.0	1.0
Marital status	10	10	0	0	0.0	0.0	1.0	1.0
Religion	10	10	0	0	0.0	0.0	1.0	1.0
Income	10	10	0	0	0.0	0.0	1.0	1.0
Health status	10	10	0	0	0.0	0.0	1.0	1.0
Family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental religion	10	10	0	0	0.0	0.0	1.0	1.0
Parental income	10	10	0	0	0.0	0.0	1.0	1.0
Parental health status	10	10	0	0	0.0	0.0	1.0	1.0
Parental family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental religion	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental income	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental health status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental religion	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental income	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental health status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental religion	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental income	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental health status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental religion	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental income	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental health status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental family size	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental parental education	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental parental occupation	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental parental parental parental marital status	10	10	0	0	0.0	0.0	1.0	1.0
Parental parental parental								



Wireless Access Reference Model



PHY Reference Model Showing Data Flow

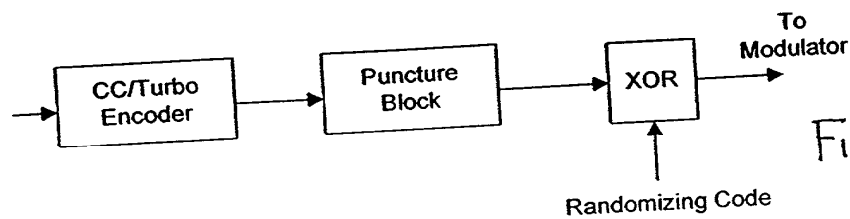


Fig. 3

Parameter	Modulation and Channel Coding		
	QPSK w/ R=4/5 Coding (1.6 bits/sym)	16-QAM w/ R=4/5 Coding (3.2 bits/sym)	64-QAM w/ R=4/5 Coding (4.8 bits/sym)
RF Channel Bandwidth	3.5 MHz	3.5 MHz	3.5 MHz
Chip Rate	2.56 Mcps	2.56 Mcps	2.56 Mcps
Communication Channel Bandwidth	4.096 Mbps	8.192 Mbps	12.288 Mbps
Peak Data Rate	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=1)	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=16)	256 kbps	512 kbps	768 kbps
CDMA Channel Bandwidth (SF=128)	32 kbps	64 kbps	96 kbps
Modulation Factor	1.17 bps/Hz	2.34 bps/Hz	3.511 bps/Hz

FIG.4 Hypothetical parameters for a 3.5 MHz RF channelization

Number of Elements	QPSK		16 QAM		64 QAM	
	Aggregate Capacity (Mbps)	Modulation Factor	Aggregate Capacity (Mbps)	Modulation Factor	Aggregate Capacity (Mbps)	Modulation Factor
1	4.096	1.17	8.192	2.34	12.288	3.511
2	8.192	2.34	16.384	4.68	24.576	7.022
4	16.384	4.68	32.768	9.36	49.152	14.044
8	32.768	9.36	65.536	18.72	98.304	28.088
16	65.536	18.72	131.072	37.44	196.608	56.176

FIG.5 Aggregate capacity and modulation factors versus modulation type and array size.

APPENDIX A

Spreading Code Hopping for DS-CDMA Systems

Abstract:

In this work, a technique whereby users in a DS-CDMA system hop or exchanging spreading codes during the transmission on a block-by-block or symbol-by-symbol basis is introduced. The concept is applicable to both fixed and variable-rate DS-CDMA systems and has many benefits to system performance. First, code hopping has the effect of randomizing the codes, much like a cover code, for the mitigation of adjacent cell interference. This is particularly important when small spreading gains ($P < 16$ chips/symbol) are used, since the design of code sets with such small spreading gain is difficult when attempting to minimize cross-correlation between adjacent cell code sets. Much like cover codes "scramble" the spreading codes in adjacent cells, code hopping results in an averaging of interference over the user population of a cell, without a single user suffering severe degradation due to adjacent cell interference. Typically, adjacent cells would use different code sets and different hopping patterns.

Code hopping has several advantages over cover codes while providing the same mitigation of adjacent cell interference. First, code hopping has a very simple hardware implementation using a memory and a finite state machine to generate the hopping pattern. Secondly, orthogonal DS-CDMA systems using cover codes require that that all CDMA channels, including the control and random access channels, must use the cover code. With a long cover code on the random access channel, new users can take longer to acquire since the phase of the cover code must be recovered. With code hopping, the codes used for random access and control can be omitted from the hopping sequence. These non-hopped codes can be acquired with reduced acquisition time and complexity. Thirdly, code hopping preserves the balance in a code set unlike cover codes, which unbalance, balanced code sets. Balanced codes can be important for orthogonal DS-CDMA systems since they prevent DC biasing problems in the receiver. Finally, orthogonal code sets constructed using randomized Walsh-Hadamard matrices typically have $P-1$ balanced codes and one completely unbalanced code, the all one's codes. Without a cover code, the all one's code would be unused due to DC bias problems and large correlation with adjacent cell codes. The omission of the all one's code reduces the capacity of the cell. With code hopping, the all one's code can be used, provided it is a hopped code. Since users only use the all one's code for a symbol or small block, the potential signal degradations due to adjacent cell interference and DC biasing problems will be sporadic and can be easily corrected using normal error control techniques. All in all, hopping of spreading codes can increase robustness and improve the capacity of a DS-CDMA system.

Introduction:

A common method to increase the data rate of a DS-CDMA system operating with a fixed chipping rate is to implement variable rate spreading codes. In this manner, very few chips modulate each symbol in order to increase the effective symbol rate of the system. As the spreading gain decreases, the design of code sets that have good cross-correlation properties with other code sets, becomes very difficult. In cellular deployments, adjacent cells using a common frequency band must have code sets that have low cross-correlation values in order to minimize adjacent channel interference. For spreading gains on the order of 8 or 16 chips/symbol, code sets with these low correlation properties are almost impossible to find.

The result of using the smaller spreading gains is that there will be instances where users in adjacent cells may end up using codes which are highly correlated for a given offset, resulting in potentially significant amounts of interference. In a DS-CDMA system where users are assigned fixed codes, using the wrong code at the wrong offset can result in significant levels of adjacent channel interference for every transmitted symbol. A users stuck in this situation would experience a much lower signal-to-noise ratio than other users in the cell. To combat this worst-case user, cover codes could be used in the adjacent cells, effectively scrambling the spreading codes and reducing the frequency of perfect and highly correlated levels of interference. A cover code would slightly reduce the signal-to-noise ratio for all users with the aim of preventing any user with a severe degradation in signal-to-noise due to adjacent cell code cross-correlation.

While the use of cover codes is attractive to solving the problem of worst-case adjacent channel interference resulting from high levels of code correlation, there are some associated problems. First, IP issues hinder the application of cover codes [1]. Second, cover codes constructed using long-period linear-feedback shift registers (LFSR) results in unbalanced spreading codes. Third, for orthogonal designs, the cover code must be applied to all CDMA channels, including the control and random access channels resulting in potentially longer and more complex acquisition schemes. To overcome the difficulties with cover codes, in this paper we propose a novel technique based on spreading code hopping to mitigate the worst-case adjacent cell interference problem and provide several benefits not available with cover codes.

Advantages of Code Hopping in a DS-CDMA System:

Code hopping for DS-CDMA allows the users to change CDMA codes on a symbol-by-symbol or block-by-block basis. The concept of code hopping in a DS-CDMA system is very much akin to the concept of frequency hopping in a frequency-hopped spread spectrum (FH-SS) system. In FH-SS, users hop between orthogonal frequency bands on a symbol-by-symbol (fast-frequency hopping) or a block-by-block (slow-frequency hopping) using a pseudo-random hopping pattern. With purely random hopping patterns, collisions may result and error control coding is required. In an orthogonal DS-CDMA system, users are isolated nearly-perfectly by the use of orthogonal spreading codes. Typically, these codes are assigned upon link establishment

and remain fixed during the duration of the link. There is no added benefit in terms of in-cell isolation for swapping spreading codes in a DS-CDMA system. However, there is a benefit in terms of mitigating adjacent cell interference.

With code hopping, the case where a single user gets "stuck" in a bad offset and experience a severe degradation in signal-to-noise is avoided since users are constantly exchanging codes. If a bad offset results, the effects are felt by all users since all users will use the offending code periodically. In this case, the average signal-to-noise ratio of all users is reduced to minimize the impact on the worst-case user, much like happens with a cover code. In fact, coding hopping is very similar to the use of a cover code.

With a cover code, each spreading code is scrambled using a different scrambling sequence for every symbol. All users within the cell must use the same cover code in order to maintain orthogonality between users. Typically, different cover codes or different shifts of a given cover code will be used in adjacent cells. For code hopping, the scrambling operation of the cover code is replaced by the periodic rotation of the codes in a sequential or pseudo-random manner. In this way, a user who uses spreading code c_1 to spread symbol 1 will use spreading code c_2 to spread symbol 2 with c_1 and c_2 being mutually orthogonal. Likewise, the user would use spreading code c_3 to modulate symbol 3 and so on. It is not difficult to show that for any code hopping pattern, there exist a cover code such that the resulting spreading sequence $[c_1 c_2 c_3 \dots]$ is the same as for the code hopping scheme. This can easily be seen from the example. Here, there exist translation codes tc_1 and tc_2 such that $c_2 = c_1 * tc_1$ and $c_3 = c_1 * tc_2$. Therefore, hopping from c_1 to c_2 to c_3 , etc. can be viewed as applying a cover code equal to $[tc_1 tc_2 \dots]$. By the orthogonality of the design, it follows that tc_1 and tc_2 must be in the original code set, i.e. there exist i and j such that $c_i = tc_1$ and $c_j = tc_2$. Therefore, for a given user, code hopping is equivalent to using a cover code constructed from the codes in the original code set. However, two users using the same code hopping pattern, with different phases would require two different cover codes for equivalence. Therefore, code hopping in a DS-CDMA system is equivalent to applying a different, orthogonal cover code to each spreading code.

The benefits to code hopping versus traditional cover code approaches are many. First, coding hopping provides the same effective "scrambling" of users necessary to avoid the worst-case adjacent cell interference problems. Secondly, code hopping has a very simple implementation as shown in Figure 1. In this Figure, a base code set containing all the base code vectors (c_i 's) is shown. It assumed that the set is constructed from orthogonal designs with the code vectors of sets $(c_1 \dots c_P)$, $(c_{P+1} \dots c_{2P})$, ... $(c_{(n-1)P+1} \dots c_{nP})$ being mutually orthogonal. The motivation for code sets constructed from mutually orthogonal designs comes from the need to mitigate adjacent cell interference. The interested reader is referred to [1] for details of a recursive and non-recursive code construction schemes.

In the circuit of Figure 1, the address generator, which can be a linear-feedback shift register or a RAM, is clocked at the hopping rate of the codes and outputs a $1 \times P$ vector of chips to modulate (or spread) the data. To hop codes every symbol, the address

generator would clock at the symbol rate of the transmission. The address generator must be designed such that collisions (i.e. two users using the same code) are avoided. The simplest implementation of code hopping is to use sequential hopping, where the address generator simply an up/down counter seeded by an integer $0 \dots P-1$. Every user would get a unique seed to avoid collisions with the seed representing a pointer into the code set table.

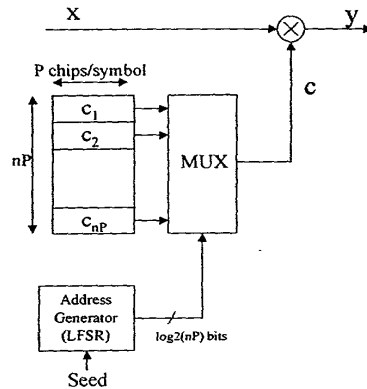


Figure 1: Circuit to implement code hopping in a DS-CDMA system

Another benefit of code hopping versus cover codes is that balanced codes are preserved. It has been shown that cover codes can be constructed which preserve balance, provided the cover code is balanced over the blocks of P chips, where P is the desired spreading gain of the system. The authors are aware of no, long cover code which exhibits this property. The fact that balance is preserved with code hopping means that DC biasing problems in the receiver are reduced.

A final benefit of code hopping is that the all one's can be used in orthogonal DS-CDMA systems. Typically, the all one's code is unused due to high levels of correlation in adjacent cells and DC biasing problems in the receiver. Without hopping, a user assigned the all one's code would expect much lower signal-to-noise ratios than other users. With code hopping, all users periodically use the all one's code, reducing the effective signal-to-noise ratio of all users, while preventing any one user from being severely degraded. Reclaiming the all one's code in a synchronous DS-CDMA system with fixed spreading gain P increases the capacity by $1/P$ percent.

Code Hopping for Fixed Rate CDMA Systems:

In a fixed-rate DS-CDMA system, all users spread with a fixed spreading gain P chips/symbol. Here, the application of code hopping is very straightforward. In a given cell or sector, the spreading code set is partitioned into hopped and non-hopped codes and a code hopping pattern and hop duration specified. In this case, the hop duration can be either the symbol rate (chipping rate / P) or multiple chips. Hopping is not allowed in the middle of symbols since orthogonality of users would be compromised. Upon link establishment, a user assigned to a hopped code would be given an initial seed or phase of the hopping pattern and begin transmission. The initial phase is sufficient for both the transmitter and receiver to be able to recover (or despread) the data correctly.

Code Hopping for Variable Rate CDMA Systems:

As with fixed rate, the application of code hopping to a variable rate CDMA system is very straightforward, but does require some explanation. In a variable rate DS-CDMA system, users operate with a fixed chipping rate, but can choose spreading codes with differing spreading gains in order to achieve different symbol rates. Typically, a minimum spreading gain is specified, say $P_{\min}$ of 8 or 16, along with a maximum spreading gain $P_{\max} = n P_{\min}$. A variable rate spreading code set is constructed from a base code set having $P_{\min}$ codes. Suffice it to say the variable rate spreading code sets can be constructed using this base code set via recursive techniques, as in [1], or non-recursive techniques, as in [2,3]. In either construction, a single base code with $P_{\min}$ chips/symbol will form two orthogonal codes with $2 P_{\min}$ chips/symbol, four orthogonal codes with $4 P_{\min}$ chips/symbol and so. The base code or parent is present in each of codes with higher spreading gain.

For code hopping applied to variable rate CDMA, the most straightforward-hopping approach is for users to hop at a multiple of the symbol rate of the lowest symbol rate (or highest spreading gain). In this scheme, a user using a spreading gain of $P_{\max}$ would use his code for $k=1,2,\dots$ etc. symbols, where as a user using a code at $P_{\min}$ would use his code for kn symbols where $P_{\max} = n P_{\min}$. With this hopping scheme, orthogonality is preserved but users with small spreading gain are forced to hop code at a slower rate than users at the larger spreading gains.

Upon further inspection of the variable rate code sets, it can be shown that code hopping can be done at the symbol rate of the lowest spreading gain users without changing the orthogonality of the users. This works for both recursive and non-recursive code constructions and results from the fact that the codes in the base code set with $P_{\min}$ form the codes with higher spreading gain. The details of code hopping at the at the symbol rate of the $P_{\min}$ users for variable rate DS-CDMA is discussed in [4].

Conclusions:

In conclusion, a scheme to hop spreading codes in a DS-CDMA system has been examined. The scheme generalizes to both fixed and variable-rate DS-CDMA systems, allowing users to use different spreading codes on a block-by-block or symbol-by-symbol

basis. Code hopping prevents severely degraded users resulting from adjacent cell interference, maintains balance in the code sets, has a simple implementation and allows the all one's code to be used, thus increasing capacity.

References

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APPENDIX B

Hybrid Synchronous Space/Code Multiple Access Scheme Using an Adaptive Antenna System

In this work, a multiple access communications system is described which combines orthogonal Synchronous Code Division Multiple Access (S-CDMA) with Space Division Multiple Access (SDMA). The system architecture envisions a central base station employing an $M > 1$ element antenna array servicing user terminals each having a single directional antenna. The base station and user terminals coexist in a defined area or cell and communicate using orthogonal synchronous direct-sequence code division multiple access with frequency division duplexing.

Assuming a single base station antenna ($M=1$), the total number of channels in the system is equal to the number of orthogonal spreading codes P . A common method to increase the number of channels and thus the capacity of the system is to employ space division multiplexing. The simplest form of SDMA is sectorization, where a given cell is divided into M sectors with each of the M base station antennas servicing a specific sector. In this scheme, the base station antennas are fixed directional and the system capacity scales linearly with the number of sectors M (and antennas).

While common in many mobile cellular systems, SDMA via sectorization suffers from several problems. First, sectorization requires additional isolation means to deal with users along the sector boundaries. Typically, frequency division is used between adjacent sectors meaning that additional frequency spectrum is required. The second disadvantage of a sectorized approach is Erlang inefficiency. The total supported traffic of a sectorized system is equal to the sum of the supported traffics in the individual sectors. This sum of supported sector traffic is typically much less than could be supported in a cell with the same total number channels but no sector constraints. As an example, a system with $P=16$ channels per sector and $M=4$ sectors can support 100 users per sector or total of 400 users per cell assuming $GOS=0.02$ and a traffic intensity of 0.1 Erlangs. A system with the same number of total channels ($MP=64$) but no sector constraints can support approximately 550 users under the same assumptions. Because sectorization places restrictions on the locations of users, it is not the most efficient approach to servicing a given area [1].

A hybrid SDMA/CDMA system that uses adaptive antenna arrays rather than sectorization with fixed beam antennas can avoid the need for frequency multiplexing and the problem of Erlang inefficiency. In a hybrid synchronous Space/Code Division Multiple Access scheme using adaptive antennas, each spreading code is reused αM times where M is the number of antenna elements in the adaptive array and $1/M \leq \alpha \leq 1$. Here, the total system capacity is αMP channels per cell. The geometry of the antenna

array can vary, with a circular array preferred and the elements may be directional or omni-directional.

In the reverse link (terminal to base station) of a hybrid space/code multiple access system, a user terminal communicates via a specific spread waveform and obtains isolation from the $\alpha M(P-1)$ different code users via the orthogonality of the spread spectrum modulation. The same user is isolated from the $\alpha M-1$ same-code users via the adaptive antenna that creates a unique antenna pattern for the user, steering nulls in the direction of the same-code interferers. At a high level, the extraction of a given users information is two stage process whereby code filtering (or despreading) is followed by spatial filtering [2].

For proper spatial filtering for same-code interference suppression, the user terminals require some spatial separation. However, the spatial separation with an adaptive antenna system is typically far less restrictive than for a sectored approach. It is conjectured that users separated by as little as 1 degree in angle of arrival from the desired user can be sufficiently suppressed using adaptive beamforming with a sufficiently large antenna array aperture. In this sense, users can be spaced (almost) arbitrarily throughout the cell allowing for greater Erlang efficiency versus sectorization. The price paid for this increased capacity is found in the complexity of beamforming algorithms at the base station. The reader is referred to [2] for the details of antenna beamforming for same-code interference suppression.

In the forward link, the base station antenna array transmits the signal of interest in the direction of the desired user while at the same time minimizing the energy of same-code users transmitted in the direction of the desired user. Similar to the reverse link, user data is first spatially filtered using the weight vector for the user of interest. Each of the M spatial filters outputs are modulated using the same orthogonal spreading waveform and transmitted using one of the M antennas in the array. Since the link is frequency division duplex, the forward link spatial filter must be computed independently from the reverse link spatial filter for all users. At the user terminal, a single directional antenna captures the transmitted signal plus interference and then despreads the signal to recover the user data. In this fashion, signal processing in the user terminal suppresses the interference from different-code users and relies solely on the spatial filter in the base station transmitter to suppress the received interference from same code-users.

The hybrid Synchronous Space/Code Division Multiple access system with adaptive antennas allows the number of channels per cell to scale linearly with the number of antenna elements with minimal spatial separation between users. To limit costs and complexity, all adaptive beamforming is performed by the base station and places no additional computational burdens on the user terminals. In the base station, significant signal processing is required to compute the weight vectors for both the forward and reverse link, as well as to perform the spatial filtering. However, it is anticipated that the cost per channel (and the cost per traffic channel supported) will scale with the number of antenna elements up to a point.

References

[1] T. Rappaport, Wireless Communications, Prentice Hall, Inc. New Jersey, USA, 1996.

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APPENDIX C

Efficient Implementation of SDMA for Synchronous CDMA Communication Systems

In this paper, an efficient implementation of Space Division Multiple Access (SDMA) is proposed for Synchronous Code Division Multiple Access (S-CDMA) wireless communications links. The proposed receiver and transmitter structures utilize an antenna array consisting of M antenna elements. In synchronous CDMA systems, several different orthogonal CDMA codes are assigned to the base station of interest. Using closed loop feedback from the base station each CDMA code transmitted on the reverse link is code aligned (synchronized), such that orthogonality of the code sequences is preserved. The number of available orthogonal codes for a given spreading factor is limited and therefore the capacity of the convention S-CDMA system is often *code limited*. However, when SDMA is used in conjunction with S-CDMA it is possible to reuse code sequences within the same cell providing a corresponding increase in system capacity. Theoretically, with an M element antenna array receiver it is possible to reuse each code sequence M times. In practice the required number of antenna elements to provide an SDMA code reuse of M is greater than M due to implementation loss, frequency selective multipath fading, and receiver noise. Regardless, significant capacity gains are achievable with SDMA.

SDMA is achieved by exploiting the differences in the spatial signature vectors of the various users in the cell. Conceptually, in a nonmultipath channel it may be viewed as steering a high antenna gain towards the signal of interest, while simultaneously steering nulls towards potential interferers, thereby providing orthogonal channels to users that are assigned identical code sequences. The level of orthogonality achievable is controlled by the number of antenna elements in the array, the number of SDMA users in the channel, the amount of spatial separation of the users, the amount of multipath, and the level of the receiver noise floor. The effective antenna pattern is controlled by linearly combining the outputs of the M receiving channels as shown in Figure 1. The array output for user n may be expressed as

$$y_n(t) = \begin{bmatrix} w_{n,1}^* & w_{n,2}^* & \cdots & w_{n,M}^* \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix}$$

where $y_n(t)$ is the spatial filter output, $w_{n,i}$ is the complex weight applied to the i th antenna element, $x_i(t)$ is the signal present on the i th channel, and $*$ denotes complex conjugate. Each user applies a unique set of weights, thereby yielding different effective antenna patterns. This process is referred to as beamforming or spatial filtering. Generally, in an SDMA/CDMA system, spatial filtering is performed prior to despreading by the CDMA code sequence. The conventional SDMA/CDMA receiver structure for the n th user is

shown in Figure 2 where c_n denotes the code sequence for the n th user. In this case the complex multiplication operation performed in the spatial filter is computed at the sample rate of the system. Also, individual code despreaders are needed for each user in the system.

In a Synchronous CDMA (S-CDMA) system all of the users are code aligned. When SDMA is used as a multiple access technique in conjunction with S-CDMA, multiple users may share the same code sequence with identical alignment. In this case, it is possible to use a single despreader to despread the signals of the users with common code sequences. The proposed receiver structure is shown in Figure 3. Each of the spatial filter blocks contains the structure shown in Figure 1.

Providing an SDMA reuse factor of K requires a minimum of K antenna elements at the base station. Therefore, the proposed implementation will require at least as many despanders as would be needed with the conventional approach. However, by beamforming after despreading, the complex multiplies performed in the spatial filter may now be applied at the symbol rate as opposed to the sample rate as is required when beamforming is applied prior to despreading. The multiplies involving the spatial filter weights require N bit by N bit multipliers. The multiplies involved in the despreader may be computed using an exclusive-OR operation, since the code sequence is a binary sequence of -1 's and 1 's. Therefore, reducing the number of multiplies required to implement the spatial filter far out weighs the overhead of adding additional despanders to the system. Finally, due to the reduction in the multiplication rate it becomes possible to multiplex the use of the multiplier over several users, thereby reducing the amount of required hardware.

A first order approximation to the relative complexity of the two proposed architectures may be obtained by comparing the number of complex multiplies per second for each system. Let N denote the total number of CDMA/SDMA users supported by the base station of interest. Let f_s denote the sampling frequency and R_s denote the symbol rate. For the case of the conventional receiver, the number of complex multiplies per second is given by $MPS_{\text{conventional}} = MNf_s$, where M is the number of antenna elements in the array. For the proposed receiver architecture the number of complex multiplies is given by $MPS_{\text{proposed}} = MNR_s$. Therefore, the proposed system architecture requires R_s/f_s fewer complex multiplies than the conventional approach. This ratio is equal to the spreading factor P times the oversampling rate R_o . For example when $P=128$ and $R_o=2$, the proposed receiver structure will require a $1/256$ of the number of multiplies of the conventional approach.

Similar reductions in complexity are possible when applying SDMA to S-CDMA in the transmitter. The proposed transmitter structure for a single user is shown in Figure 4. When multiple users are presented which have identical code sequences, the outputs of the individual spatial filter channels may be combined prior to the spreading. Therefore, only one set of spreaders is needed for each code sequence. Again, the spatial filter is applied at the symbol rate.

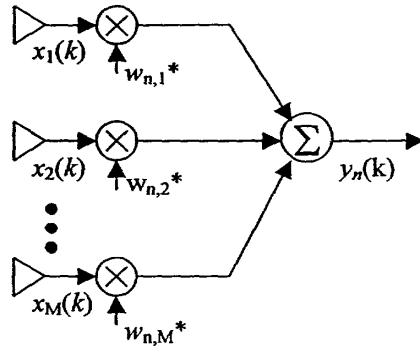


Figure 1: Spatial filter for the kth user.

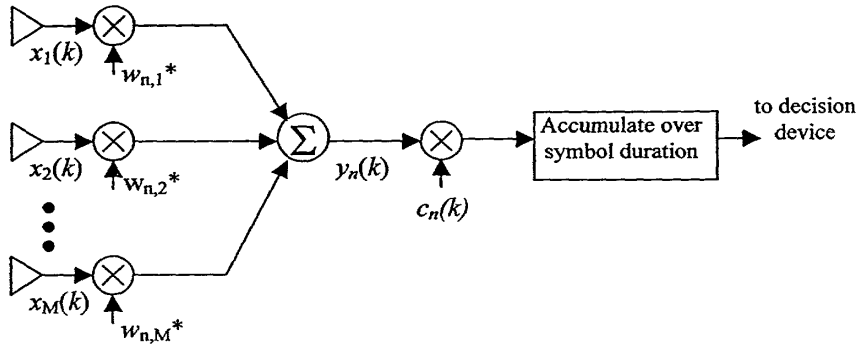


Figure 2: Conventional CDMA/SDMA approach.

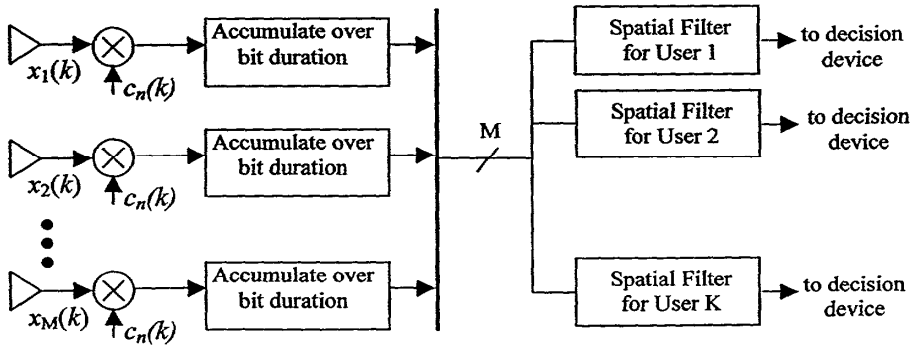


Figure 3: Proposed receiver structure for despreading multiple S-CDMA users with a common despreader.

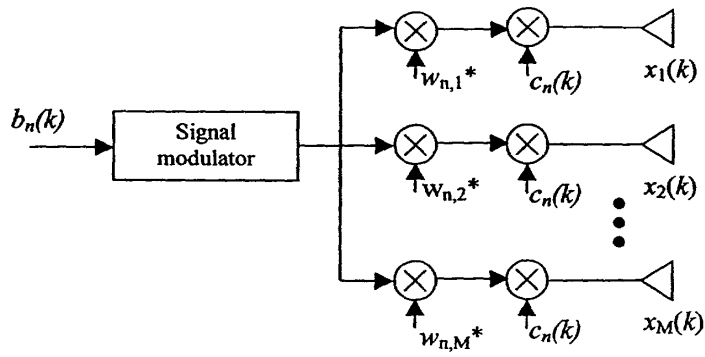


Figure 4: Proposed transmitter structure for a single user.

C-4

APPENDIX D

PN Code Design for Flexible Bandwidth Direct-Sequence CDMA

Introduction:

In this work, a technique that allows the required signal bandwidth and the capacity of a DS-CDMA system to be reduced without requiring hardware modifications is examined. The technique involves shaping the spectrum of the DS-CDMA system via proper spreading code design, rather than modifying the chipping rate and spreading gain (chips/symbol). The code design procedure involves designing a new code set via chip repetition. If the spreading gain of the original system is P chips/symbol, where P is a power of two, a new code set can be constructed having P/N usable codes, each of length P where N is a power of two. The new code set is constructed from a base code set of size $P/N \times P/N$, with each of the chips in the base code repeated to form the new $P/N \times P$ code set. With only P/N usable codes, the capacity of the new code set is reduced by a factor of N versus the original code set. However, it will be shown that the use of chip repetition reduces the number of chip transitions per symbol, thus reducing the required signal bandwidth of the new code set. Furthermore, since both the repetition code and original code have the same length in chips/symbol, the spreading/despreading hardware does not need to change in system.

The proposed scheme applies to both synchronous and asynchronous DS-CDMA with orthogonal designs possible for the both cases. The major advantage provided by the code design technique is to allow an existing DS-CDMA system designed for a particular bandwidth to adjust to fit into a smaller bandwidth without hardware modifications.

Spectral Properties of PN Codes:

The occupied signal bandwidth of a DS-CDMA system is determined by the chipping rate R_{chip} , the pulse shape filtering and the spectral properties of the spreading codes. In this work, a fixed chipping rate is assumed and the spectral properties of the spreading codes are examined assuming an adjustable FIR pulse shape filter. For a given spreading code, the number and frequency of chip transitions determines the spectrum of the code. To illustrate, consider a 4×4 Hadamard code set with spreading factor of $P=4$ chips/symbol. Here, the spreading code set is given by

D-1

$$H_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix}$$

where h_i is a $1 \times P$ spreading code vector.

When each of the spreading codes is modulated with random binary data, the resulting signals have very different occupied signal bandwidths. Data spread using $h_1 = [+1 +1 +1 +1]$ results in a signal having an occupied bandwidth equal to the bandwidth of the data modulation or in this case $R_{\text{chip}}/4$. Spreading with spreading codes $h_3 = [+1 +1 -1 -1]$ or $h_4 = [+1 -1 -1 +1]$ will result in a spectrum having bandwidth roughly equal to $R_{\text{chip}}/2$, since there are exactly two transitions per chip sequence. The spreading code $h_2 = [+1 -1 +1 -1]$ will result in the largest occupied bandwidth signal, as there are can be four transitions per spreading code. In Figure 1, we show the power spectral density the four PN codes with random data modulation. As can be seen, the resulting 3-dB bandwidth of the signal is directly related to the number of transitions per code sequence.

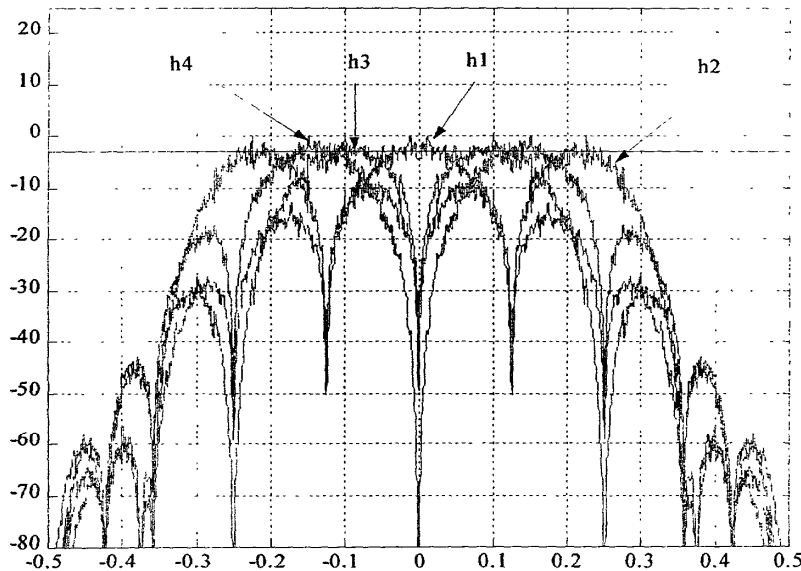


Figure 1: Power spectral density of DS-SS system using H_4 with Root-raised Cosine pulse shaping ($\beta=0.35$) and random data modulation.

In Figure 1, it can be seen that the occupied signal bandwidth is conditioned on which spreading code is used. When all four codes are used, the occupied signal bandwidth of this system is

D-2

roughly equal to the chip rate. However, if the spreading code h_2 was not used, the capacity of the system reduces to 3 users while the occupied signal bandwidth drops to $R_{\text{chip}}/2$. In this example, throwing away the large bandwidth code results in reduced capacity and required bandwidth without hardware modifications.

If the Hadamard set is the base code set for the DS-CDMA system, throwing away high-bandwidth codes is an attractive technique for flexibly balancing bandwidth and capacity. However, DS-CDMA systems commonly use code sets constructed from randomized Hadamard matrices that may be scrambled using cover codes. Code sets constructed in this manner typically have a single code with low bandwidth (all one's code), while the other $P-1$ spreading codes have roughly $P/2$ transitions and thus require a bandwidth of roughly R_{chip} . The "throw away" technique does not work in this case since $P-1$ codes have roughly the same occupied signal bandwidth.

Code Set Design by Chip Replication:

Since throwing away high-bandwidth codes does not seem attractive except for the Hadamard set, an alternative technique based on chip repetition is suggested. Suppose a DS-CDMA system with spreading gain P chips/symbol and chip rate R_{chip} where P is a power of two. The goal is to design a spreading code set having P/N spreading codes with P chips/symbol which have spectral properties such that the occupied signal bandwidth of the system is R_{chip}/N . It is required that N be a multiple of two to ensure that the length of the new code set is P . To design the new code set, a $P/N \times P/N$ base code set is constructed which could be a Hadamard or randomized Hadamard design. Each chip in the base code set is repeated N times to construct the new code set of size $P/N \times P$. Since each chip has been replicated N times, each $1 \times P$ spreading code is guaranteed to have no more than P/N , equally-spaced transitions and thus a bandwidth less than or equal to R_{chip}/N . Furthermore, if the base code set is an orthogonal design (i.e. all codewords are orthogonal), the orthogonality is preserved in the over-sampling process. The proof of this is trivial. If a cover code is to be applied to the system, it too must be over-sampled by N in order to maintain the bandwidth reduction of $1/N$. Since the spreading codes in the new code set are the same length in chips/symbol as the original spreading codes, the bandwidth and user capacity is reduced without hardware modifications in the chip spreader/despreader.

Design Example: $P=8, N=2$

As an example, consider a DS-CDMA system operating with $P=8$ and $R_{\text{chip}} = 2.72$ Mcps, which is the chipping rate for Prime Wave 2000. To design a code set with half the capacity which requires half the bandwidth, a new code set is designed based on chip repetition and $N=2$. A 4×4 Hadamard set is used as the base code set given by

$$H_{4 \times 4} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

D-3

From the base code set, each chip is repeated twice, to produce the new code set

$$H_{4 \times 8} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ +1 & +1 & -1 & -1 & +1 & +1 & -1 & -1 \\ +1 & +1 & +1 & +1 & -1 & -1 & -1 & -1 \\ +1 & +1 & -1 & -1 & -1 & -1 & +1 & +1 \end{bmatrix}$$

If the original code set was an 8 x 8 Hadamard set given by

$$H_{8 \times 8} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 & +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 & +1 & +1 & -1 & +1 \\ +1 & +1 & +1 & +1 & -1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 & -1 & +1 & -1 & +1 \\ +1 & +1 & -1 & -1 & -1 & -1 & +1 & +1 \\ +1 & -1 & -1 & +1 & -1 & +1 & +1 & -1 \end{bmatrix}$$

the new code set has half the available codes and half the required signal bandwidth as illustrated in Figure 2. Figure 2 shows the power spectral density for the original system assuming 8 active users and code set $H_{8 \times 8}$ along with a system with 4 active users using code set $H_{4 \times 8}$ with random data modulation. As can be seen, the system with half the capacity also occupies half the signal bandwidth. Thus, the capacity and required signal bandwidth of the system have been effectively scaled without hardware modifications by simply using different spreading code set having fewer available codes.

D-4

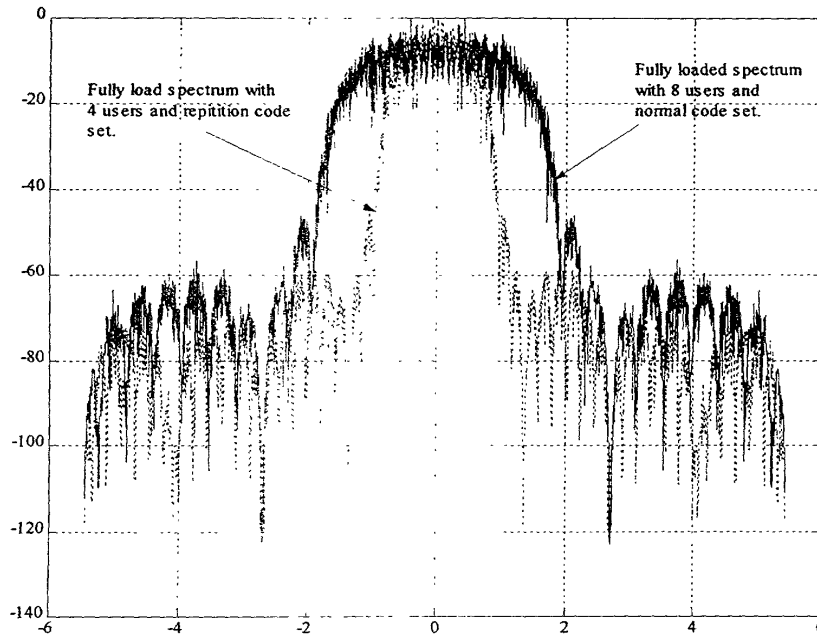


Figure 2: Power spectral density for a DS-CDMA system with $R_{chip}=2.72$ Mcps and Root-raised cosine pulse shaping ($\beta=0.35$) using a 8x8 Hadamard code set and a 4x8 Repetition code set based on a 4x4 Hadamard base set.

Summary of Chip Repetition Code Design:

To reduce the capacity and required signal bandwidth by a factor N of a DS-CDMA system with processing gain P , where P and N are powers of two, the following steps should be taken:

1. Generate a $P' \times P'$ Hadamard code set where $P' = P / N$
2. Randomize the Hadamard code set (row/column permutation)
3. Replicate chips in each code by N to produce a $P' \times P$ code matrix
4. If a cover code is used, replicate the cover code by P .
5. Load the new spreading matrix and cover code into the system hardware.

Primary Benefit of Chip Repetition

The primary motivation for designing code sets with reduced bandwidth is to provide frequency flexibility for DS-CDMA systems. Designed with a given chipping rate, most DS-CDMA

D-5

systems are tailored for a particular frequency plan. As examples, WCDMA cellular systems use a chip rate of 4.096 Mcps and are designed for a 5 MHz channel. Prime Wave 2000 uses a chipping rate of 2.72 Mcps and is designed for a 3.5 MHz channel. In some cases, systems designed for one channel spacing are asked to fit into a different channel spacing which has been standardized in a given region. Suppose a W-CDMA system designed for a 5 MHz channel plan was asked to operate in an ETSI 3.5 MHz channel plan. The use of a new spreading code set based on chip repetition with $N=2$ could be used to allow the 5 MHz system to become a 2.5 MHz system in order to fit within the 3.5 MHz channel plan. In scaling from 5 to 2.5 MHz, there could be a loss in spectral efficiency, but the waveform would comply with the specified channelization.

Benefits of Chip Repetition for Next Generation Prime Wave 2000

The next generation Prime Wave 2000 system (a.k.a. WIN3) is a DS-SS system operating with variable spreading rate of $P=1$ and $P=8$ up to $P=128$ with $R_{\text{chip}} = 2.72$ Mcps. The system is specifically designed to operate within a 3.5 MHz channel plan and the variable rate code sets are discussed in [1]. It is straightforward to apply the chip repetition technique to design codes with variable bandwidth and capacity. Applying the chip repetition techniques to WIN3, Table 1 and Figure 3 illustrate the achievable signal bandwidths and user capacities assuming root-raised cosine filtering ($\beta=0.35$) and chip repetition. It should be noted that for $N>1$, clear-mode operation is not supported.

Replication Factor N	Maximum Number of 32 kbps Users C	Sub-Channel Bandwidth	Capacity
1	128	3.5 MHz	4.096 Mbps
2	64	1.75 MHz	2.048 Mbps
4	32	875 kHz	1.024 Mbps
8	16	437.5 kHz	512 kbps

Table 1: Chip repetition in a single frequency sub-channel for WIN3.

D-6

efficiency of the 5 MHz system is actually greater than the spectral efficiency of the 3.5 MHz system! In terms of hardware, a 5MHz WIN3 system would require 3 RBU modem cards per 5 MHz channel serviced, with a maximum of two 5 MHz channels serviced per RBU. In Figure 3, we show the spectrum for the 5 MHz system along with the spectral mask for a 5 MHz ETSI system [4].

If the desire is to service a 10 MHz channel, WIN3 could easily fit into the channel plan using three, 3.5 MHz sub-channels. Since the chipping rate is roughly 80% of the channel spacing, pulse shaping filtering can provide sufficient roll-off to allow three equally space 3.5 MHz channels to fit within a 10 MHz spectral mask as shown in Figure 4. It should be noted that the spectral efficiency of a 10 MHz system is 1.23 bps/Hz and requires 6 RBU modem cards.

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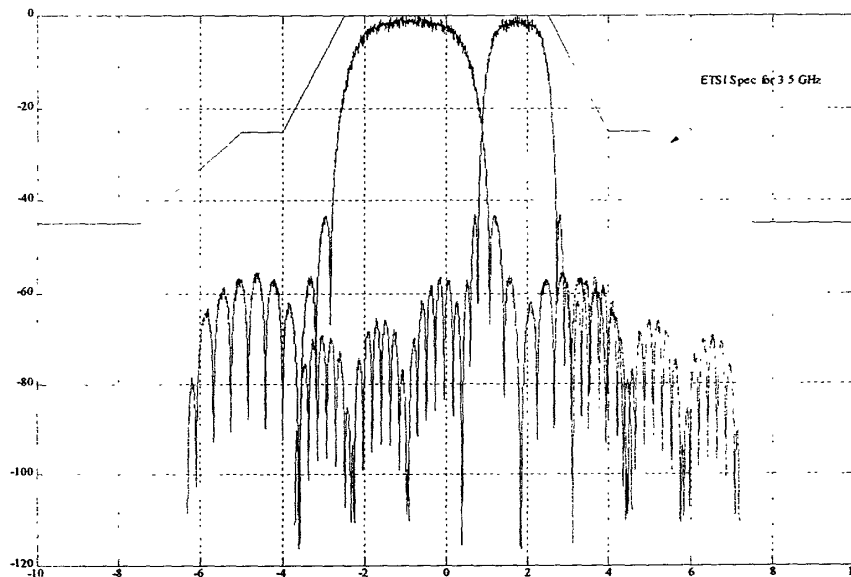


Figure 3: Servicing a 5 MHz channel using 2 frequency sub-channels in WIN3

D-8

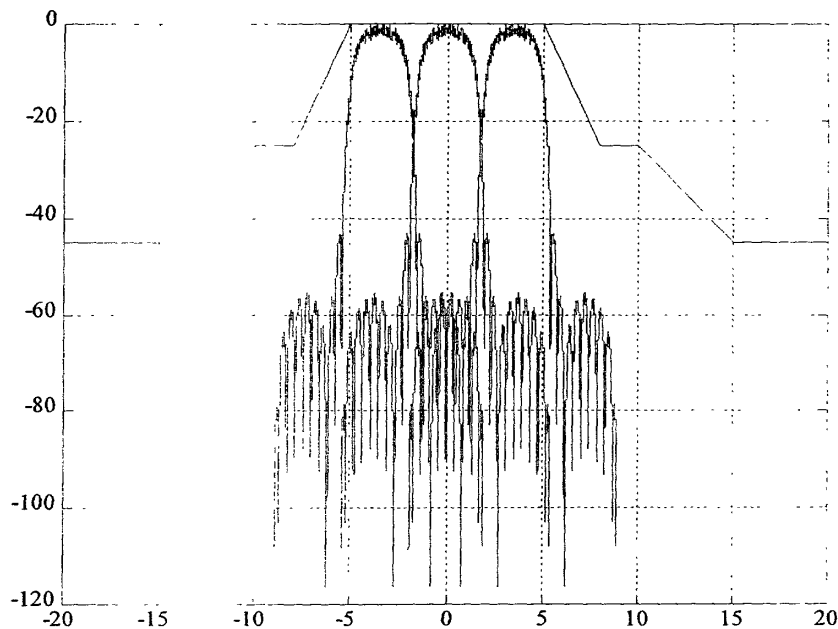


Figure 4: Servicing a 10 MHz channelization in WIN3 using 3 frequency sub-channels

Conclusions:

In conclusion, a technique to scale the bandwidth and capacity of a DS-CDMA system by designing code sets with improved spectral properties has been discussed. The code sets are designed beginning with a base code set with a smaller spreading gain and repeating chips. The result is a code set with fewer spreading codes and smaller aggregate signal bandwidth. The code design processes allows existing DS-CDMA systems to scale bandwidth and capacity without hardware modifications provided the number of chips/symbol does not change. The primary benefit of this code design technique is to allow DS-CDMA systems designed for a particular channelization to fit into smaller channel plans.

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APPENDIX E

Code Assignment Algorithm for Synchronous DS-CDMA links with SDMA Using Channel Scanning

1. Introduction

This paper describes a code assignment algorithm for Synchronous Code Division Multiple Access (S-CDMA) wireless communication systems that utilizes Space Division Multiple Access (SDMA) to enhance capacity. The algorithm is based upon a channel scanning step that assigns the code with the lowest amount of power at the output of a beamformer steered towards the current user. This approach attempts to minimize the similarity between the spatial properties of the users assigned to a given code. The proposed code assignment scheme is applicable to both the forward and reverse channels, although for convenience we focus only on the reverse link in this paper.

Synchronous CDMA systems use a set of orthogonal direct sequence CDMA codes. The number of available orthogonal codes is limited by the spreading factor and therefore the capacity of the conventional S-CDMA system is often *code limited*. The capacity may be enhanced with space division multiple access (SDMA) in which each CDMA code sequence is assigned to multiple users within a single cell. Theoretically, with an M element antenna array receiver it is possible to reuse each code sequence M times.

The ability of an SDMA system to provide orthogonal channels to each user is a function of the spatial properties of the users that are assigned to identical codes. Therefore, when assigning codes to new users, care should be taken to insure that the set of users that are assigned an identical code are spatially compatible. A good code assignment scheme will assign identical codes to users that have the most dissimilar spatial properties.

In this paper we suggest propose a code assignment algorithm for placing users into spatially compatible groups using a channel scanning procedure. The organization of the paper is as follows. Section 2 describes the assumed signal model. Section 3 discusses the implementation of SDMA with antenna array systems. In Section 4, we present the proposed initial code assignment algorithm. In Section 5, simulation results are presented indicating the effectiveness of the code assignment algorithm. Finally, Section 6 concludes the paper with a summary of results and recommendations for further study.

2. Signal Model

It is assumed that the radio base unit (RBU) is equipped with an M element antenna array. Let $x(t)$ denote the received signal vector which is observed at the antenna outputs at time t . For a multipath channel, the analytic received signal vector component due to user n is given by

E-1

$$\mathbf{x}_n(t) = \sum_{l=1}^{L_n} \alpha_{n,l} \mathbf{a}(\theta_{n,l}) s_n(t - \tau_{n,l})$$

where L_n is the number of signal components and $s_n(t)$ is the analytic transmitted signal of the n th user. For CDMA systems, $s_n(t) = c_n(t) b_n(t) \exp(-j\omega_c t)$, where $c_n(t)$ is the CDMA spreading code, $b_n(t)$ is the sequence of data bits, and ω_c is the carrier frequency in radians per second. The parameters $\alpha_{n,l}$, $\tau_{n,l}$, and $\theta_{n,l}$, denote the complex amplitude, path delay, and azimuth angle of arrival of the l th path of the n th user, respectively. The vector, $\mathbf{a}(\theta_{n,l})$, is the array response vector in the direction of $\theta_{n,l}$. Assuming a flat fading channel environment, $\mathbf{x}_n(t)$ may be expressed as

$$\mathbf{x}_n(t) = \mathbf{v}_n s_n(t)$$

where

$$\mathbf{v}_n = \sum_{l=1}^{L_n} \alpha_{n,l} \mathbf{a}(\theta_{n,l}) \exp(-j\omega_c \tau_{n,l})$$

$\mathbf{v}_n$ is defined as the spatial signature vector (SSV) of user n . It is the SSV's of each of the users that will determine the performance of the SDMA system.

The composite received signal vector is the summation of the signal vector due to each user plus some assumed additive noise term. Therefore, we may write

$$\mathbf{x}(t) = \sum_{n=1}^N \mathbf{v}_n s_n(t) + \mathbf{n}(t)$$

where N denotes the number of users in the channel, and $\mathbf{n}(t)$ denotes a length M vector which accounts for additive white noise. Generally $\mathbf{n}(t)$ is modeled as spatially and temporally white Gaussian noise.

3. SDMA using Antenna Arrays

SDMA exploits differences in the spatial characteristics of the various users in the channel to provide nearly orthogonal channels to the users. An illustration of SDMA is shown in Figure 1. The base station uses different effective beam patterns to isolate the users' signals. In this case, the antenna pattern of user 1 has a null in the direction of user 2 and vice versa. In this way, the two users are able to access the base station resources using the same frequency, at the same time, with the same spreading code, without interfering with one another.

E-2

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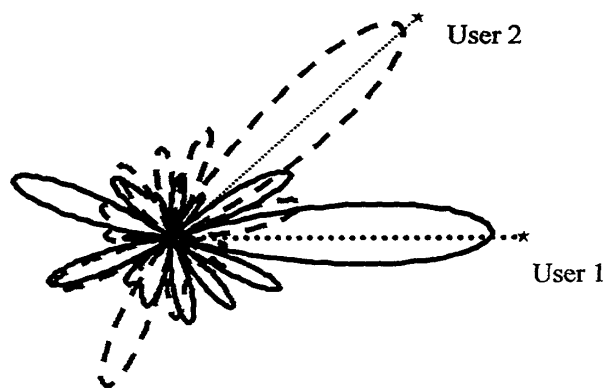


Figure 1: SDMA illustration for two users. Antenna patterns are used to provide orthogonal channels to the users.

The effective antenna patterns of each user are generated by summing amplitude scaled and phase rotated versions of the signals observed at each antenna element as shown in Figure 2. The array output for user n may be expressed as

$$y_n(t) = \begin{bmatrix} w_{n,1}^* & w_{n,2}^* & \cdots & w_{n,M}^* \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix} = \mathbf{w}_n^H \mathbf{x}(t)$$

where $y_n(t)$ is the spatial filter output, $w_{n,i}$ is the complex weight applied to the i th antenna element, $x_i(t)$ is the signal present on the i th channel, and $*$ denotes complex conjugate. Each user applies a unique set of weights, thereby yielding different effective antenna patterns. This process is referred to as beamforming or spatial filtering.

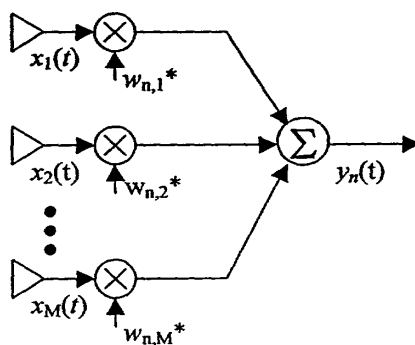


Figure 2: Spatial filter for user n .

In a flat fading channel, it can be shown that the weight vector which maximizes the output signal to interference plus noise ratio (SINR) is given by

$$\mathbf{w}_n = \mathbf{R}_{ii}^{-1}(n) \mathbf{v}_n$$

where $\mathbf{v}_n$ is the spatial signature vector of user n and $\mathbf{R}_{ii}(n)$ is the corresponding interference plus noise correlation matrix. The matrix, $\mathbf{R}_{ii}(n)$, may be expressed as,

$$\mathbf{R}_{ii}(n) = \sum_{i=1, i \neq n}^N \sigma_s^2 \mathbf{v}_i \mathbf{v}_i^H + \sigma_n^2 \mathbf{I}_M$$

where N denotes the number of interfering signals, σ_s^2 is the variance of analytic received signal which is assumed to be equal for each user due to power control, and σ_n^2 is the variance of the additive white noise in the channel. The output SINR present at the array output corresponding to the optimum weight vector is given by,

$$\text{SINR}_{opt} = \sigma_s^2 \mathbf{v}_n^H \mathbf{R}_{ii}^{-1}(n) \mathbf{v}_n.$$

4. Channel Scanning Code Assignment Algorithm

The assignment of codes can have a major impact on the performance of the SDMA system. In this section, we propose a code assignment algorithm that assigns codes to users in an attempt to minimize the similarity of the SSVs of the users that share any given code. The algorithm involves measuring the output power on each code through a beamformer steered towards the current user. The receiver architecture used to implement the proposed algorithm is shown in Figure 3. The sampled data at each branch of the receiving array is multiplied by the n th code sequence. The despread data is then summed over the symbol duration. The output of the accumulator on the i th channel is then multiplied by the i th complex weight value. The beamformer output $y(k)$ is created by summing of the scaled despread signals. To estimate the power, we find the average magnitude squared value of the beamformer output over several symbol durations. The number of symbols over which the power is estimated will determine the accuracy of the power estimate and hence will impact the assignment of codes. The greater the number of symbols, the better the performance of the code assignment algorithm. However, increasing the number of symbols also increases the system complexity and the required scanning time.

E-4

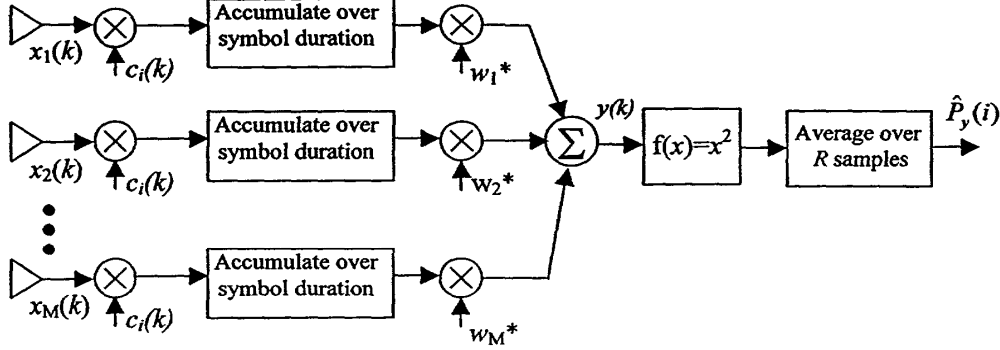


Figure 3: Code searching receiver architecture.

It is assumed that the SSV corresponding to the current user has been estimated. Typically this would be done while the user is active on a side channel. Let $\mathbf{v}_d$ denote the estimated SSV. To steer the beamformer in the direction of the current user, we set the weight vector equal to the SSV, i.e. $\mathbf{w} = \mathbf{v}_d$. Using this weight vector we then find the output power which is correlated with each code sequence. This is done by finding the average squared value of the array output which has been despread using code i . Consider the output signal when there are N_i users using code i . Assuming that the users' data are uncorrelated, the corresponding estimated output power is given by

$$\hat{P}_y(i) = \sum_{n=1}^{N_i} |\mathbf{v}_d^H \mathbf{v}_n|^2 G^2 \sigma_s^2 + |\mathbf{v}_d^H \mathbf{v}_d|^2 G \sigma_n^2 = G^2 \sigma_s^2 \sum_{n=1}^{N_i} \rho_{d,n} + C$$

where G is the CDMA processing gain, $\rho_{d,n} = |\mathbf{v}_d^H \mathbf{v}_n|^2$, and $C = |\mathbf{v}_d^H \mathbf{v}_d|^2 G \sigma_n^2$ is a constant. The code with the minimum value of $\hat{P}_y(i)$ is assigned to the current user.

To motivate this code selection criterion, consider the separation of two users. For this case the optimum output SINR equation presented in the previous section may be expressed as,

$$\text{SINR}_{\text{opt}}(2) = \frac{\sigma_s^2}{\sigma_n^2} \left[\|\mathbf{v}_1\|^2 - \frac{\sigma_s^2 |\mathbf{v}_1^H \mathbf{v}_2|^2}{\sigma_n^2 + \sigma_s^2 \|\mathbf{v}_2\|^2} \right].$$

For equal power users in a LOS channel, $\|\mathbf{v}_1\|^2 = \|\mathbf{v}_2\|^2 = M$ where M is the number of antenna elements in the array. In this case the optimum output SINR for both users becomes

E-5

$$\text{SINR}_{opt}(2) = \frac{\sigma_s^2}{\sigma_n^2} \left[M - \frac{\sigma_s^2 |\mathbf{v}_1^H \mathbf{v}_2|^2}{\sigma_n^2 + M\sigma_s^2} \right] \approx M \frac{\sigma_s^2}{\sigma_n^2} \left[1 - \frac{|\mathbf{v}_1^H \mathbf{v}_2|^2}{M^2} \right]$$

Note, that the optimum output SINR is a function of the squared inner product of $\mathbf{v}_1$ and $\mathbf{v}_2$. For convenience, let $\rho_{i,j} = |\mathbf{v}_i^H \mathbf{v}_j|^2$. When there are more than two users in the environment, then the optimum output SINR is no longer a function of just

$\rho_{i,j} = |\mathbf{v}_i^H \mathbf{v}_j|^2$ for each user, but is also dependent upon the phase of the inner products of the SSV's. Regardless, it can be shown through simulation that there is a negative correlation between the output SINR and the quantity

$$\xi_d(c) = \sum_{n \in S_c} |\mathbf{v}_d^H \mathbf{v}_n|^2 = \sum_{n \in S_c} \rho_{d,n}$$

where S_c denotes the set of users already assigned to code c . It is easily verified that choosing the value of c to minimize $\hat{P}_y(i) = G^2 \sigma_s^2 \xi_d(c) + C$ is equivalent to minimizing $\xi_d(c)$. Therefore, our code selection criterion is justified.

The following steps summarize the code assignment algorithm:

1. Estimate the SSV of the current user.
2. Using the estimated SSV as the weight vector, find the output power that is correlated with each available code sequence.
3. Finally, assign to user n the code with the minimum measured output power.

5. Simulation Results

In this section we compare the performance of the proposed code assignment algorithm with a random assignment of codes. It is assumed that the RBU is equipped with a 16 element circular antenna array with an adjacent element separation of 5 wavelengths. There are 120 codes shared amongst the users. The total number of active users is equal to $16 * 120 = 1920$. Users are distributed in azimuth according to a random uniform distribution over the range of $[0, 2\pi]$. Only the LOS signal for each user is considered. It is assumed that power control is used on the reverse link, such that all of the users are received with equal power. The assumed SNR of the signal observed on each antenna element for a given user after despreading is 15dB. The cumulative distribution function (cdf) of the array output signal to interference plus noise ratio (SINR) is calculated from the SINR of each user, over ten independent trials of user placements.

Figure 4 shows the number of users per antenna element per code that have an array output SINR greater than the specified threshold level. For example, 0.8 users per element per code have an array output SINR which exceeds 15 dB using the proposed

E-6

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code assignment algorithm with perfect power estimates, whereas only 0.48 have an array output SINR which exceeds 15 dB using a random code assignment. As the number of symbols used to estimate the received signal power on each code decreases, the performance of the code assignment algorithm degrades. For the case considered roughly between 16 and 64 samples are needed to achieve near optimum performance.

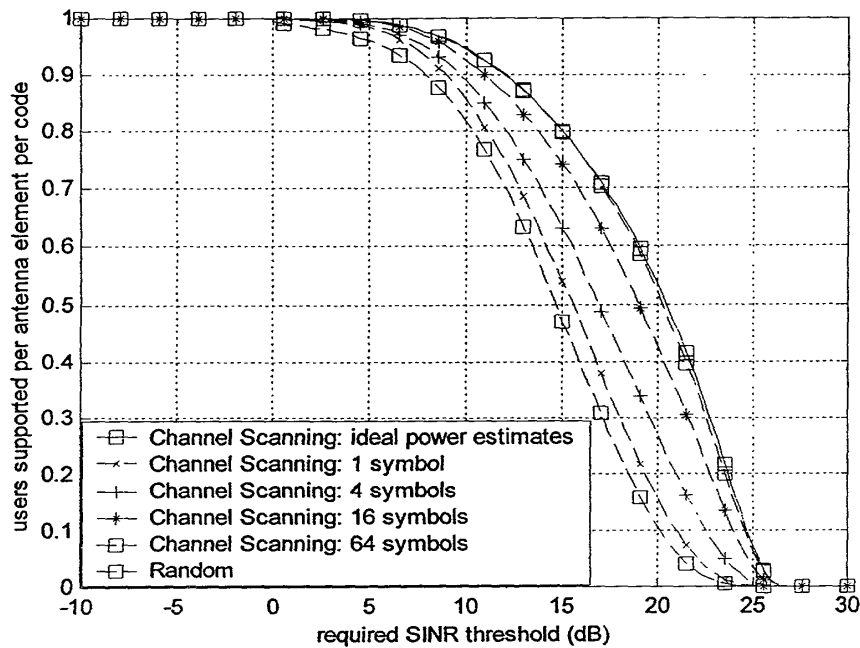


Figure 4: Number of users supported per antenna element per code versus the required array output SINR for the proposed code assignment algorithm and random code assignment. Several curves are shown for the proposed algorithm performance for various number of symbols used to estimate the received signal power.

6. Conclusions

A channel scanning code assignment algorithm is proposed. The algorithm allows approximately 1.6 times as many users with an output SINR which exceeds the original input SNR when compared to a random code assignment. The performance and complexity of the code assignment algorithm is linked to the number of symbols used to estimate the received signal power on each code.

E-7

APPENDIX F

Code Assignment Algorithm for Synchronous DS-CDMA links with SDMA Using Estimated Spatial Signature Vectors

1. Introduction

This paper describes a code assignment algorithm for Synchronous Code Division Multiple Access (S-CDMA) wireless communication systems that utilizes Space Division Multiple Access (SDMA) to enhance system capacity. The proposed code assignment scheme is applicable to both the forward and reverse channels.

In synchronous CDMA systems, a set of orthogonal direct sequence CDMA codes is assigned to the cell of interest. The number of available orthogonal codes for a given spreading factor is limited and therefore the capacity of the conventional S-CDMA system is often *code limited*. However, when SDMA is used in conjunction with S-CDMA it is possible to reuse code sequences within the same cell providing a corresponding increase in system capacity. Theoretically, with an M element antenna array receiver it is possible to reuse each code sequence M times.

SDMA is achieved by exploiting differences in the spatial signature vectors (SSVs) of the various users in the cell. In general, the greater the difference between the SSVs of users assigned to a given code, the greater the SDMA isolation of the users signals. Since, the performance of the SDMA system is tightly linked to spatial properties of the users with the same code, care should be taken to insure that the set of users that are assigned an identical code are spatially compatible. Clearly, a good code assignment scheme will assign identical codes to users that have the most dissimilar spatial properties. In this paper we propose a code assignment algorithm that is based upon estimating the SSVs of all active users. The properties of the estimated SSVs are then used in an attempt to place users into spatially compatible groups. We refer to the proposed algorithm as the SSV Based Code Assignment Algorithm (SBCAA).

The organization of the paper is as follows. Section 2 describes the assumed signal model. Section 3 discusses the implementation of SDMA with antenna array systems. In Section 4, we present the details of the SSV Based Code Assignment Algorithm. In Section 5, simulation results are presented indicating the effectiveness of the code assignment algorithm. Finally, Section 6 concludes the paper with a summary of results and recommendations for further study.

2. Signal Model

It is assumed that the radio base unit (RBU) is equipped with an M element antenna array. Let $x(t)$ denote the received signal vector that is observed at the antenna outputs at

F-1

time t . For a multipath channel, the analytic received signal vector component due to user n is given by

$$\mathbf{x}_n(t) = \sum_{l=1}^{L_n} \alpha_{n,l} \mathbf{a}(\theta_{n,l}) s_n(t - \tau_{n,l})$$

where L_n is the number of signal components and $s_n(t)$ is the analytic transmitted signal of the n th user. For CDMA systems, $s_n(t) = c_n(t) b_n(t) \exp(-j\omega_c t)$, where $c_n(t)$ is the CDMA spreading code, $b_n(t)$ is the sequence of data bits, and ω_c is the carrier frequency in radians per second. The parameters $\alpha_{n,l}$, $\tau_{n,l}$, and $\theta_{n,l}$, denote the complex amplitude, path delay, and azimuth angle of arrival of the l th path of the n th user, respectively. The vector, $\mathbf{a}(\theta_{n,l})$, is the array response vector in the direction of $\theta_{n,l}$. Assuming a flat fading channel environment, $\mathbf{x}_n(t)$ may be expressed as

$$\mathbf{x}_n(t) = \mathbf{v}_n s_n(t)$$

where

$$\mathbf{v}_n = \sum_{l=1}^{L_n} \alpha_{n,l} \mathbf{a}(\theta_{n,l}) \exp(-j\omega_c \tau_{n,l})$$

is defined as the spatial signature vector (SSV) of user n . It is the SSV's of each of the users that will determine the performance of the SDMA system.

3. SDMA using Antenna Arrays

SDMA exploits differences in the spatial characteristics of the various users in the channel to provide nearly orthogonal channels to the users. An illustration of SDMA is shown in Figure 1. The RBU uses different effective beampatterns to isolate the users' signals. In this case, the antenna pattern of user 1 has a null in the direction of user 2 and vice versa. In this way, the two users are able to access the base station resources using the same frequency, at the same time, with the same spreading code, without interfering with one another.

F-2

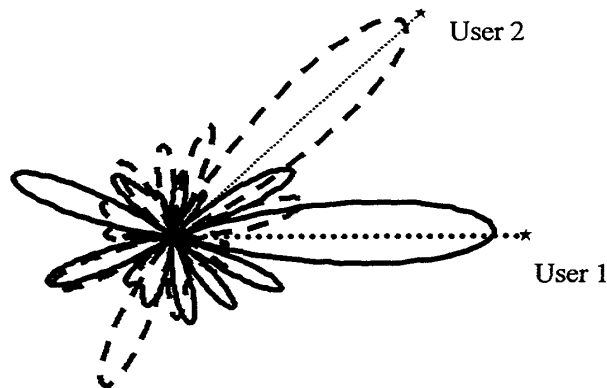


Figure 1: SDMA illustration for two users. Antenna patterns are used to provide orthogonal channels to the users.

The effective antenna patterns of each user are generated by summing amplitude scaled and phase rotated versions of the signals observed at each antenna element as shown in Figure 2. The array output for user n may be expressed as

$$y_n(t) = \begin{bmatrix} w_{n,1}^* & w_{n,2}^* & \dots & w_{n,M}^* \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix} = \mathbf{w}_n^H \mathbf{x}(t)$$

where $y_n(t)$ is the spatial filter output, $w_{n,i}$ is the complex weight applied to the i th antenna element, $x_i(t)$ is the signal present on the i th channel, and $*$ denotes complex conjugate. Each user applies a unique set of weights, thereby yielding different effective antenna patterns. This process is referred to as beamforming or spatial filtering.

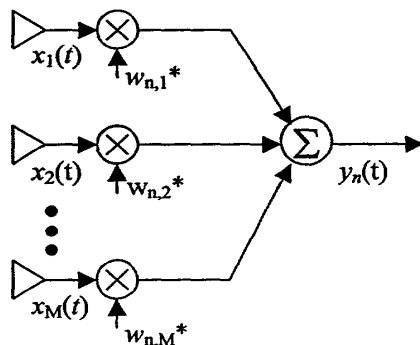


Figure 2: Spatial filter for user n .

It can be shown that the weight vector which maximizes the output signal to interference plus noise ratio (SINR) is given by $\mathbf{w}_n = \mathbf{R}_u^{-1}(n) \mathbf{v}_n$ where $\mathbf{v}_n$ is the spatial

signature vector of user n and $\mathbf{R}_n(n)$ is the corresponding interference plus noise correlation matrix. The matrix, $\mathbf{R}_n(n)$, may be expressed as,

$$\mathbf{R}_n(n) = \sum_{i=1, i \neq n}^N \sigma_s^2 \mathbf{v}_i \mathbf{v}_i^H + \sigma_n^2 \mathbf{I}_M$$

where N denotes the number of interfering signals, σ_s^2 is the variance of analytic received signal which is assumed to be equal for each user due to power control, and σ_n^2 is the variance of the additive white noise in the channel. The output SINR present at the array output corresponding to the optimum weight vector is given by,

$$\text{SINR}_{opt} = \sigma_s^2 \mathbf{v}_n^H \mathbf{R}_n^{-1}(n) \mathbf{v}_n.$$

4. SSV Based Code Assignment Algorithm

The assignment of codes can have a major impact on the performance of the SDMA system. In this section we propose a code assignment algorithm for assigning CDMA codes to users which attempts to minimize the similarity of the SSVs of the users in each code set. The metric used to measure the similarity of the spatial signature vectors of the users is the squared sum of the inner products of the same code users' SSV with the current user's SSV.

To motivate this metric, consider the separation of two users. In this case the optimum output SINR equation presented in the previous section may be expressed,

$$\text{SINR}_{opt}(2) = \frac{\sigma_s^2}{\sigma_n^2} \left[\|\mathbf{v}_1\|^2 - \frac{\sigma_s^2 |\mathbf{v}_1^H \mathbf{v}_2|^2}{\sigma_n^2 + \sigma_s^2 \|\mathbf{v}_2\|^2} \right].$$

For equal power users in a LOS channel, $\|\mathbf{v}_1\|^2 = \|\mathbf{v}_2\|^2 = M$ where M is the number of antenna elements in the array. In this case the optimum output SINR for both users becomes

$$\text{SINR}_{opt}(2) = \frac{\sigma_s^2}{\sigma_n^2} \left[M - \frac{\sigma_s^2 |\mathbf{v}_1^H \mathbf{v}_2|^2}{\sigma_n^2 + M\sigma_s^2} \right] \approx M \frac{\sigma_s^2}{\sigma_n^2} \left[1 - \frac{|\mathbf{v}_1^H \mathbf{v}_2|^2}{M^2} \right].$$

Note, that the optimum output SINR is a function of the squared inner product of $\mathbf{v}_1$ and $\mathbf{v}_2$. For convenience, let $\rho_{i,j} = |\mathbf{v}_i^H \mathbf{v}_j|^2$. When there are more than two users in the environment, then the optimum output SINR is no longer a function of just

$\rho_{i,j} = |\mathbf{v}_i^H \mathbf{v}_j|^2$ for each user, but is also dependent upon the phase of the inner products of

F-4

the SSV's. Regardless, it can be shown through simulation that there is a negative correlation between the output SINR and the quantity

$$\xi_n(c) = \sum_{i \in S_c} |\mathbf{v}_n^H \mathbf{v}_i|^2 = \sum_{i \in S_c} \rho_{n,i}$$

where S_c denotes the set of users already assigned to code c .

The following steps summarize the SSV based code assignment algorithm:

1. Estimate the SSV of all active users.
2. Calculate the magnitude squared inner product of the spatial signature vectors of all pairs of active users.
3. Using the values calculated in step 2, find $\xi_n(c)$ for each code that is not already used the specified maximum number of times.
4. Finally, assign to user k the code with the minimum $\xi_n(c)$.

5. Simulation Results

In this section we compare the performance of the proposed initial code assignment algorithm with a random assignment of codes. It is assumed that the RBU is equipped with a 16 element circular antenna array with an adjacent element separation of 5 wavelengths. There are 120 codes shared amongst the users. The total number of active users is equal to $16 * 120 = 1920$. Users are distributed in azimuth according to a random uniform distribution over the range of $[0, 2\pi]$. Only the LOS signal for each user is considered. It is assumed that power control is used on the reverse link, such that all of the users are received with equal power. The assumed SNR of the signal observed on each antenna element for a given user after despreading is 15dB. The cumulative distribution function (cdf) of the array output signal to interference plus noise ratio (SINR) is calculated from the SINR of each user, over ten independent trials of user placements.

The cdf of the array output SINR is shown in Figure 3. The output SINR obtained by using the proposed code assignment algorithm is between 3 to 5 dB higher than that obtained through random code assignment. In Figure 4, we show the number of users that have an array output SINR greater than the specified threshold level. For example, 1541 users have an array output SINR which exceeds 15 dB using the proposed code assignment algorithm, whereas only 954 have an array output SINR which exceeds 15 dB using a random code assignment. Finally, Figure 5 shows the number of users per antenna element per code with an output SINR greater than the mantissa (This quantity is a good figure of merit in which to compare the performance of antenna arrays with differing number of antenna elements.)

F-5

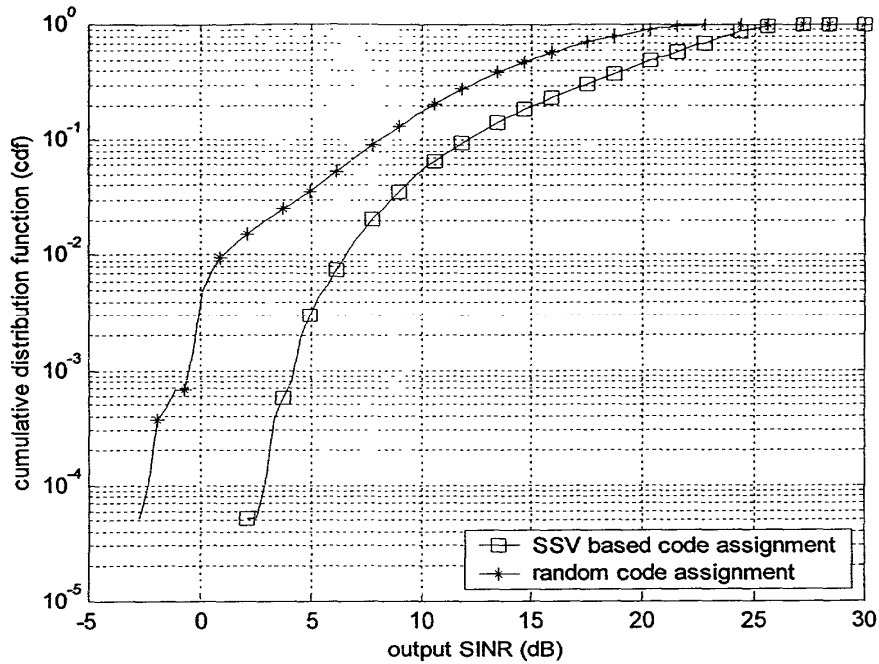


Figure 3: Output SINR cdf for SSV based code assignment and for random code assignment.

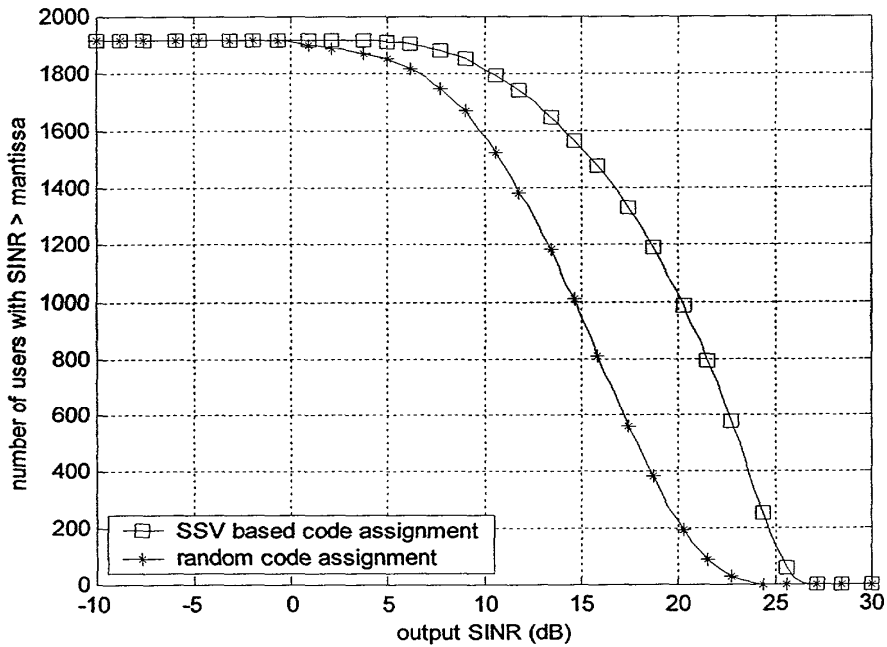


Figure 4: Number of users supported versus the required array output SINR for the SSV based code assignment and for random code assignment.

F-6

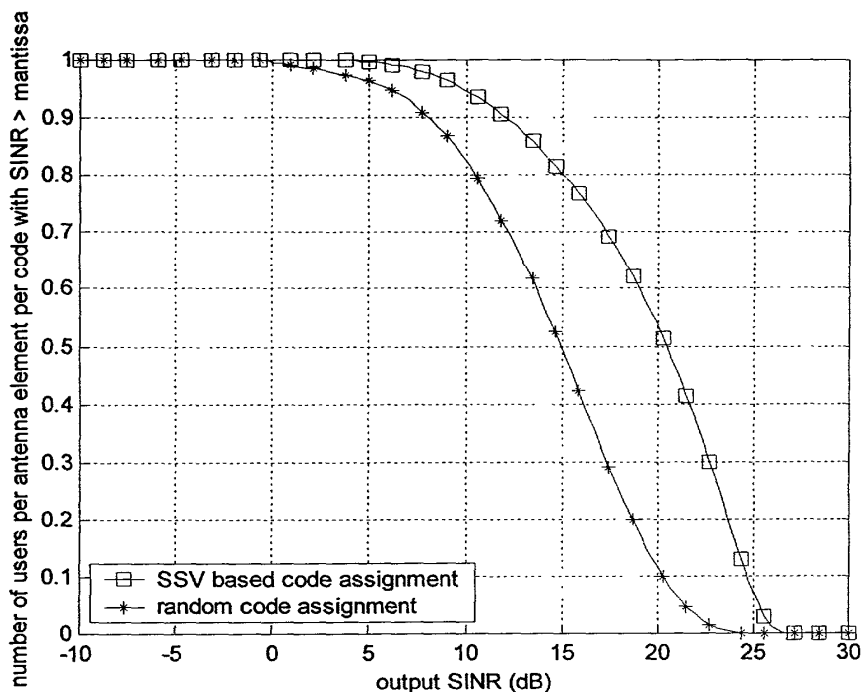


Figure 5: Number of users supported per antenna element per code versus the required output SINR for SSV based code assignment and for random code assignment.

6. Conclusions

An SSV based code assignment algorithm is proposed. With the proposed code assignment algorithm approximately 1.6 times as many users have an output SINR which exceeds the original input SNR when compared to a random code assignment. The factor of improvement is even greater when comparing the number of users at higher output SINRs. Further studies are needed to determine the performance of the code assignment algorithm when the number of allowable users is set less than the number of antenna elements times the number of code sequences

The results shown here indicate that substantial benefits are achievable by using an intelligent code assignment algorithm as compared to a random code assignment. Practical implementation issues of the proposed method still need to be addressed.

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APPENDIX G

The Use Of Wide Element Spacings To Improve The Flexibility Of A Circular Basestation Antenna Array

Abstract

In this paper, we propose the use of a wide antenna element spacing to improve the flexibility of installation and code assignment in a synchronous code division multiple access (S-CDMA) system utilizing space division multiple access (SDMA). The wide spacing permits the same code to be assigned to multiple users within a narrow angular range within a cell. It also permits us to install the antenna array lower on a pyramid-style tower, thus reducing tower rental fees considerably.

1. Introduction

Synchronous CDMA systems, such as the Primewave 2000 system developed by L3 Communications, will have a capacity that is limited by the number of available orthogonal codes, assuming that the channel multipath is not too severe and that the system is well designed. In order to improve the capacity of a code-limited S-CDMA system, we must either tolerate the presence of non-orthogonal codes, or reuse orthogonal codes multiple times within a cell. One very good way to reuse the same code multiple times within a cell is to use an adaptive array antenna at the radio base unit (RBU) to provide sufficient antenna isolation between the same-code users. The use of an antenna array to isolate users and provide spatially orthogonal channels through which multiple users can coexist is referred to as space division multiple access (SDMA). The idea of SDMA has been around for many years, but only recently has the idea been proposed of combining S-CDMA and SDMA to create a point-to-multipoint communication link with a high spectral efficiency, [1].

For the fixed wireless local loop application, in which a base station provides telephone and data service to a 360 degree cell, a circular antenna array is a very attractive antenna configuration. It is possible to split the cell into sectors and service each sector with a linear antenna array, however this approach has the disadvantage of having sector boundaries. Users that are located on a boundary between two sectors will provide a substantial amount of interference to the adjacent sector. In order to eliminate explicit sector boundaries, the use of SDMA with a circular antenna array may be used to permit one basestation to service 360 degrees. With this better approach, CDMA codes may be reused within adjacent virtual sectors with only a minimal amount of interference.

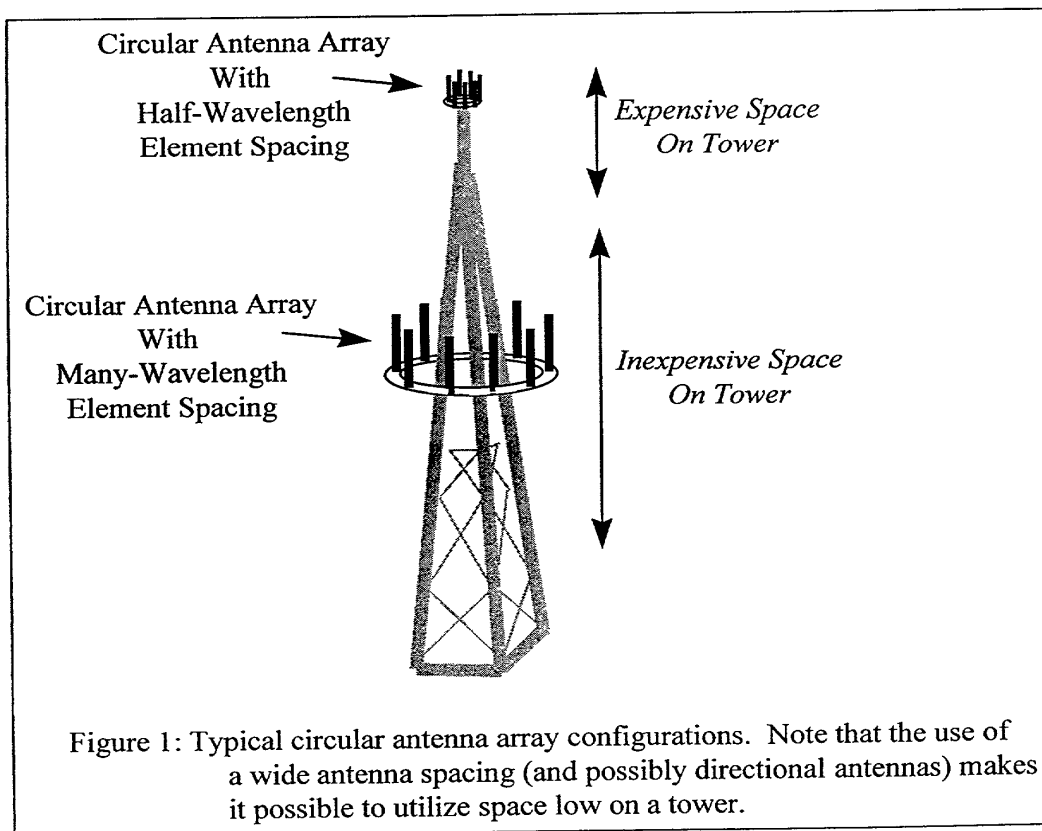
In virtually all of the literature on SDMA, it is common to initially assume that antenna arrays may be implemented with an arbitrary element spacing, but then to go on

G-1

to make the simplifying assumption that the elements are a half-wavelength apart. In this report, we propose that the elements be spaced widely apart (widely in this case meaning more than a wavelength apart). This wide spacing will have a number of advantages which will be discussed in the next section.

2. The Advantages Of Wide Element Spacing In Circular Arrays

There are two major advantages of using an antenna spacing of greater than a half-wavelength. The first advantage is that it permits the diameter of a circular array to be sufficient to mount the array below the very top of the tower. For frequencies of operation in the 2-4 GHz range, the carrier wavelength is between 7.5 and 15 centimeters. This implies that the elements will need to be very close together if half wavelength spacing is desired. For example, a system operating at 3 GHz will have a carrier wavelength of 10 centimeters. If a half wavelength spacing is desired in a 16 element array, then the diameter of the circular array will be approximately 25 cm. Figure 1 illustrates the fact that this 25 cm cylinder of antennas would need to reside on the top of a tower if it is to have a 360 degree view.



G-2

The attached Appendix H (13 pages) also forms a part of this provisional patent application, and is incorporated by reference herein in its entirety.

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APPENDIX H 13 PAGES

Synchronous DS-CDMA/FDMA PHY Proposal for IEEE 802.16.3

Eric K. Hall, Richard B. Ertel, Thomas R. Giallorenzi and Randy. R. Sylvester

L-3 Communications

1 Introduction

In this document, we detail a preliminary PHY proposal for IEEE 802.16.3. The proposal uses a hybrid synchronous DS-CDMA (S-CDMA) and FDMA scheme with adaptive quadrature phase shift key (QPSK) and quadrature amplitude modulation (QAM) and trellis coding. For background on S-CDMA with trellis-coded QAM, the interested reader is referred to [1] and [2]. While the focus of this proposal is on a frequency division duplexing (FDD) mode, a time division duplexing mode is also possible for unpaired frequency allocations.

2 Overview

Below is a bulleted overview of the characteristics of the proposed PHY.

- Synchronous direct-sequence code division multiple access (S-CDMA) for both up and downstream
 - Spread RF sub-channel bandwidths from 1.75-7 MHz depending on channelization of interest
 - Constant chip rate from 1-6 Mcps within each RF sub-channel with common I-Q spreading [chip rate depends on channelization of interest (e.g. 3.5 MHz or 6 MHz)]
 - Orthogonal, variable-length spreading codes using Walsh-Hadamard designs with spread factors (SF) from 1 to 128 chips/symbol
 - Unique spreading code sets for adjacent, same-frequency cells/sectors
 - Upstream and downstream power control and upstream link timing control
 - Single S-CDMA channel data rates from 32 kbps up to 16 Mbps depending on SF and chip rate
 - S-CDMA channel aggregation for highest data rates
- FDMA for large bandwidth allocations with S-CDMA in each FDMA RF sub-channel
- S-CDMA/FDMA channel aggregation for highest data rates
- Code, frequency and/or time division multiplexing for both up and downstream
- Frequency division duplex (FDD) or time division duplex (TDD) [TDD option not discussed]
- Coherent QPSK and 16-QAM modulation with optional support for 64-QAM
- End-to-end raised-cosine Nyquist pulse shape filtering
- Adaptive coding, using high-rate punctured, convolutional coding (K=7) and/or Turbo coding
- Data randomization using spreading code sequences
- Linear equalization in downstream with possible transmit pre-equalization for upstream
- Space division multiple access (SDMA) using adaptive beam-forming antenna arrays (1 to 16 elements possible) at the BS

3 Reference Model

Figure 3.1 shows the wireless access reference model per the IEEE 802.16.3 FRD [3]. Within this model, the proposed PHY provides access between one or more subscriber stations (SS) to support the user and core network interface requirements. In Figure 3.2, the PHY reference model is shown. This reference model will be useful in discussing the various aspects of the proposed PHY.

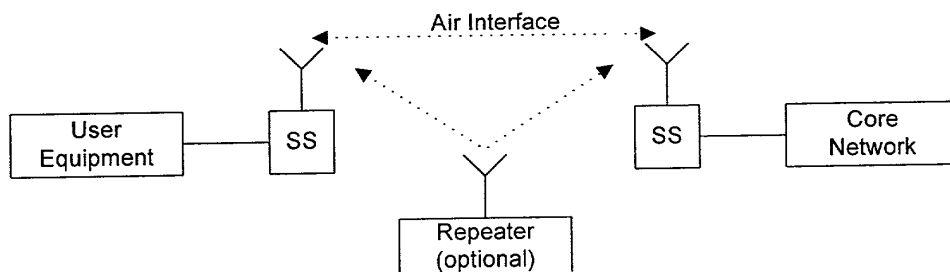


Figure 3.1: Wireless Access Reference Model

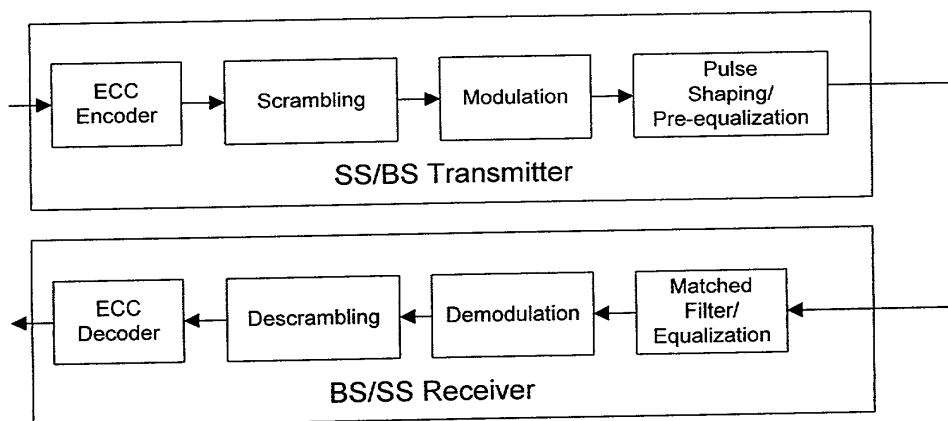


Figure 3.2: PHY Reference Model Showing Data Flow

The proposed PHY must interface with the MAC, carrying MAC packets and enabling MAC functions based on QoS requirements and Service Level Agreements (SLAs). As a S-CDMA system, the PHY must interact with the MAC for purposes of power and timing control. Both power and timing control should originate from the BS, with feedback from the SS needed for forward link power control. The PHY must also interact with the MAC for link adaptation (e.g. bandwidth allocation and SLAs), allowing adaptation of modulation formats, coding, data multiplexing, etc.

4 Frequency Bands and RF Channel Bandwidths

The primary frequency bands of interest for this PHY proposal include the ETSI frequency bands from 1-3 GHz and 3-11 GHz ([4] and [5]) along with the MMDS/MDS frequency bands. In [4], the radio characteristics for DS-SS systems in the fixed frequency bands around 1.5, 2.2, 2.4 and 2.6 GHz are given, allowing

channelizations of 3.5, 7, 10.5 and 14 MHz. Here, the FDD separation is specific to the center frequency and ranges from 54 to 175 MHz. In [5], the radio characteristics of DS-CDMA systems with fixed frequency bands centered around 3.5, 3.7 and 10.2 GHz are specified, allowing channelizations of 3.5, 7, 14, 5, 10 and 15 MHz. Again, FDD separation is frequency band dependant and ranges with range from 50 to 200 MHz. Also targeted in this proposal are the MMDS/MDS/ITSF frequency bands between 2.5 and 2.7 GHz with 6 MHz channelizations.

5 Multiple Access, Duplexing and Multiplexing Schemes

We propose a frequency division duplex (FDD) PHY using a hybrid S-CDMA/FDMA multiple access scheme with SDMA for increased spectral efficiency. In our approach, each FDMA RF sub-channel has an RF channel bandwidth from 1.75 to 7 MHz. The choice of FDMA RF sub-channel bandwidth is dependent on the frequency band of interest with 3.5 MHz and 6 MHz being typical per the IEEE 802.16.3 FRD [3]. Within each FDMA RF sub-channel, S-CDMA is used with users transmitting in the up and downstream using a constant chipping rate from 1 to 6 Mcips/second. TDD could be used in a single RF sub-channel but we only discuss an FDD mode of operation in this work. With FDD, one or more FDMA RF sub-channel is used in the downstream while at least one FDMA sub-channel is required for the upstream. The approach is flexible to asymmetric data traffic, allowing more downstream FDMA RF sub-channels than upstream FDMA sub-channels when traffic patterns and frequency allocation warrant. Based on the target frequency bands, typical upstream/downstream FDD separation will range from 50 to 200 MHz.

5.1 Synchronous DS-CDMA (S-CDMA)

Within each FDMA sub-channel, S-CDMA is used in both the up and downstream [1]. The chipping rate is constant for all SS with rates ranging from 1 to 6 Mcips/second depending on the FDMA RF sub-channel bandwidth. Common I-Q spreading is performed using orthogonal, variable-length spreading codes based on Walsh-Hadamard designs with spread factors ranging from 1 up to 128 chips per symbol [See [8] for a review of spreading code design for CDMA]. For multi-cell deployments with low frequency reuse, unique spreading code sets are used in adjacent cells to minimize interference. It should be noted that a symmetric waveform is envisioned within each FDMA sub-channel, where both the upstream and downstream utilize the same chipping rate (and RF channel bandwidth), spreading code sets, modulation, channel coding, pulse shape filtering, etc.

5.2 Code and Time Division Multiplexing and Channel Aggregation

With a hybrid S-CDMA/FDMA system, it is possible to multiplex data over codes and frequency sub-channels. Furthermore, for a given code or frequency channel, time division multiplexing could also be employed. In our approach, we suggest the following multiplexing scheme. For the downstream transmission with a single FDMA sub-channel, the channel bandwidth (i.e. capacity measured in bits/second) is partitioned into a single TDM pipe and multiple CDM pipes. The TDM pipe could be created via the aggregation of multiple S-CDMA channels (e.g. spreading codes). The purpose of this partition is based on the desire to provide Quality of Service (QoS). Within the bandwidth partition, the TDM pipe would be used for best effort service (BES) and some assured forwarding (AF) traffic for packet services. The CDM channels would be used for expedited forwarding (EF) services, such as VoIP connections or other stream applications, where the data rate of the CDM channel is *matched* to the bandwidth requirement of the service.

Of course, the downstream could be configured as a single TDM pipe, without use of CDM. Here, time slot assignment would be used for bandwidth reservation, with typical slot sizes ranging from 4 –16 ms in length.

While a pure TDM downstream is possible with our approach, we favor a mixed TDM/CDM approach since long packets can induce jitter into EF services in a pure TDM link. Having a CDMA channels (single or aggregated) dedicated to a single EF service (or user) reduces jitter without the need for packet fragmentation and reassembly. Furthermore, these essentially “circuit-switched” CDM channels would enable better support of legacy circuit-switched voice communications equipment and public switched telephone networks. As an example, full or partial T1/E1 lines could be provided via CDM channels.

For the upstream, we envision a similar partition of TDM/CMD channels. The TDM channel(s) would be used for random access, using a slotted-Aloha protocol. In keeping with a symmetric waveform, we recommend burst lengths on the order of the slot times for the downlink, ranging from 4-16 ms with multi-slot bursts possible. The BS monitors bursts from SS and allocates upstream CDM channels to SSs upon recognition of impending bandwidth requirements or based on service level agreements (SLAs). As an example, a BS recognizing the initiation of a VoIP connection could move the transmission from the TDM channel to a dedicated CMD channel with a channel bandwidth matched to the rate of the VoIP connection (e.g. 32 kbps or 64 kbps).

When multiple FDMA sub-channels are present in the up and/or downstream, similar partitioning could be used. Here, extra bandwidth exists meaning more channel aggregation is possible. With a single TDM channel, data would be multiplexed across CDMA codes and across frequency sub-channels.

5.3 Space Division Multiple Access (SDMA) Extensions

The final aspect of our proposed multiple access scheme involves the use of space division multiple access (SDMA) implemented with adaptive beamforming antenna systems [See [6] for details of beamforming with CDMA systems]. We envision an adaptive antenna array at the BS, with narrow, fixed-beam SS antennas. In the approach, S-CDMA/FDMA channels can be directed or formed to individual SS. The isolation provided by the beamforming allows the CDMA spreading codes to be reused within the same cell, greatly increasing spectral efficiency. Beamforming is best suited to CDM rather than TDM channels. In the downstream, TDM would require beamforming on a per slot (or packet) basis, increasing complexity. In the upstream, beamforming would be difficult since the BS would have to anticipate transmission from SS in order to form the beams appropriately. In either case, reuse of CDMA spreading codes in a TDM-only environment would be difficult. With CDM, the BS could allocate bandwidth (i.e. CDMA channels) to SS based on need or SLAs. Once allocated, the BS would form a beam to the SS to maximize signal-to-interference ratios (SIR). Once formed, the BS could reallocate the same CDMA channel to other SSs in the same cell. It is theoretically possible for the spectral efficiency of the cell to scale linearly with the number of antennas in the BS array.

SDMA greatly favors the approach of “fast circuit-switching” over pure, TDM packet-switching in a CDMA environment. By “fast circuit-switching”, we mean packet-services handled using temporary, dedicated connections, which are allocated and terminated based on bandwidth requirements and/or SLAs. To provide effective packet-services using this approach, the BS must be able to rapidly 1.) determine bandwidth needs and 2.) allocate and terminate connections matched to the bandwidth required. With fast channel allocation and termination, SDMA combined with the low frequency reuse offered by S-CDMA is the best option in terms of spectral efficiency and providing QoS for BWA applications.

6 Waveform Specifications

The waveform includes the channel coding, scrambling, modulation, pulse shaping and equalization functions of the air interface. Also included are waveform control functions, including power and timing control. In our proposed PHY, each CDMA channel (i.e. spreading code) uses a common waveform, with the spreading factor dictating the communications channel rate (e.g. bits per second or symbols per second).

6.1 Error Control Coding (ECC)

The error control coding should be high-rate and adaptive. High rate codes are needed to maximize the spectral efficiency of S-CDMA systems that are code-limited. High rate codes are also appropriate for S-CDMA since in-cell interference is virtually eliminated. Thus, in S-CDMA, capacity is limited, not by the interference level, but rather by the code set cardinality (e.g. number of available orthogonal spreading codes). Adaptive coding is needed to provide robust performance and graceful degradation of system capacity in multipath fading environments. For the coding options, the baseline code is a punctured, convolutional code (CC). The constituent code is the industry standard, rate 1/2, constraint length 7 code with generator (133/171)₈. Puncturing is used to increase the rate of the code, with rates of 3/4, 4/5, 5/6 or 7/8 supported using optimum free distance puncturing patterns. The puncturing rate of the code may be adaptive to mitigate fading conditions. For decoding, a Viterbi decoder should be used. [See [2] for analysis of trellis-coded S-CDMA]

Turbo coding, including block turbo codes and/or traditional parallel and serial concatenated convolutional codes, should be supported as an option at the coding rates suggested above. In this document, we do not propose a specific turbo code design.

Each CDMA channel should be coded independently. Independent coding of CDMA channels furthers the symmetry of the upstream and downstream waveform and enables a similar time-slot structure on each CDMA channel. The upstream and downstream waveform symmetry aids in cost reduction allowing the SS and BS to share baseband hardware. The independent coding of each S-CDMA/FDMA channel is a key distinction between our approach and other multi-carrier CDMA schemes discussed in the literature [7].

6.2 Randomization

Randomization should be implemented on the coded bit stream. Rather than using a traditional randomizing circuit, we propose the CDMA spreading sequences as randomizing codes in the transmitting station. Using the spreading codes allows different randomizing sequences to be used by different users, providing more robust randomization and eliminating problems with inter-user correlated data due to periodically transmitted sequences (e.g. preambles and start-of-frame delimiters). Since the receiving station has knowledge of the spreading codes, de-randomization is trivial at the receiving station. Randomization may be disabled on a per channel or per symbol basis. In Figure 6.2.1, the proposed channel coding and scrambling method is illustrated.

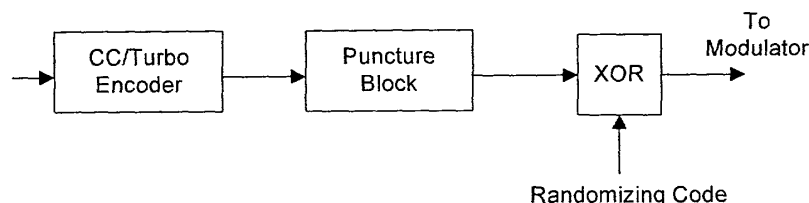


Figure 6.2.1: Proposed ECC and scrambling method for a single CDMA channel**6.3 Modulation Formats**

Coherent QPSK and square 16-QAM modulation formats must be supported, with optional support for square 64-QAM. Using a binary channel coding technique, Gray-mapping should be used for constellation bit-labeling to achieve optimum decoded performance. This combined coded modulation scheme allows simple Viterbi decoding hardware designed for binary codes to be used. Differential detection for all modulation formats may be supported as an option. Depending on the channel coding, waveform spectral efficiencies from 1 to 6 information bits/symbol will be supported.

The modulation format should be adaptive based on the channel conditions (SIR) and bandwidth requirements. Both up and downstream links must be achievable using QPSK waveform provided adequate SNR. In environments with higher SNR, up and downstream links may utilize 16-QAM and /or 64-QAM modulation formats for increased capacity and spectral efficiency. The allowable modulation format will depend on the channel conditions, hardware limitations (e.g. phase noise) and the channel coding being employed on the link.

6.4 Pulse Shape Filtering

End-to-end raised-cosine Nyquist pulse shaping should be applied. Pulse shape filtering should be designed to meet relevant spectral masks, mitigate inter-symbol interference (ISI) and adjacent FDMA sub-channel interference.

6.5 Equalization

To mitigate multipath fading, a linear equalizer is suggested for the downstream. Equalizer training could be done using a preamble, with decision-direction used following initial training. With S-CDMA, equalizing the aggregate signal in the downlink effectively equalizes all CDMA channels, thus restoring orthogonality between codes in frequency selective fading environments. Multipath delay spread less than 3 μ s is expected for Non-Line Of Sight (NLOS) deployments using narrow-beam (10-20°) subscriber station antennas [12][13]. This low delay spread allows simple, linear equalizers with 8-16 taps that effectively equalize most channels. For the upstream, pre-equalization may be used as an option, but requires feedback from the subscriber station due to frequency division duplexing and thus is not recommended.

Rake processing to exploit the multipath environments is left as an option. However, we argue linear equalization to restore code orthogonality is a more appropriate technique for mitigating multipath for non-mobile systems.

6.6 Timing and Power Control

Timing control is required for upstream orthogonal S-CDMA. In the downstream, timing control is trivial. In the upstream, timing control is controlled by the BS. Timing-control results in reduce in-cell interference levels.

While infinite in-cell signal-to-interference ratios (SIRs) are theoretically possible with orthogonal S-CDMA, timing errors, multipath fading and pulse shape filtering result in loss of code orthogonality leading to realistic in-cell SIRs from 30-40 dB. Asynchronous DS-CDMA (A-CDMA) systems have higher in-cell interference levels exist resulting in less tolerance of out-of-cell interference and higher frequency reuse factors [9]. The

ability of timing-control to limit in-cell interference in the upstream is the key to frequency reuse of one in a S-CDMA system.

Power control is required for S-CDMA systems. Power control acts to mitigate in-cell and out-of-cell interference while also ensuring appropriate signal levels at the SS or BS to meet bit error rate requirements and QoS requirements. For SS that are close to the BS, less transmitted power is required for a given SIR, while for a distant SS, more transmit power is required in both the up and downstream to attain the same SIR. As with timing control, power control is a key technique towards achieving a frequency reuse of one with S-CDMA.

7 Capacity, Spectral Efficiency and Data Rates

7.1 Single-Cell Performance

For a single, spread FDMA channel, the proposed S-CDMA waveform is capable of providing channel bandwidths from 1 to 32 Mbps in both the up and downstream depending on the RF channel bandwidth. Using variable-length spreading codes and a constant chipping rate, each CDMA channel can be configured to operate at a variety of rates ranging from tens of kbps up to tens of Mbps. As illustrated in (1), the communications channel bandwidth of a single CDMA channel depends on the modulation format, channel coding rate, chipping rate, and the spread factor, with higher data rates resulting from lower spreading factors [fewer chips/symbol].

With S-CDMA channel aggregation, high data rates are possible without requiring a SF of one and 64-QAM. In general, the use of S-CDMA along with our proposed interference mitigation techniques will allow the system to be code-limited. Mobile cellular A-CDMA systems are always interference-limited, resulting in frequency reuse and lower spectral efficiency. In code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. In a code-limited environment, the communications channel bandwidth of the system is equal to the communications channel bandwidth of the waveform assuming SF of one. In Table 1, we show sample parameters for a hypothetical system using different coded modulation schemes and assuming a code-limited DS-CDMA environment.

Parameter	Modulation and Channel Coding		
	QPSK w/ R=4/5 Coding (1.6 bits/sym)	16-QAM w/ R=4/5 Coding (3.2 bits/sym)	64-QAM w/ R=4/5 Coding (4.8 bits/sym)
RF Channel Bandwidth	3.5 MHz	3.5 MHz	3.5 MHz
Chip Rate	2.56 Mcps	2.56 Mcps	2.56 Mcps
Communication Channel Bandwidth	4.096 Mbps	8.192 Mbps	12.288 Mbps
Peak Data Rate	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=1)	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=16)	256 kbps	512 kbps	768 kbps
CDMA Channel Bandwidth (SF=128)	32 kbps	64 kbps	96 kbps
Modulation Factor	1.17 bps/Hz	2.34 bps/Hz	3.511 bps/Hz

Table 7.1.1: Hypothetical parameters for a 3.5 MHz RF channelization

Table 7.1.1 illustrates potential performance assuming a single 3.5 MHz channel in both the up and downstream. The numbers reported in Table 7.1.1 apply to both the upstream and downstream, meaning that upwards of 24 Mbps full duplex is possible in 3.5 MHz [12 Mbps upstream and 12 Mbps downstream]. With additional FDMA RF channels or wider RF channels [e.g. 6 MHz], additional communication bandwidth is possible with the same modulation factors from Table 7.1.1. As an example, allocation of 14 MHz could be serviced using 4 FDMA RF channels with the parameters described in Table 7.1.1. In 14 MHz, peak data rates to a SS up to 48 Mbps would be achievable, with per CDMA channel data rates scaling up from 32 kbps. With a 6 MHz channel allocation, a chipping rate of 4.48 Mcps could be used giving communication channel bandwidths of 14 Mbps with 16-QAM and upwards of 20 MHz with 64-QAM using a single 6 MHz RF channel. The proposed channel aggregation method is very flexible in servicing symmetric versus asymmetric traffic, as well as providing reserved bandwidth for QoS and SLA support.

7.2 Multi-Cell Performance

To this point, capacity and spectral efficiency have been discussed in the context of a single, isolated cell. In a multi-cell deployment, S-CDMA will allow for a true frequency reuse of one eliminating the need for frequency planning, improving spectral efficiency and reducing costs. With a frequency reuse of one, the total system spectral efficiency is equal to the modulation factor of a given cell. Comparing S-CDMA to a single carrier TDMA approach with a typical frequency reuse of 4, TDMA systems must achieve much higher modulation factors in order to compete in terms of overall system spectral efficiency. Assuming no sectorization and a frequency reuse of one, S-CDMA systems can achieve system spectral efficiencies from 1 to 6 bps/Hz with improvements possible using SDMA with adaptive beamforming.

While frequency reuse of one is theoretically possible for DS-CDMA, the true allowable reuse of a specific deployment is dependent on the propagation environment (path loss) and user distribution. For mobile cellular systems, it has been shown that realistic reuse factors range from 0.3 up to 0.7 for A-CDMA; factors that are still much higher than for TDMA systems [9]. In a S-CDMA system, in-cell interference is mitigated by the orthogonal nature of the S-CDMA, implying that the dominant interference results from adjacent cells. For the fixed environments using S-CDMA, true frequency reuse of one can be achieved for most deployments using directional SS antennas and up and downstream power control to mitigate levels of adjacent cell interference. In a S-CDMA environment, true frequency reuse of one implies that a cell is code-limited, even in the presence of adjacent cell interference.

For sectorized deployments with S-CDMA, a frequency reuse of two will be required to mitigate the adjacent channel interference contributed by users on sector boundaries. In light of this reuse issue, we recommend implementing SDMA with adaptive beamforming rather than sectorization to improve cell capacity.

Since spectral efficiency translates directly into cost for IEEE 802.16.3 systems, frequency reuse of one achieved with S-CDMA is an important, perhaps the most important, argument for developing the BWA PHY based on S-CDMA.

7.3 Performance with SDMA

The use of SDMA in conjunction with S-CDMA offers the ability to dramatically increase system capacity and spectral efficiency. SDMA uses an antenna array at the BS to spatially isolate same code users in the cell. The number of times that a code may be reused within the same cell is dependent upon the number of antenna elements in the array, the array geometry, the distribution of users in the cell, the stability of the channel, and the available processing power. Theoretically, in the absence of noise, with an M element antenna array it is possible to reuse each code sequence M times, thereby increasing system capacity by a factor of M . In practice, the code reuse is slightly less than M due to implementation loss, frequency selective multipath fading, and receiver noise. Regardless, significant capacity gains are achievable with SDMA. With appropriate array geometry and careful grouping of users sharing CDMA codes, it is possible to achieve a code reuse of $0.9M$ or better [6].

In real deployments, the number of antenna elements is limited by the available processing power, the physical tower constraints, and system cost [e.g. additional RF front ends (RFFE)]. Selected array sizes will vary depending upon the required capacity of the given cell on a cell-by-cell basis. Table 7.3.1 shows achievable aggregate capacity and modulation factors with typical array sizes assuming a code reuse equal to the number of antenna elements. The aggregate capacity is defined as the total data rate of the BS. Modulation factors exceeding 56 bps/Hz are achievable with 64-QAM and a sixteen-element antenna array.

Number of Elements	QPSK		16 QAM		64 QAM	
	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)
1	4.096	1.17	8.192	2.34	12.288	3.511
2	8.192	2.34	16.384	4.68	24.576	7.022
4	16.384	4.68	32.768	9.36	49.152	14.044
8	32.768	9.36	65.536	18.72	98.304	28.088
16	65.536	18.72	131.072	37.44	196.608	56.176

Table 7.3.1: Aggregate capacity and modulation factors versus modulation type and array size.

It should be noted that while SDMA can dramatically increase the capacity of cell, it does not increase the peak data rate to a given SS. SDMA will allow an S-CDMA system to increase capacity, thus meeting growing user demands, without new spectral allocation. With SDMA, the peak data rate will not increase, but the number of users supported at a given rate can be dramatically increased.

8 Implementation and Deployment Issues

8.1 Flexibility

From previous discussion, our proposed PHY is very flexible. Using narrowband S-CDMA channels, our proposal can adapt to a variety of frequency allocations, easily handling non-contiguous frequency allocations. The proposed data multiplexing scheme allows great flexibility in servicing traffic asymmetry and support of traffic patterns created by higher-layer protocols such as TCP/IP. The use of variable rate CDMA channels allows efficient QoS support, with rate matching to meet bandwidth requirements.

8.2 Scalability

Deployments using our proposed PHY are very scalable. When traffic demands increase, new frequency allocation can be used. In our proposal, this amounts to adding additional FDMA channels, which may or may not be contiguous with the original allocation. Without additional frequency allocation, cell capacity can be increased using SDMA with an adaptive antenna array.

8.3 Complexity

Implementation complexity of the proposed PHY is fairly low. From mobile cellular systems and standards, CDMA is a proven technology. S-CDMA has also been proven in fielded systems. We envision significant complexity required at the MAC layer, regardless of the PHY, for efficient support of QoS and efficiency utilization of the PHY.

8.4 Cost

The high spectral efficiency of our waveform leads to cost benefits. First, low frequency reuse reduces costs associated with licensing spectrum. Secondly, high spectral efficiency allows providers to service more billable users in a given frequency allocation. Service providers with small spectral allocations will be capable of handling a larger customer base per cell.

Using a symmetric waveform (same in up and downstream) is a cost saving feature, allowing common baseband hardware in the SS and BS. The use of proven CDMA technology also aids in cost reduction, leveraging the CDMA development efforts and components used for mobile cellular systems.

9 Robustness

9.1 Robustness to Interference

As a spread spectrum signal, the proposed waveform offers inherent robustness to interference sources. Interference sources will be reduced by the spreading factor, which ranges from 1 to 128 (interference suppression of 0 to 21 dB.) At the SS, equalization further suppresses narrowband jammers by adaptively placing spectral nulls at the jammer frequency. Additional robustness to interference is achieved by the directionality of the SS antennas, since off-boresight interference sources will be attenuated by the antenna pattern in the corresponding direction. At the BS, the antenna array used to implement SDMA will offer the additional benefit of adaptively steering nulls towards unwanted interference sources.

9.2 Robustness to Channel Impairments

The proposed waveform has several properties that make it robust to channel impairments. The use of a spread spectrum makes the waveform robust to frequency selective fading channels through the inherent suppression of inter-chip interference. Further suppression of inter-chip interference is provided by equalization at the SS.

The proposed waveform is also robust to flat fading channel impairments. The proposed adaptive channel coding provides several dB of coding gain. The antenna array used to implement SDMA also functions as a diversity combiner. Assuming independent fading on each antenna element, diversity gains of M are achieved, where M is equal to the number of antenna elements in the array. Finally, since the S-CDMA system is code-limited rather than interference limited the system may run with a large amount of fade margin. Even without equalization or diversity, fade margins on the order of 10 dB are possible. Therefore, multipath fades of 10 dB or less will not increase the BER beyond the required level. Fade margins allow very high link availabilities in

S-CDMA systems. Availabilities of 99.9% above 10^{-9} are not uncommon with S-CDMA, whereas availabilities of 95% with 10^{-3} bit error rate are common for A-CDMA and other multiple access alternatives.

9.3 Robustness to Radio Impairments

Adaptive modulation provides robustness to radio impairments. For receivers with larger phase noise, the QPSK modulation offers more tolerance to receiver phase noise and filter group delay. The adaptive equalizer at the SS of will reduce the impact of linear radio impairments. Finally, clipping may be used in the SS and BS to reduce the peak-to-average power ratio of the transmitted signal and help to avoid amplifier saturation, for a given average power output.

10 Relation to Existing Standards

The proposed PHY is most similar to mobile cellular standards including IS-95, W-CDMA and cdma2000. While similar to mobile cellular A-CDMA standards, it is important to note that many key differences exist which reflects optimization of the CDMA technology for the fixed, BWA environment. The most important difference is the use of a synchronous upstream, which allows a true frequency reuse of one. Due to some similarity with mobile cellular standards, cost savings are possible using existing, low-cost CDMA components and test equipment. Our proposed PHY is quite different from cable modem and xDSL industry standards as well as IEEE 802.11 standards. However, with a spreading factor of one chip/symbol, the proposed PHY supports a single-carrier QAM waveform similar to DOCSIS 1.1 and IEEE 802.16.1 draft PHY [10][11].

11 Statement of Intellectual Property Rights

L-3 Communications may have intellectual property rights (IPR) in the proposed PHY. If L-3 Communications has any applicable essential patents, it will comply with the IEEE IPR rules regarding disclosure and licensing.

12 Conclusions

We feel that a S-CDMA based PHY is optimum for the fixed, BWA application. Below we list the most important benefits along with the associated drawbacks of our proposed PHY. We feel that the most important aspect of the PHY should be spectral efficiency, as this will translate directly to cost measured in cost per line or cost per carried bit for BWA systems. With a frequency reuse of one, higher-order adaptive modulation and efficient support of SDMA for increased spectral efficiency, we feel S-CDMA combined with FDMA is the correct technology for the BWA market.

PHY Benefits

- High spectral efficiency - 1-6 bps/Hz system-wide without SDMA
- Perfectly compatibility with smart antenna systems implementing SDMA
 - 1-50 bps/Hz system-wide with SDMA and adaptive beamforming
- True frequency reuse of one possible (increased spectral efficiency and no frequency planning)
- S-CDMA gives:
 - Robustness to channel impairments (e.g. multipath fading)
 - Robustness to co-channel interference (allows frequency reuse of one)
 - Robustness to interference (e.g. receiver noise, clipping and quantization, etc.)

- Security from eavesdropping
- Bandwidth flexibility and efficiency support of QoS requirements
- Support most frequency allocations using a combination of narrowband S-CDMA and FDMA
- Adaptive coding and modulation yield robustness to channel impairments and traffic asymmetries
- Leverages mobile cellular technology for reduced cost and rapid technology development and test
- Cost savings using a symmetric waveform and identical SS and BS hardware

Drawbacks

- Overhead and complexity due to power and timing control
- Inconsistent with IEEE 802.16.1 PHY

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- | 1. 1990年12月31日 | | 2. 1991年12月31日 | | 3. 1992年12月31日 | | 4. 1993年12月31日 | | 5. 1994年12月31日 | | 6. 1995年12月31日 | | 7. 1996年12月31日 | | 8. 1997年12月31日 | | 9. 1998年12月31日 | | 10. 1999年12月31日 | | 11. 2000年12月31日 | | 12. 2001年12月31日 | | 13. 2002年12月31日 | | 14. 2003年12月31日 | | 15. 2004年12月31日 | | 16. 2005年12月31日 | | 17. 2006年12月31日 | | 18. 2007年12月31日 | | 19. 2008年12月31日 | | 20. 2009年12月31日 | | 21. 2010年12月31日 | | 22. 2011年12月31日 | | 23. 2012年12月31日 | | 24. 2013年12月31日 | | 25. 2014年12月31日 | | 26. 2015年12月31日 | | 27. 2016年12月31日 | | 28. 2017年12月31日 | | 29. 2018年12月31日 | | 30. 2019年12月31日 | | 31. 2020年12月31日 | | 32. 2021年12月31日 | | 33. 2022年12月31日 | | 34. 2023年12月31日 | | 35. 2024年12月31日 | | 36. 2025年12月31日 | | 37. 2026年12月31日 | | 38. 2027年12月31日 | | 39. 2028年12月31日 | | 40. 2029年12月31日 | | 41. 2030年12月31日 | | 42. 2031年12月31日 | | 43. 2032年12月31日 | | 44. 2033年12月31日 | | 45. 2034年12月31日 | | 46. 2035年12月31日 | | 47. 2036年12月31日 | | 48. 2037年12月31日 | | 49. 2038年12月31日 | | 50. 2039年12月31日 | | 51. 2040年12月31日 | | 52. 2041年12月31日 | | 53. 2042年12月31日 | | 54. 2043年12月31日 | | 55. 2044年12月31日 | | 56. 2045年12月31日 | | 57. 2046年12月31日 | | 58. 2047年12月31日 | | 59. 2048年12月31日 | | 60. 2049年12月31日 | | 61. 2050年12月31日 | | 62. 2051年12月31日 | | 63. 2052年12月31日 | | 64. 2053年12月31日 | | 65. 2054年12月31日 | | 66. 2055年12月31日 | | 67. 2056年12月31日 | | 68. 2057年12月31日 | | 69. 2058年12月31日 | | 70. 2059年12月31日 | | 71. 2060年12月31日 | | 72. 2061年12月31日 | | 73. 2062年12月31日 | | 74. 2063年12月31日 | | 75. 2064年12月31日 | | 76. 2065年12月31日 | | 77. 2066年12月31日 | | 78. 2067年12月31日 | | 79. 2068年12月31日 | | 80. 2069年12月31日 | | 81. 2070年12月31日 | | 82. 2071年12月31日 | | 83. 2072年12月31日 | | 84. 2073年12月31日 | | 85. 2074年12月31日 | | 86. 2075年12月31日 | | 87. 2076年12月31日 | | 88. 2077年12月31日 | | 89. 2078年12月31日 | | 90. 2079年12月31日 | | 91. 2080年12月31日 | | 92. 2081年12月31日 | | 93. 2082年12月31日 | | 94. 2083年12月31日 | | 95. 2084年12月31日 | | 96. 2085年12月31日 | | 97. 2086年12月31日 | | 98. 2087年12月31日 | | 99. 2088年12月31日 | | 100. 2089年12月31日 | | 101. 2090年12月31日 | | 102. 2091年12月31日 | | 103. 2092年12月31日 | | 104. 2093年12月31日 | | 105. 2094年12月31日 | | 106. 2095年12月31日 | | 107. 2096年12月31日 | | 108. 2097年12月31日 | | 109. 2098年12月31日 | | 110. 2099年12月31日 | | 111. 2100年12月31日 | | 112. 2101年12月31日 | | 113. 2102年12月31日 | | 114. 2103年12月31日 | | 115. 2104年12月31日 | | 116. 2105年12月31日 | | 117. 2106年12月31日 | | 118. 2107年12月31日 | | 119. 2108年12月31日 | | 120. 2109年12月31日 | | 121. 2110年12月31日 | | 122. 2111年12月31日 | | 123. 2112年12月31日 | | 124. 2113年12月31日 | | 125. 2114年12月31日 | | 126. 2115年12月31日 | | 127. 2116年12月31日 | | 128. 2117年12月31日 | | 129. 2118年12月31日 | | 130. 2119年12月31日 | | 131. 2120年12月31日 | | 132. 2121年12月31日 | | 133. 2122年12月31日 | | 134. 2123年12月31日 | | 135. 2124年12月31日 | | 136. 2125年12月31日 | | 137. 2126年12月31日 | | 138. 2127年12月31日 | | 139. 2128年12月31日 | | 140. 2129年12月31日 | | 141. 2130年12月31日 | | 142. 2131年12月31日 | | 143. 2132年12月31日 | | 144. 2133年12月31日 | | 145. 2134年12月31日 | | 146. 2135年12月31日 | | 147. 2136年12月31日 | | 148. 2137年12月31日 | | 149. 2138年12月31日 | | 150. 2139年12月31日 | | 151. 2140年12月31日 | | 152. 2141年12月31日 | | 153. 2142年12月31日 | | 154. 2143年12月31日 | | 155. 2144年12月31日 | | 156. 2145年12月31日 | | 157. 2146年12月31日 | | 158. 2147年12月31日 | | 159. 2148年12月31日 | | 160. 2149年12月31日 | | 161. 2150年12月31日 | | 162. 2151年12月31日 | | 163. 2152年12月31日 | | 164. 2153年12月31日 | | 165. 2154年12月31日 | | 166. 2155年12月31日 | | 167. 2156年12月31日 | | 168. 2157年12 | |
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