A key aspect of the present invention is that the timing of the downlink and uplink portions of each TDD frame must be precisely aligned in order to avoid interference between sectors within the same cell and/or to avoid interference between cells. It is recalled from above that each sector of a cell site is served by an individual RF modem in RF modem shelves 140A-140D and the internal RF modem shelves of central office facilities 160A and 160B. Each RF modem uses an individual antenna to transmit and to receive in its assigned sector. The antennas for different sectors in the same cell site are mounted on the same tower and are located only a few feet apart. If one RF modem (and antenna) are transmitting in the downlink while another RF modem (and antenna) are receiving in the uplink, the power of the downlink transmission will overwhelm the downlink receiver.

Thus, to prevent interference between antennas in different sectors of the same cell site, the present invention uses a highly accurate distributed timing architecture to align the start points of the downlink transmissions. The present invention also determines the length of the longest downlink transmission and ensures that none of the uplink transmissions begin, and none of the base station receivers begin to receive, until after the longest downlink is completed.

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Furthermore, the above-described interference between uplink and downlink portions of TDD frames can also occur between different cell sites. To prevent interference between antennas in different cell sites, the present invention also uses the highly accurate distributed timing architecture to align the start points of the downlink transmissions between cell sites. The present invention also determines the length of the longest downlink transmission among two or more cell sites and ensures that none of the base station receivers in any of the cells begins to receive in the uplink until after the longest downlink transmission is completed.

Within a cell site, a master interface control processor (ICP), as described below in FIGURE 4, may be used to align and allocate the uplink and downlink portions of the TDD frames for all of the RF modems in an RF modem shelf. Between cell sites, the access processor may communicate with several master ICPs to determine the longest downlink. The access processor may then allocated the uplinks and downlinks across several cell sites in order to minimize interference between cell sites and may designate on master ICP to control the timing of all of the master ICPs.

FIGURE 4 illustrates the timing recovery and distribution circuitry in exemplary RF modem shelf 140 according to one

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embodiment of the present invention. RF modem shelf 140 comprises front panel interface 410 having connectors 411-414 for receiving input clock references and transmitting clock references. Exemplary connector 411 receives a first clock signal from a first external source (External Source A) and exemplary connector 414 receives a second clock signal from a second external source (External Source B). Connector 412 outputs an internally generated clock signal (Master Source Out) and connector 413 receives an external one second system clock signal (External 1 Second Clock).

RF modem shelf 140 also comprises a plurality of interface control processor (ICP) cards, including exemplary ICP cards 450, 460, 470 and 480. ISP card 450 is designated as a master ICP card and ICP card 480 is designated as a spare ICP card in case of a failure of master ICP card 450. Within RF modem shelf 140, the ICP cards provide for control functions, timing recovery and distribution, network interface, backhaul network interface, protocol conversion, resource queue management, and a proxy manager for EMS for the shelf. The ICP cards are based on network processor(s) that allow software upgrade of network interface protocols. The ICP cards may be reused for control and routing functions and provide both timing and critical TDD coordinated burst timing for all the RF modems in RF modem

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shelf 140 and for shelf-to-shelf timing for stacked frequency high density cell configurations.

The timing and distribution architecture in RF modem shelf 140 allows for three reference options:

Primary - An external input derived from another remote modem shelf acting as a master. BITS (Building Integrated Timing Supply) reference is a single building master timing reference (e.g., External Source A, External Source B) that supplies DS1 and DS0 level timing throughout an office (e.g., 64K or 1.544/2.048 Mbps).

Secondary - A secondary reference may be derived from any designated input port in RF modem shelf 140. For remote RF modem shelf 140, this is one of the backhaul I/O ports. An ICP card is configured to recover a timing source and that source is placed on a backplane as a reference (i.e., Network Reference (A/B)) to master ICP card 450.

Tertiary - An internal phase locked loop (PLL) may be used.

By default, two ICP cards are configured as a master ICP card and a spare ICP card. The active master ICP card distributes timing for all of RF modem shelf 140. The timing distribution architecture of RF modem shelf 140 meets Stratum 3 levels of performance, namely a free-run accuracy of +/- 4.6 PPM (parts per million), a pull-in capability of 4.6 PPM, and a holdover stability

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of less than 255 slips during the first day.

There are three components to the timing distribution for the access processor backplane:

1. Timing masters (ICP cards 450 and 480).
2. Timing slaves (ICP cards 460 and 470).
3. Timing references.

The timing masters are capable of sourcing all clocks and framing signals necessary for the remaining cards within the AP backplane. Within a backplane, there are two timing masters (ICP cards 450 and 480), which are constrained to the slots allocated as the primary and secondary controllers. The timing masters utilize the redundant timing references (External Source A, External Source B, External 1 Second Clock) found on the backplane to maintain network-qualified synchronization. ISP card 450 (and ISP card 480) comprises backhaul network input/output (I/O) port 451, multiplexer 452 and PLL-clock generator 453. MUX 452 selects anyone of External Source A, External Source B, Network Reference (A/B), and the signal from I/O port 451 to be applied to PLL-clock generator 453. The timing master has missing clock detection logic that allows it to switch from one timing reference to another in the event of a failure.

Timing is distributed across a redundant set of clock and

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framing signals, designated Master Clock Bus in FIGURE 4. Each timing master (i.e., ICP cards 450 and 480) is capable under software control of driving either of the two sets of clock and framing buses on the backplane. Both sets of timing buses are edge-synchronous such that timing slaves can interoperate while using either set of clocks.

The timing supplied by the timing master (e.g., ICP card 450) consists of a 65.536 MHZ clock and an 8 KHz framing reference. There is a primary and secondary version of each reference. To generate these references, the primary and secondary timing masters are provisioned to recover the timing from one of the following sources:

Source	Frequency
External BITS (EXT REF A)	64K, 1544K, 2048K
External BITS/GPS (EXT REF B)	64K, 1544K, 2048K
External GPS Sync. Pulse	1 second pulse
On-Card Reference	Per I/O reference
Network I/O Derived Reference A	Per I/O reference
Network I/O Derived Reference B	Per I/O reference

Table of Clock Source Interface Definitions

To simplify clock distribution and to provide redundancy all the clocks are derived from a common clock source. The following

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table summarizes the backplane reference clocks as well as the clock rates of the various backplane resources and how they are derived from these references.

Clock	Frequency	Division or Ratio
Common Reference Clock	65.536 MHZ	Not Applicable
Common Sync Pulse	1 Hz	Not Applicable
Framing Reference	8 KHz (125 usec)	Free-run framing provided by Primary or Secondary Clock Masters Referenced to Common Reference Clock
Cell/Packet Clock Rate	32.768 MHZ	Reference Clock/2
TDM Bus Rate	8.192 MHZ	Reference Clock/8
RF Reference Clock	10.000 MHZ	Free-run RF reference clock
Communications Bus	100 MHZ	Derived from free-run Reference Clock
High-speed Serial Links	1.31072 GHz	REF. Clock x 20
High-speed Serial Links	2.62144 GHz	REF. Clock x 40
High-speed Serial Links	TBD	REF. Clock x N

Table of Buses and Associated Clocks

Timing slaves (i.e., ICP cards 460 and 470) receive the timing provided by redundant sets of clock and framing buses. Under

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software control, timing slaves choose a default set of clocks from either the A-side or B-side timing buses. They also contain failure detection logic such that clock and framing signal failures can be detected. Once a clock or framing failure is detected, the timing slave automatically switches to the alternate set of timing buses. ICP cards 460 and 470 contain backhaul I/O ports 461 and 471, respectively, which may be used to bring in external timing signals from other RF modem shelves in the network. The timing masters (i.e., ICP cards 450 and 480) also contain the timing slave function insofar as they also utilize the timing provided on the backplane clock and framing buses.

A qualified timing reference is required for the timing master to derive backplane timing and to maintain synchronization within network 100 and with any outside network. Under software control, an access processor card can be assigned to derive this timing and to drive one of the two timing reference buses. Ideally, a second, physically separate card will contain a second qualified timing source and drive the second backplane timing reference.

In the event that no qualified timing is present from trunk interfaces, the access processor backplane has connections which allow external reference timing (e.g., a GPS-derived clock) from the interface tray to be applied to the backplane. A one pulse-

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per-second (1PPS) signal is distributed to all system cards for time stamping of system events and errors. Installations involving multiple access processor shelves require the timing reference to be distributed between all access processor backplanes. In this scenario, the timing reference for a given backplane is cabled to the remaining backplanes through external cabling. Multiple remote modem shelves are utilized to distribute high-capacity back-haul traffic to one or more additional co-located modem shelves. Traffic is distributed among the shelves through T1, T3, OC3 and/or other broadband telecommunication circuits. To maintain network timing, the additional shelves are slaved to these distribution links and recover timing through the same PLL mechanisms as the head-end shelf.

FIGURE 5A illustrates exemplary time division duplex (TDD) frame 500 according to one embodiment of the present invention. FIGURE 5B illustrates exemplary transmission burst 520 containing a single FEC block according to one embodiment of the present invention. FIGURE 5C illustrates exemplary transmission burst 530 containing multiple FEC blocks according to one embodiment of the present invention.

TDD frame 500 comprises a downlink portion containing preamble field 501, management field 502, and N modulation groups, including

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modulation group 503 (labeled Modulation Group 1), modulation group 504 (labeled Modulation Group 2), and modulation group 505 (labeled Modulation Group N). As explained above in FIGURE 3, a modulation group is a group of downlink slots transmitted to one or more subscribers using a common scheme of one or more of: 1) modulation format, 2) FEC codes, and 3) physical beam forming.

TDD frame 500 also comprises an uplink portion containing transmitter-transmitter guard (TTG) slot 506, 0 to N registration (REG) minislots 506, 1 to N contention (CON) request minislots 508, N sub-burst groups, including sub-burst group 509 (labeled Sub-Burst 1) and sub-burst group 510 (labeled Sub-Burst N), and receiver-transmitter guard (RTG) slot 511. As explained above in FIGURE 3, a sub-burst group is a group of uplink slots transmitted to one or more subscribers using a common scheme of one or more of: 1) modulation format, 2) FEC codes, and 3) physical beam forming.

Each modulation group and each sub-burst group comprises one or more transmission bursts. Exemplary transmission burst 520 may be used within a single modulation group in the downlink and covers one or more downlink slots. Transmission burst 520 also may be used within a single sub-burst group in the downlink and covers one or more uplink slots. Transmission burst 520 comprises physical media dependent (PMD) preamble field 521, MAC header field 522,

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data packet data unit (PDU) field 523, and block character redundancy check (CRC) field 524. Transmission burst 530 comprises physical media dependent (PMD) preamble field 531, MAC header field 532, data PDU field 533, block CRC field 534, data PDU field 535, block CRC field 536.

The start of every frame includes a Start-Of-Frame (SOF) field and a PHY Media Dependent Convergence (PMD) field. PMD preambles are used to assist in synchronization and time-frequency recovery at the receiver. The SOF field allows subscribers using fixed diversity to test reception conditions of the two diversity antennas.

The SOF PMD field is 2^N symbols long (typically 16, 32, 64 symbols long) and consists of pseudo-random noise (PN) code sequences, Frank sequences, CAZAC sequences, or other low cross-correlation sequences, that are transmitted using BPSK or QPSK modulation. The SOF field is followed by downlink management messages broadcast from the base station to all subscribers using the lowest modulation or FEC index and orthogonal expansion. Management messages are transmitted both periodically (N times per hyperframe) and as required to change parameters or allocate parameters. Management messages include:

1. DownLink Map indicating the physical slot (PS) where

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downstream modulation changes (transmitted every frame);

2. UpLink Map indicating uplink subscriber access grants and associated physical slot start of the grant (transmitted when changed and at a minimum of one second hyperframe periods (shorter periods are optional));

3. TDD frame and physical layer attributes (periodic at a minimum of one second hyperframe period); and

4. Other management messages including ACK, NACK, ARQ requests, and the like (transmitted as required).

The downlink management messages are followed by multi-cast and uni-cast bursts arranged in increasing modulation complexity order. The present invention introduces the term "modulation group" to define a set of downstream bursts with the same modulation and FEC protection. A subscriber continuously receives all the downstream data in the TDD frame downlink until the last symbol of the highest modulation group supported by the link is received. This allows a subscriber maximum time to perform receive demodulation updates.

The downlink-to-uplink transition provides a guard time (TTG) to allow for propagation delays for all the subscribers. The TTG position and duration is fully programmable and set by management physical layer attribute messages. The TTG is followed by a set of

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allocated contention slots that are subdivided between acquisition uplink ranging mini-slots and demand access request mini-slots. The Uplink Map message establishes the number and location of each type of slot. Ranging slots are used for both initial uplink synchronization of subscribers performing net entry and for periodic update of synchronization of active subscribers. Contention slots provide a demand access request mechanism to establish subscriber service for a single traffic service flow. As collisions are possible, the subscriber uses random back-off, in integer TDD frame periods and retries based on a time out for request of service. Contention slots use the lowest possible modulation, FEC, and orthogonal expansion supported by the base station.

The contention slots are followed by individual subscriber transmissions (sub-bursts) that have been scheduled and allocated by the base station in the uplink Map. Each subscriber transmission burst is performed at the maximum modulation, FEC, and orthogonal expansion supported by the subscriber. Finally, the subscriber transmissions are followed by the uplink-to-downlink transition which provides a guard time (RTG) to allow for propagation delays for all the subscribers. The RTG duration is fully programmable and set by management physical layer attribute

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messages.

In the downlink, the Physical Media Dependent (PMD) burst synchronization is not used. The transmission burst begins with the MAC header and is followed by the packet data unit (PDU) and the associated block CRC field that protects both the PDU and the header. The PDU may be a complete packet transmission or a fragment of a much larger message. When a channel requires more robust FEC, the PDU may be broken into segments that are protected by separate FEC CRC fields. This avoids wasting bandwidth with additional MAC headers.

One significant difference between the uplink and the downlink is the addition of the PMD preamble. The PMD preamble length and pattern can be programmed by transceiver base station 110. Like the SOF field at the beginning of the TDD Frame, the preamble provides a synchronization method for the base station receiver. Uplink registration and ranging packet bursts use longer PMD preambles.

The medium access control (MAC) layer protocol is connection oriented and provides multiple connections of different quality of service (QoS) to each subscriber. The connections are established when a subscriber is installed and enters operation fixed wireless access network 100. Additional connections can be established and

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terminated with the base station transceivers as subscriber requirements changes.

As an example, suppose a subscriber access device supports two voice channels and a data channel. The quality of service (QoS) on both of the voice channels and data can set based on the service structure set by the wireless service provider. At installation, a subscriber may start with two service connections: a toll quality voice channel and a medium data rate broadband data connection. At a later point in time, the subscriber may order and upgrade service to two toll quality voice channels and high speed data connection (a total of three connections).

The maintenance of connections varies based on the type of connection established. T1 or fractional T1 service requires almost no maintenance due to the periodic nature of transmissions. A TCP/IP connection often experiences bursty on-demand communication that may be idle for long periods of time. During those idle periods, periodic ranging and synchronization of the subscriber is required.

In an exemplary embodiment of fixed wireless access network 100, each subscriber maintains a 64-bit EUI for globally unique addressing purposes. This address uniquely defines the subscriber from within the set of all possible vendors and

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equipment types. This address is used during the registration process to establish the appropriate connections for a subscriber. It is also used as part of the authentication process by which the transceiver base station and the subscriber each verify the identity of the other.

In the exemplary embodiment, a connection may be identified by a 16-bit connection identifier (CID) in MAC header 522 or MAC header 532. Every subscriber must establish at least two connections in each direction (upstream and downstream) to enable communication with the base station. The basic CIDs, assigned to a subscriber at registration, are used by the base station MAC layer and the subscriber MAC layer to exchange MAC control messages, provisioning and management information.

The connection ID can be considered a connection identifier even for nominally connectionless traffic like IP, since it serves as a pointer to destination and context information. The use of a 16-bit CID permits a total of 64K connections within the sector.

In an exemplary embodiment of fixed wireless access network 100, the CID may be divided into 2 fields. Bits [16:x] may be used to uniquely identify a subscriber. In a cyclo-stationary receiver processing at a base station, this would set the antenna, equalizer, and other receiver parameters. Bits [x:1] may be used

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to indicate a connection to a type of service. Each subscriber service can have individual modulation format, FEC, and ARQ. Thus, within a single sub-burst group transmitted by a subscriber, the voice data may use one type of modulation format, FEC, and ARQ, and the broadband internet service may use a different modulation format, FEC, and ARQ. Similarly, within a single modulation group transmitted to the subscriber, the voice data may use one type of modulation format, FEC, and ARQ, and the broadband internet service may use a different modulation format, FEC, and ARQ.

As an example, bits [16:7] of the CID may identify 2^10 (or 1024) distinct subscribers and bits [6:1] may identify 2^6 = 64 possible connections. An apartment building could be given a set of subscriber ports [16:9] so that bits [9:7] allow 2^8 connections or 256 connections.

Requests for transmission are based on these connection IDs, since the allowable bandwidth may differ for different connections, even within the same service type. For example, a subscriber unit serving multiple tenants in an office building would make requests on behalf of all of them, though the contractual service limits and other connection parameters may be different for each of them.

Many higher-layer sessions may operate over the same wireless connection ID. For example, many users within a company may be

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communicating with TCP/IP to different destinations, but since they all operate within the same overall service parameters, all of their traffic is pooled for request/grant purposes. Since the original LAN source and destination addresses are encapsulated in the payload portion of the transmission, there is no problem in identifying different user sessions.

Fragmentation is the process by which a portion of a subscriber payload (uplink or downlink) is divided into two or more PDUs. Fragmentation allows efficient use of available bandwidth while maintaining the QoS requirements of one or more of services used by the subscriber. Fragmentation may be initiated by a base station for a downlink connection or the subscriber access device for the uplink connection. A connection may be in only one fragmentation state at any given time. The authority to fragment data traffic on a connection is defined when the connection is created.

The MAC layer protocol in wireless access network 100 also supports concatenation of multiple PDUs in a single transmission in both the uplink and the downlink, as shown in FIGURE 5C. Since each PDU contains a MAC header with the CID, the receiving MAC layer can determine routing and processing by higher layer protocols. A base station MAC layer creates concatenated PDUs in

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the uplink Map. Management, traffic data, and bandwidth may all be concatenated. This process occurs naturally in the downlink. In the uplink, concatenation has the added benefit of eliminating additional PMD preambles.

FIGURE 6 depicts flow diagram 600, which illustrates the adaptive modification of the uplink and downlink bandwidth in the air interface in wireless access network 100 according to one embodiment of the present invention. Initially, an RF modem shelf, such as RF modem shelf 140A, receives new access requests from subscriber access devices in fixed wireless access network 100 and determines traffic requirements for each new and existing subscriber in each sector of a single cell site (process step 605). The traffic requirements of each subscriber may be established in a number of ways, including minimum QoS requirements, service level agreements, past usage, and current physical layer parameters, such as modulation index, FEC codes, antenna beam forming, and the like. The RF modem shelf then determines from the subscriber traffic requirements the longest downlink portion of any TDD frame in each sector of a single cell site (process step 610).

Next, the access processor for the RF modem shelf (or the RF modem shelf itself) determines the appropriate allocation of downlink and uplink portions of TDD frames for a single cell site

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in order to minimize or eliminate interference within the cell site (process step 615). Bandwidth is allocated, and TDD transition period 350 is positioned, such that the longest downlink transmission is complete before any receiver in the cell site starts to listen for the uplink transmission.

Next, if global allocation of downlink and uplink bandwidth across multiple cell sites is being implemented (generally the case), the access processor determines the longest downlink portion of any TDD frame across several closely located cell sites stations (process step 620). The access processor then determines the allocation of uplink and downlink bandwidth for all TDD frames across several closely located cell sites in order to minimize or eliminate cell-to-cell interference (process step 625). Again, bandwidth is allocated, and TDD transition period 350 is positioned, such that the longest downlink transmission is complete before any receiver in any of the closely located cell sites starts to listen for uplink transmissions. Finally, the downlink portions of the TDD frames are launched simultaneously using the highly accurate clock from the distributed timing architecture (process step 630).

The dynamic application of TDD bandwidth allocation is bounded by set minimum and maximum boundaries set by the service provider,

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based on traffic and network analysis. Further, the bandwidth bounds may be allocated in sub-groupings based on established quality of service (QoS) requirements (e.g., voice data) and Service Level Agreements (SLA) (e.g., broadband data rate) as the primary consideration and with best efforts, non-QoS data, and IP traffic as secondary considerations. The bandwidth bounds may be allocated based on the fact that a subscriber may support more that one interface and thus more than one modulation format in order to achieve required error rates for one or more services provided to the subscriber.

FIGURE 7 depicts flow diagram 700, which illustrates the adaptive assignment of selected link parameters, such as modulation format, forward error correction (FEC) codes, and antenna beam forming, to the uplink and downlink channels used by each subscriber in wireless access network 100 according to one embodiment of the present invention. The RF modem shelf monitors data traffic between subscribers and base station and determines for each subscriber the most efficient combination of modulation format, FEC code, and/or antenna beam forming for the uplink and downlink.

The selected combination is based at least in part on the error rates detected by the RF modem shelf when monitoring the data

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traffic. If the error rate for a particular subscriber is too high in either the uplink or the downlink, the RF modem shelf can decrease the modulation format complexity and use a higher level of FEC code protection in either the uplink or the downlink in order to reduce the error rate. Conversely, if the error rate for a particular subscriber is very low in either the uplink or the downlink, the RF modem shelf can increase the modulation format complexity and use a lower level of FEC code protection in either the uplink or the downlink in order to increase the spectral efficiency, provided the error rate remains acceptably low. Different modulation formats and FEC codes may be used for different services (e.g., voice, data) used by a subscriber (process step 705).

Next, the RF modem shelf assigns subscribers to modulation groups in the downlink and to sub-burst groups in the uplink (process step 710). The base station transceiver then transmits media access fields (e.g., signaling, ACK & NACK) using the lowest modulation format/FEC code complexity. The base station transceiver then transmits the remaining modulation groups in the downlink to the subscribers in increasing order of modulation format/FEC code complexity (process step 715). When the downlink is complete, the base station transceiver receives registration &

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contention minislots transmitted by the subscriber access devices using the lowest modulation format/FEC code complexity. The base station transceiver then receives the remaining sub-burst groups transmitted by the subscribers in increasing order of modulation format/FEC code complexity (process step 720).

The use of adaptive link parameters improves the link throughput and correspondingly affects the bandwidth allocation described above in FIGURE 6. Link parameters apply not only to the transmitter but to the receiver as well. The present invention uses a bounded (finite) set of modulation formats to maximize bandwidth utilization to each subscriber in a channel or sector. In an exemplary embodiment of the present invention, the low complexity (low bandwidth efficiency) modulation formats used for media access fields (e.g., signaling, ACK, NACK) are binary phase shift keying (BSPK or 2-PSK) and quadrature phase shift keying (QPSK or 4-PSK). The present invention may also use multiple-code orthogonal expansion codes in conjunction with the low complexity modulation formats for extremely robust communication. The higher complexity (higher efficiency) modulation formats used for the modulation groups and the sub-burst groups may be 8-PSK, 16 quadrature amplitude modulation (QAM), 32 QAM, 64 QAM, 128 QAM, and the like.

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The present invention also uses bounded set of FEC codes to maximize bandwidth utilization to each subscriber in a channel or sector. The level of FEC code protection is based on the services provided. Each subscriber may support multiple services.

In an advantageous embodiment of the present invention, the RF modem shelf may use packet fragmentation to transport data in either the uplink or the downlink. Fragmentation is the division of larger packets into smaller packets (fragments) combined with an ARQ (automatic request for retransmission) mechanism to retransmit and recover erroneous fragments. The RF modem shelf automatically reduces fragment size for high error rate channels. Fragmentation is applied for guaranteed error-free sources. The degree of fragmentation and ARQ is based on the service provided, since each subscriber may support multiple services.

FIGURE 8 depicts flow diagram 800, which illustrates the adaptive assignment of selected link parameters to the different service connections used by each subscriber in wireless access network 100 according to one embodiment of the present invention. The RF modem shelf assigns connection identification (CID) values to the uplink and to the uplink connections used by a subscriber. If a subscriber uses more than one service (e.g., two voice, One data), the RF modem shelf assigns separate CID values to each

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uplink connection and separate CID values to each downlink connection (process step 805). As noted above, the CID comprises a bit field with the uppermost bits identifying the subscriber and the lowermost bits identifying a specific connection to the subscriber. While many sets of adaptive transmission and reception parameters are possible, there are a finite number of combination that make logical sense. These combinations are grouped into physical layer usage codes that are broadcast to subscribers as part of the general header of TDD superframe or frame header on a periodic basis. These apply to both the base station transmissions and the subscriber transmissions.

The RF modem shelf monitors data traffic between subscriber and base station and determines for each connection the most efficient combination of modulation format, FEC code, and/or antenna beam forming for the uplink and downlink (process step 810). The RF modem shelf then assigns each subscriber connection to a modulation group in the downlink and to a sub-burst group in the uplink (process step 815). The base station transmits media access fields (e.g., signaling, ACK & NACK) using the lowest modulation format/FEC code complexity. Then base station then transmits modulation groups to subscribers in increasing order of modulation format/FEC code complexity (process step 820). Finally,

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the base station receives registration & contention minislots using the lowest modulation format/FEC code complexity. Then base station then receives sub-burst groups from subscribers in increasing order of modulation format/FEC code complexity (process step 825).

Physical layer usage codes are bound to subscriber CID values by a service establishment protocol. If there is a degradation or improvement in the channel between a subscriber and the base station, a protocol exists so the subscriber access device and the base station may revise the physical layer usage code and subscriber CID code. The codes and bindings can be added and deleted based on services requirements of the subscriber.

The present invention applies beam forming in the transmit and receive paths of wireless access network 100 for a number of reasons, including greatly improved to carrier-to-interference ratio, which allows frequency reuse patterns that require less spectrum, two to four times the amount of spatial reuse using multiple simultaneous beams, and increased cell radius, particularly for the band where the uplink from the subscriber to the base can use higher receive gain to overcome uplink loss problems. The use of advanced antenna technology introduces an additional level of media access control (MAC) complexity.

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The MAC layer and physical (PHY) layer have an added spatial/beam component that must be factored into MAC layer coordination of the PHY layer. On a subscriber-by-subscriber basis (i.e., link-by-link basis), the MAC layer and PHY layer must coordinate the following parameters:

1) Communications burst duration

   a) Individual uplink or downlink for TDD system; and

   b) Joint uplink and downlink for FDD system;

2) Modulation complexity;

3) FEC rate; and

4) Beam/combining parameters.

Beam forming and advanced antennas change the basic paradigm that all subscribers have the capability of simultaneously receiving broadcast information from the base station. Transmit and receive beams are formed to optimize communications with a given subscriber with a channel response $H_n(t)$ and beam parameters $B_n(t)$. The base station forms the beam and either sends or receives from the subscribers in an order determined by the MAC layer.

To support advanced antenna systems both FDD and TDD links must be designed to provide transmissions based on self-contained bursts. Conceptually, TDD is easy to understand. A beam is formed

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for each transmitted burst in either the upstream or the downstream. These simple sequential cases can be expanded to advanced beam forming techniques to provide simultaneous multiple access to spatially independent users. A beam-forming network can create two or more independent beams with low self-interference that allow simultaneous communications using the same frequency. While beam-forming complexity is increased, spectral reuse is also increased. The complexity of PHY layer hardware and MAC layer scheduling software also increase proportionally with the number of beams created. The MAC and PHY also need to perform burst scheduling and transmission based on spatial concatenation. One or more subscribers can be supported by a single set of beam-forming parameters due to close physical proximity.

A beam-forming network is a series of antenna elements combined with a delay-weight network that combines the RF energy of a wave front incident on the antenna elements. This enhances gain in a given direction or steers a null in a specific direction. A beam-forming system consisting of N antenna elements is generally arranged in a line or in a rectangular array. The N element array can theoretically steer N-1 nulls. Beam-forming networks are much less efficient at creating gain patterns for distinct beams.

The array elements are spaced by W/N, where N is an integer

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value 1, 2, 4, 8,..., and W is the wavelength of the signal. Typically, the elements are spaced at W/4. Each of these elements is connected to a circuit that can be programmed with a variable delay and phase to each element. The signal products are summed together to form the final beam (e.g., the ideal constructed beam diagram). Conceptually this is very much like a FIR signal filter. The array coherently sums the wave front components from a given direction by forming a time/phased delay at each element.

Beam forming can be performed at RF frequencies using analog delay and phase elements or at baseband frequencies using digital techniques. FIGURE 9 illustrates selected portions of the receive path of conventional analog beam-forming system 900. Analog beam-forming system 900 comprises beam-forming network 910, antennas 931-936, and modem/MAC layer control block 950. Beam-forming network 910 comprises programmable delay and phase controller 920, delay (D) elements 921-926, and signal combiner 940. An incident wave front is detected by antenna 931 at time T1, by antenna 932 at time T2, by antenna 933 at time T3, by antenna 934 at time T4, by antenna 935 at time T5, and by antenna 936 at time T6.

As FIGURE 9 illustrates, the delay of the signal wave at each element for a given angle of signal arrival is given by:

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$$t = L/c$$

where c is the speed of light. The distance, L, between wave fronts to each element is based on the angle of arrival of the signal relative the antenna elements. As an example, if the delay, D, for the antenna elements are all set to be equal, then the antenna has maximum gain at 0 degrees. If the delays are incrementally set from delay element 926 to delay element 921 to have the values 0, W/4c, 2W/4c, 3W/4c,..., 5W/4c, then the beam that is formed at the output of signal combiner 940 has maximum gain at 90 degrees (i.e., to the right).

FIGURE 10 represents an exemplary spatial response of the receive path of conventional analog beam-forming system 900. Power lobe 1010 represents the received beam formed by conventional analog beam-forming system 900. The signal gain maximum occurs at an angle of approximately +40 degrees to the right of an arbitrary 0 degree reference in the sector covered by the antennas of conventional analog beam-forming system 900.

Analog beam forming has numerous benefits. Analog beam-forming capabilities can be retrofitted to existing systems by adding telemetry and time coordination. There is a much lower cost relative to the baseband configuration. Analog beam-forming systems also have excellent back-lobe/front-to-back emission

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characteristics to meet ETSI TM4 standards. However, analog beam forming systems are limited in the number of simultaneous beams according to the maximum number of RF cables up a tower and RF combiner losses.

FIGURE 11 illustrates selected portions of the transmit path and the receive path of conventional digital beam-forming system 1100. Digital beam-forming system 1100 comprises modem processors 1110, 1120 and 1130, transmit signal combiner 1140, digital signal bus 1145 and a plurality of transceiver front-end elements. Modem processor 1110 is representative of modem processors 1120 and 1130. Modem processor 1110 comprises modem 1111, programmable transmitter (TX) weight/delay controller 1112, and programmable receiver (RX) weight/delay controller 1113.

Three exemplary transceiver front-end elements are illustrated. A first transceiver front-end element comprises antenna 1151, radio frequency/intermediate frequency (RF/IF) converter 1152, analog-to-digital converter (ADC) 1153, and digital-to-analog (DAC) 1154. A second transceiver front-end element comprises antenna 1161, radio frequency/intermediate frequency (RF/IF) converter 1162, analog-to-digital converter (ADC) 1163, and digital-to-analog (DAC) 1164. Finally, the first

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transceiver front-end element comprises antenna 1171, radio frequency/intermediate frequency (RF/IF) converter 1172, analog-to-digital converter (ADC) 1173, and digital-to-analog (DAC) 1174.

As FIGURE 11 illustrates, each antenna has a RF/IF down-converter and up-converter (i.e., RF/IF converters 1152, 1162, and 1172), an A/D converter, and a D/A converter. The receive path signals are distributed on high-speed digital signal bus 1145 to be processed by programmable RX weight/delay controller 1113 and modem 1110 in each baseband modem processor 1110. The transmit path differs slightly from the receive path. Programmable TX weight/delay controller 1112 performs the delay and phase adjustments to the signal to be feed to each antenna element. Then, transmit signal combiner 1140 (generally an individual card) sums the transmit signals from the multiple simultaneous channels if more than one channel is to be transmitted. This summed signal is presented to the RF/IF converter for each antenna.

Digital baseband beam forming has the numerous benefits. Digital baseband beam-forming systems provide the most flexible configuration and provide all antenna data to the receiver circuits to allow for rapid calculation of adaptive cancellation. Digital baseband beam-forming systems also provide all-digital processing of weights and delay values and reduce the size of the RF

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amplifier. However, digital baseband beam-forming systems have a very high up-front cost. To limit costs, sparse arrays (as opposed to array panel configurations) are sometimes used, which causes beam pattern back-lobe problems and sometimes results in failure to consistently meet ETSI TM4 (i.e., cell-to-cell interference) standards. Also, critical tower loading is still a problem. High performance (large number of antenna element) configurations must have full demodulation and electro-optic interfaces at the tower.

The present invention uses a combination of the following techniques to maximize frequency re-use and the number of subscribers per base station in wireless access network 100:

1) beam scanning within a cell sector; and

2) spread spectrum transmission to allow down-link broadcast of synchronization and beam maps for the MAC layer with a cell sector.

The present invention uses pre-programmed sets of directed beam patterns to cover a cell in an angular fashion. This is referred to herein as "beam scanning". FIGURE 12A illustrates exemplary beam scanning pattern 1210 according to one embodiment of the present invention. Beam scanning pattern 1210 covers an cell sector that is approximately 90 degrees wide. Beam scanning patter 1210 is covered by nine directed scanning beams, each

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approximately 10 degrees wide. The base station establishes a set of beams to cover the cell. Based on physical location in the sector, a specific beam is used to communicate with one or more subscribers that lie in that sector. The nine scanning beams may be transmitted or received in any order.

FIGURE 12B represents exemplary spatial response 1220 of the transmit and receive scanning beams in beam scanning pattern 1210. Nine signal gain maximums occur, one for each scanning beam. The leftmost signal gain maximum is formed at an angle of approximately -40 degrees to the left of an arbitrary 0 degree reference in the sector. The rightmost signal gain maximum is formed at an angle of approximately +40 degrees to the right of an arbitrary 0 degree reference in the sector. The nine signal gain maximums are spaced 10 degrees apart.

An important issue when using a spatial/beam component in wireless access network 100 is subscriber acquisition and maintaining system synchronization. If wireless access network 100 could guarantee equal distribution of subscribers into the sector beam set, a simple round robin polling method could be used. However, uniform distribution is not guaranteed and wireless access network 100 may use a large number of beams to cover a sector. The revisit time to any specific beam may result in subscribers falling

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out of synchronization.

One alternative to a guaranteed minimum revisit time is to have a full-sector coverage broadcast beam and use of spread spectrum processing gain in the air interface. The broadcast beam is shown in FIGURES 13A and 13B. FIGURE 13A illustrates exemplary broadcast pattern 1310 according to one embodiment of the present invention. Broadcast pattern 1310 covers all of the 90 degree cell sector in FIGURE 12A. FIGURE 13B represents exemplary spatial response 1320 of the broadcast beam. The broadcast beam covers the 90 degree sector fairly uniformly.

By introducing spread spectrum and a broadcast beam operating on the Start of Frame (SOF) field of every frame, the present invention provides improved performance for acquisition and synchronization as opposed to either equal duration round robin polling per scan beam or dynamic weighted polling per scan beam based on the throughput per cell.

The key elements for the air interface are:

1) subscriber receiver (RX) acquisition and synchronization;

2) transmitter (TX) acquisition and ranging;

3) map information for beam scheduling and up/down link maps for a given frame; and

4) demand access mechanisms.

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According to an advantageous embodiment of the present invention, the air interface is implemented using a TDD frame format. According to one embodiment, beam switching occurs on a frame-by-frame basis so that for a complete TDD frame, only one beam is active. However, in alternate embodiments of the present invention, more than one beam may be used in each TDD frame, particularly in the downlink due to typical 4:1 asymmetry. The uplink may be limited to a single scanning beam per frame.

To implement the added complexity of switched beam access, the exemplary TDD frame in FIGURE 14 may be used. FIGURE 14 illustrates the use of broadcast beams and scanning beams in exemplary time division duplex (TDD) signal 1400 according to one embodiment of the present invention. In FIGURE 14, single beam per frame mode is depicted.

TDD signal 1400 comprises a first TDD frame having a downlink portion comprising a first start-of-frame field (SOF1), a first beam map field (Beam Map 1), and a first scan map field (Scan Map 1). The remainder of the downlink portion comprises preamble field 501, management field 502, and N modulation groups, including exemplary modulation groups 503 and 505, which were described above in greater detail in FIGURE 5. The first TDD frame also has an uplink portion comprising a transmitter-transmitter guard (TTG)

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slot, a plurality of registration (REG) minislots, a plurality of contention (CON) request minislots, and N sub-burst groups, including sub-burst groups 509 and 510, and receiver-transmitter guard (RTG) slot 511, which were described above in greater detail in FIGURE 5.

The first TDD frame is followed by a second TDD frame in which portions of the downlink are shown. The second TDD frame comprises a second start-of-frame field (SOF2), a second beam map field (Beam Map 2), and a second scan map field (Scan Map 2).

According to one embodiment of the present invention, an exemplary spread spectrum Broadcast Beam is used to transmit the start-of-frame fields (SOF1 and SOF2) and the beam map fields (Beam Map 1 and Beam Map 2) in each TDD frame, and distinct scan beams (i.e., Scan Beam A and Scan Beam B) are used to transmit the scan map fields (Scan Map 1 and Scan Map 2) and the remainder of the uplink and downlink portions of each TDD frame.

The Broadcast Beam Maps provide data indicating which scanning beam (or beams) are used at which time (measured in symbols or other baud-oriented time unit) for the frame. For each scanning beam used, an uplink map and a downlink map must be provided. The Scanning Beam Map provides the Uplink and downlink maps. The Scanning Beam Map states at which time in the frame, using the

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scanning beam described in the Broadcast Beam Map, the downlink modulation groups and specific uplink slots with associated CIDs are allocated for the frame using the specific scanning beam.

According to an exemplary embodiment, the Broadcast Beam uses DSSS spectrum spreading to make up antenna gain loss and transmits as few fields and frame information as possible to maintain efficiency. The Broadcast Beam transmits the SOF synchronization field so that all subscribers, even those that are not actively communicating (i.e., idle subscribers) can maintain synchronization.

Beam Map 1 and Beam Map 2 comprise a Frame Beam Map and Super-Frame Beam Map containing information that defines scanning beams that cover the sector, the adjoining sectors of the same base station, and the sectors of adjoining base stations. The Frame Beam Map defines the number of downlink beams in the remainder of the current frame and lists a beam number and frame time (physical slot) in which each beam starts. The Frame Beam Map also defines the Uplink beam numbers for each subscriber. The Super-Frame Beam Map defines the number of beams in the relevant sector.

Scan Beams A and B provides 802.16 MAP/MAC and standard packet communications using standard modulation formats. The remainder of the TDD frame is processed using the Uplink/Downlink Map

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information provided by the Broadcast Beam. In such an embodiment, the Broadcast Beam and the associated Super-Frame and Frame Beam Maps inform all subscriber wireless access devices which beams are used. Once the scanning beam is activated, communications are limited to the subscribers associated with that beam.

As note above, the Scanning Beam Map used in the scanning beams are downlink maps and uplink maps. The downlink map indicates the modulation format and forward error correction code (FEC) and time slots enabled on the downlink (i.e., modulation group). The uplink map indicates the specific subscriber, modulation format, FEC, and equalizer (cyclo-stationary processing) for the allowed uplink data bursts.

The acquisition steps are as follows:

1) SOF and Beam Map fields allow initial acquisition identical to a conventional single beam system, including coarse and fine frame alignment, baud and frequency NCO lock, and equalizer initialization;

2) access equipment at the subscriber premises creates a histogram of received signal strength and quality on a per beam basis;

3) subscriber access equipment selects the best scan beam based on the histogram data; and

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