A Review of Medium Access Control Protocols in Next Generation Wireless Networks (IEEE 802.16)

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Abstract: *The IEEE 802.16 standard for broadband wireless access has recently been approved. It is an emerging global broadband wireless access standard capable of delivering multiple megabits of shared data throughput supporting fixed, portable, and mobile operation. The standard offers a great deal of design flexibility including support for licensed and license-exempt frequency bands, channel widths ranging from 1.25 to 20 MHz, Quality of Service (QoS) establishment on a per-connection basis, strong security primitives, multicast support, and low latency/low packet loss handovers. This paper discusses the main features of the various IEEE 802.16 standards with emphasis on the MAC protocol. The focus is on analyzing the differences between MAC layer implementations in several version of the standard like 802.16, 802.16a and 802.16e. This review can be used as the foundation to conduct detailed performance analysis of the emerging WIMAX/802.16 systems.*

1. INTRODUCTION

As currently defined through IEEE Standard 802.16, provides network access to buildings through exterior antennas communicating with central radio base stations (BSs). The wireless MAN offers an alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and DSL links. Because wireless systems have the capacity to address broad geographic areas without the costly infrastructure development required in deploying cable links to individual sites, the technology may prove less expensive to deploy and may lead to more ubiquitous broadband access. Such systems have been in use for several years, but the development of the new standard marks the maturation of the industry and forms the basis of new industry success using second-generation equipment [7].

A central BS may exchange MAC protocol data with an individual laptop computer in a home. The links from the BS to the home receiver and from the home receiver to the laptop would likely use quite different physical layers, but design of the WirelessMAN MAC could accommodate such a connection with full Quality of Service (QoS). With the technology expanding in this direction, it is likely that the standard will evolve to support nomadic and increasingly mobile users. For example, it could be suitable for a stationary or slow moving vehicle. The amendment document of 802.16a will extend the air interface support to lower frequencies in the 2–11 GHz band, including both licensed and license exempt spectra. Compared to the higher frequencies, such spectra offer the opportunity to reach many more customers less expensively, although at generally lower data rates. This suggests that such services will be oriented toward individual homes or small to medium-sized enterprises [7]. As in Figure 1 typical point to multipoint (PMP) Broadband Wireless Access (BWA) systems are composed of two key elements: base station (BS) and subscriber station (SS). The base station connects to the network backbone and uses an outdoor antenna to send and receive high-speed data and voice to subscriber station, thereby eliminating the

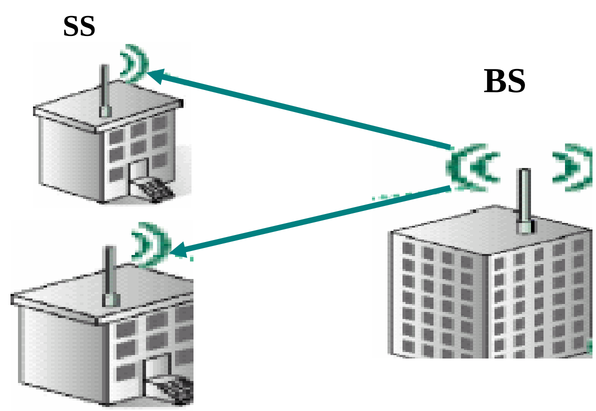

Figure 1. PTM BWA System

need for extensive and expensive wire line infrastructure and providing highly flexible and cost-effective last-mile solutions [9].

This paper will start with an introduction of IEEE 802.16. Then an overview of MAC protocol and different standards is presented in a chronological way. In the next part the main differences between the main standards is highlighted and their comparative analysis is discussed. Finally the conclusion of the paper will be given based on the comparative analysis.

2. OVERVIEW OF 802.16 MAC PROTOCOL

IEEE 802.16 MAC is a connection-oriented MAC able to tunnel any protocol across the air interface with full QoS support. To allocate a wide variety of services, the MAC allows both continuous and bursty traffic.

The central purpose of the MAC protocol layer in IEEE 802.16 is sharing of radio channel resources. The

MAC protocol defines how and when a BS or SS may initiate transmission on the channel. Since key layers above the MAC, such as ATM and STM, require service guarantees, the MAC protocol defines interfaces and procedures to provide guaranteed service to the upper layers.

In the downstream direction, since only one base station is present, it controls its own transmission without need of a protocol operating between stations. But in the upstream direction, if a radio channel is used by more than one SS, the MAC protocol resolves contention and bandwidth allocation.

The downlink from the base station to the user operates on a PMP basis. The IEEE 802.16 wireless link operates with a central BS and a sectorized antenna that is capable of handling multiple independent sectors simultaneously. Within a given frequency channel and antenna sector, all stations receive the same transmission. The base station is the only transmitter operating in this direction, hence it can transmit without having to coordinate with other stations, except for the overall time-division duplexing that divides time into upstream and downstream transmission periods. It broadcasts to all stations in the sector (and frequency); stations check the address in the received messages and retain only those addressed to them. However, the user stations share the upstream period on a demand basis. Depending on the class of service utilized, the SS may be issued continuing rights to transmit, or the right to transmit may be granted by the base station after receipt of a request from the user. In addition to individually addressed messages, messages may also be sent to multicast groups as well as broadcast to all stations [8].

2.1 MAC Protocol Layering

The MAC comprises three sub-layers. The Service-Specific Convergence Sub-layer (CS) provides any transformation or mapping of external network data, received through the CS service access point (SAP), into MAC Service Data Units (SDUs) received by the MAC Common Part Sub-layer (CPS) through the MAC SAP. The 802.16 specifies two service specific CSs. The ATM CS is defined for mapping ATM services and Packet CS is defined for packet services to and from 802.16 MAC.

The MAC Common Part Sub-layer (CPS) provides the core MAC functionality of system access, bandwidth allocation, connection establishment, and connection maintenance. It receives data from the various CSs, through the MAC SAP, classified to particular MAC connections.

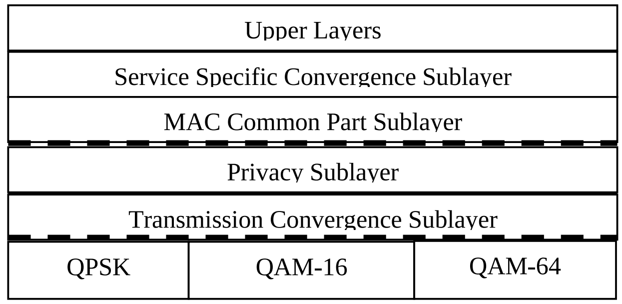

Figure 2. IEEE 802.16 Protocol Layering

Quality of Service (QoS) is applied to the transmission and scheduling of data over the PHY using four basic service classes [7]:

- Unsolicited Grant Service (UGS)
- Real-time Polling Service (rtPS)
- Non-real-time Polling Service (nrtPS)
- Best Effort Service (BE)

The MAC also contains a separate security sublayer providing authentication, secure key exchange, and encryption. Data, PHY control, and statistics are transferred between the MAC CPS and the PHY via the PHY SAP. The PHY definition includes multiple specifications, each appropriate to a particular frequency range and application [7].

2.2 MAC Protocol Data Unit (PDU) Headers

The MAC PDU length is variable. Two different MAC PDU headers are defined, the Generic MAC Header and the Bandwidth Request header.

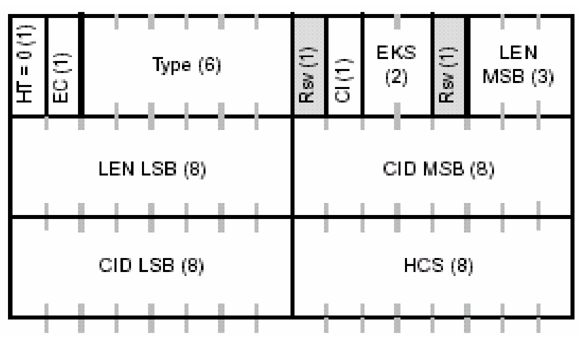

Figure 3. Generic MAC Header Format

The headers are shown in Fig 3 and Fig 4. The type field of the generic MAC PDU header indicates the presences of the sub-headers. The sub-headers are considered to be a part of the MAC PDU payload [10].

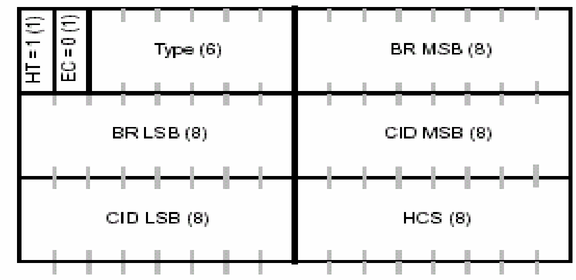

Figure 4. Bandwidth Request Header Format

3. MAC OPERATION – (NE PROCESS)

In order to communicate on the network an SS needs to successfully complete the network entry process at MAC level with the desired BS. Each and every step of the network entry process is shown in the following diagram.

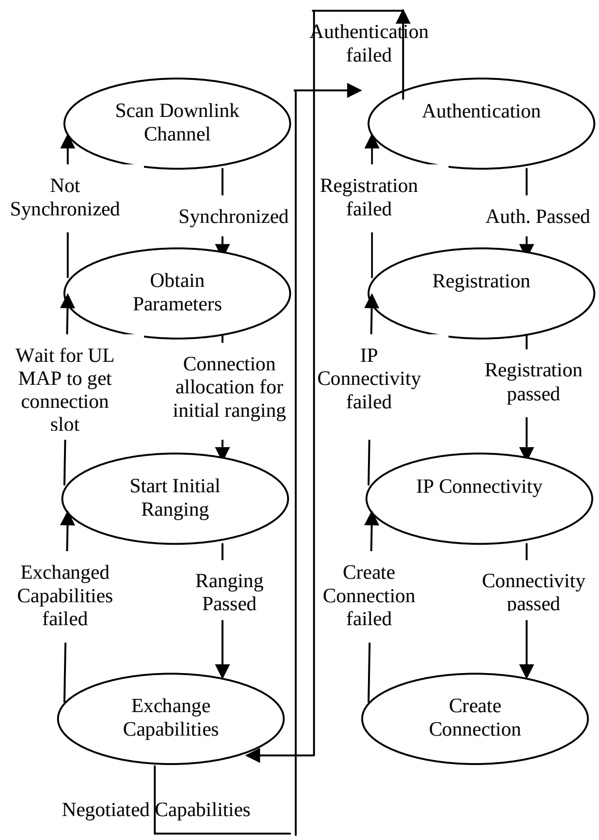

Figure 5. MAC Operation - Network Entry Process

4. IEEE 802.16 EXTENSIONS

IEEE 802.16 technology is evolving through different standards. IEEE organization is working on those standards to increase the efficiency of this technology from PMP technology to Mobility Enhancements.

4.1 IEEE 802.16a

The IEEE has developed 802.16a for use in licensed and license-exempt frequencies from 2 to 11 GHz. At the lower ranges, the signals can penetrate barriers and thus do not require a line of sight between transceiver and antenna. This enables more flexible WIMAX implementations while maintaining the technology's data rate and transmission range. IEEE 802.16a supports mesh deployment, in which transceivers can pass a single communication on to other transceivers, thereby extending basic 802.16's transmission range.

4.2 IEEE 802.16b

This extension increases the spectrum the technology can use in the 5 and 6 GHz frequency bands and provide quality of service.

4.3 IEEE 802.16c

IEEE 802.16c represents a 10 to 66 GHz system profile that standardizes more detail of the technology. This encourages more consistent implementation, and therefore, interoperability.

4.4 IEEE 802.16d

IEEE 802.16d includes minor improvements and fixes to 802.16a. This extension also creates system profiles for compliance testing of 802.16a devices.

4.5 IEEE 802.16e

This technology will standardize networking between carriers' fixed base stations and mobile devices, rather than just between base stations and fixed recipients. IEEE 802.16e would enable the high-speed signal handoffs necessary for communications with users moving at vehicular speeds.

5. COMPARISONS OF 802.16, 802.16a and 802.16e STANDARDS

There is not much difference between 802.16b, 802.16c and 802.16d. This paper will focus on 802.16a and 802.16e standards, which have brought a lot of changes at the MAC level and PHY level in the initial 802.16 technology. In this part of work the main differences will be discussed and brought forward.

5.1 IEEE 802.16a Standard

5.1.1 Mesh Network Architecture

The main difference between 802.16 PMP mode and 802.16a Mesh mode is that in PMP mode traffic only occurs between BS SSs, while in Mesh mode traffic can be routed through other SSs and can occur directly between

SS. This can be done on the basis of equality using distributed scheduling, or on a combination of both [22].

5.1.2 Addressing and Connection

Each SS have a 48-bit universal MAC address in both 802.16 and 802.16a, which uniquely defines the SS. In 802.16 connections are identified by a 16-bit Connection Identifier (CID). The CIDs for the connections shall be assigned in the RNG_RSP and REG_RSP messages. Whereas in 802.16a, when a candidate node is authorized to the network, it receives 16-bit node identifier (Node ID) upon a request to the Mesh BS. Node ID is the basis for identifying nodded during the normal operation. Node ID is transferred in Mesh subheader, which always follows generic MAC header. For addressing nodes in the local neighborhood, 8-bit link identifier (Link IDs) is used. The link ID is distributed as a part of CID in the generic MAC header. This link ID is used in distributed scheduling to identify resources, requests and grants [22].

5.1.3 MAC Service Definitions

The IEEE 802.16 MAC supports the following primitives at the MAC Service Access Point in Mesh mode:

- MAC_CREATE_CONNECTION.indication
- MAC_CHANGE_CONNECTION.indication
- MAC_TERMINATE_CONNECTION.request
- MAC_TERMINATE_CONNECTION.indication
- MAC_DATA.request
- MAC_DATA.indication
- MAC_FORWARDING_UPDATE.request
- MAC_FORWARDING_UPDATE.indication

5.1.4 MAC Management Messages Tunneling in Mesh

In Mesh networks during network entry certain MAC message protocols take place between entities separated by multiple hops. In these cases the Sponsor Node shall relay the MAC messages from the new node acting as the SS to the peer performing the duties of the PMP BS. The sponsor shall also relay the messages from the BS entity to the New Node. The Sponsor shall tunnel the MAC Messages received from the New Node (SS) over UDP to the entity performing the BS part of the protocol. The sponsor shall also extract the MAC messages from the UDP packets arriving from the BS entity and transmit them over the air to the New Node [23].

5.2 IEEE 802.16e Standard

The 802.16e mobility standard, is an improvement on the modulation schemes stipulated in the original (fixed) WiMAX standard. It allows for fixed wireless and mobile Non Line of Sight (NLOS) applications primarily by enhancing the Orthogonal Frequency Division Multiple Access (OFDMA).

5.2.1 Scalable OFDMA

Scalability is one of the most important advantages of OFDMA. With the OFDMA sub-carrier structure, it can support a wide range of bandwidths. The scalability is achieved by adjusting the FFT size to the channel bandwidth while fixing the sub-carrier frequency spacing. By fixing the sub-carrier spacing and symbol duration, the basic unit of physical (time and frequency) resource is fixed. Therefore, the impact to higher layers is minimal when scaling the bandwidth.

This modulation will bring a lot of benefits to this technology. Some of them are discussed below

- Improving NLOS coverage by utilizing advanced antenna diversity schemes.
- Introducing downlink sub-channelization, allowing administrators to trade coverage for capacity or vice versa.
- Improving coverage by introducing Adaptive Antenna Systems (AAS) and Multiple Input Multiple Output (MIMO) technology.

5.2.2 Sub-Channelization

Each sector is allocated with different set of sub-channels as the usable resources. Those set of sub-channels, which is allocated to each BS is referred as logical channels. The allocation of logical channels to the BSs may be dynamic and can be dependent of the current load distribution within the cell.

By the introduction of these logical channels the OFDMA UL-MAP and DL_MAP of 802.16 is replaced with some new information, which is highlighted in the following tables [21].

Table 1. Uplink MAP Header Information Element

Syntax	Size
DL-Map_Information_Element() {	
DIUC	4 bits
if (DIUC == 15) {	
Extended DIUC dependent IE	Variable
} else {	
OFDM Symbol offset	**8 bits**
Subchannel offset	**5 bits**
No. OFDM Symbols	**8 bits**
Boosting	**2 bits**
No. Subchannels	**5 bits**
}	
}	

Table 2. Downlink MAP Header Information Element

Syntax	Size
UL-Map_Information_Element() {	
CID	16 bits
UIUC	4 bits
if (UIUC == 4) {	
CDMA_Allocation_IE()	52 bits
} else if (UIUC == 15) {	
Extended UIUC dependent IE	Variable
} else {	
OFDM Symbol offset	**10 bits**
Subchannel offset	**6 bits**
No. OFDM Symbols	**8 bits**
No. Sub channels	**6 bits**
}	
}	

5.2.3 MAC Protocol Stack

In the 802.16e Mobile Agent (MA) has been added in the MAC protocol stack of the previous version.

Figure 6. BS Protocol Stack

The functions of MA are similar to functions of Foreign Agent of Mobile IP working in "foreign agent care-of address" mode. MA provides the functions like termination of tunnel carrying data from MSS home network including de-capsulation of incoming data units and communication to CS about: After arrival of new MSS to the cell, creation of new connections etc [21].

5.2.4 Hybrid Automatic Repeat Request (HARQ)

It is a variation of the Automatic Repeat Request (ARQ) error control method, which gives better performance than ordinary ARQ, particularly over wireless channels, at the cost of increased implementation complexity. It combines Forward Error Correction (FEC) and ARQ by encoding the data block plus error-detection information (such as CRC) with an error-correction code prior to transmission. When the coded data block is received, the receiver first decodes the error-correction code. If the channel quality is good enough, all transmission errors should be correctable, and the receiver can obtain the correct data block. If the channel quality is bad and not all transmission errors can be corrected, the receiver will detect this situation using the error-detection code, then the received coded data block is discarded and a retransmission is requested by the receiver, similar to ARQ.

5.2.5 Scanning Information Element (IE)

A BS may allocate time intervals to MSS's for the purpose of seeking and monitoring neighbor BS suitability as targets for HO. Such a time interval will be referred to as a scanning interval. Scanning_IE is placed in the DL-MAP. The Scanning_IE shall either grant the requesting MSS a scanning interval that is at least as long as requested by that MSS, or deny the request [21].

5.2.6 Ranging Adjustment

For MSS's that have used their scanning interval to do ranging with target BS this stage should be immediate. Otherwise, this stage is similar to the one performed at initial network entry. As opposed to initial network entry, where this stage is performed on contention basis, here the ranging opportunity may be allocated individually by the BS based on an MSS's 48-bit MAC address identifier. This identifier is forwarded to the target BS via the backbone network. This is done using the Fast_UL_ranging_IE() in the UL-MAP. When an initial ranging opportunity is not allocated individually, this procedure defaults to the one specified for initial network entry.

5.2.7 Preamble Only Signal

<table>
<tr><th colspan="2">Mobility Agent</th></tr>
<tr><td>CS</td><td rowspan="3">Backhaul Protocol Stack</td></tr>
<tr><td>MAC
(Common Part)</td></tr>
<tr><td>PHY</td></tr>
</table>

In 802.16e OFDMA system is extended for working in deployment scenario with frequency reuse of 1 in order to satisfy requirement of reliability, coverage, capacity, location base service and mobility. It means the same RF frequency is allocated to all sectors in the cell.

5.2.8 MAC Service Definition for Mobility Support

Some further service definitions are added in the MAC to support the mobility [21].

- Sleep Request Message (MOB_SLP_REQ)
- Sleep Response Message (MOB_SLP_RSP)
- Traffic Indication Message (MOB_TRF_IND)
- Neighbor Advertisement Message (MOB_NBR_ADV)
- Scanning Interval Allocation Request Message (MOB_SCN_REQ)
- BS HO Request Message (MOB_BSHO_REQ)
- MSS HO Req. Message (MOB_MSSHO_REQ)
- HO Response Message (MOB_HO_RSP)
- HO Indication Message (MOB_HO_IND)

5.2.9 Sleep Mode for Mobility Support SS

Sleep-mode is intended to enable mobility-supporting SS's to minimize their energy usage while staying connected to the network. Implementation of power-save mode is optional.

6. COMPARATIVE ANALYSIS

The journey of IEEE 802.16 technology started from the idea of giving higher data rate to the user and to cover more distance at the same time. In this period of journey several standards come forward to enhance the efficiency of this technology. The summary of the comparisons of those standards is also given in table 3.

The 802.16 MAC is designated for long distance point-to-multipoint wireless links. It supports QoS for real-time traffic and it is connection oriented, thus providing increased efficiency through header compression.

The MAC can make use of bandwidth-efficient burst profiles under favorable link conditions but shift to more reliable, although less efficient, alternatives as required to support the planned 99.999 percent link availability. The request-grant mechanism is designed to be scalable, efficient, and self-correcting.

To overcome the disadvantage of the line-of-sight requirement between transmitters and receivers in the 802.16 standard, the **802.16a standard** was approved to support non-line-of-sight links, operational in both licensed and unlicensed frequency bands from 2 to 11 GHz.

The 802.16a MAC supports the use of a mesh architecture in which some subscriber stations communicate with other data-forwarding subscriber stations rather than directly with the base station. This allows extending the cells and reaching customers not directly reachable from the base station. The defined scheduling algorithms provide for collision-free transmissions in mesh deployment.

Other QoS features include Automatic Retransmission Request (ARQ). This feature assures that the frame is received properly and in order. Per-connection QoS feature gives higher data rate to every user. Another feature like Automatic power control helps the SS to enhance the battery of its equipment.

For operating in Mesh mode it was necessary to identifying the node in time and properly. So proper addressing and connection feature as added by adding few MAC messages and Mesh sub-header.

In mesh mode the data is traveled from node to node. Proper network entry and synchronization can help the system to improve the identification of every node. For this purpose the Network Entry procedure is changed to the new procedure. Tunneling procedure is introduced to transfer the MAC management messages from node to node.

Table 3. Summary of Comparative Analysis

	802.16	**802.16a**	**802.16e**
Transmissi-on method	SC	SC, OFDM256, OFDMA	SOFDMA
Frequency Band	10 - 66 GHz	2 – 11 GHz	< 6 GHz
Alignment Mode	Required LOS	NLOS	NLOS
Bit Rate	32 – 134 Mbit/s at 28 MHz Ch-annelization	1.0 – 75 Mbps at 20 MHz chan-nelization	15 Mbps at 5 MHz chan-nelization
Channel Bandwidth	20, 25 and 28 MHz	Between 1.25 and 20 MHz	Same as 802.16a
Duplexing	FDD, H-FDD, TDD	Same	Same
UL / DL Access Techniques	TDMA / TDM (TDMA)	Same	OFDMA
Modulation	QPSK, 16QAM, 64 QAM	QPSK, 16QAM, 64 QAM, 256 QAM	QPSK, 16QAM, 64 QAM
Mobility	Fixed	Portable	Mobility, < 150 KM/H
Coverage Radius	2 –5 km	6 – 9 Km	2 – 5 km
Network	PMP	Mesh	Mobility
Error Control	Req. Grant Method	ARQ	HARQ
Handoff Capability	NA	NA	Yes

Although 802.16e is generally perceived as the mobile version of the standard, in reality it serves the dual purpose of adding extensions for mobility and including new enhancements to the Orthogonal Frequency Division Multiplexing Access (OFDMA) physical layer. This new enhanced 802.16e physical layer is now being referred to as Scalable OFDMA (SOFDMA) and includes a number of important features for fixed, nomadic, and mobile networks.

Introducing 802.16e into the market brought a lot of impact in the market. These impacts will become the reason to be the future for the BWA in the mobility section. Some of the benefits of this technology have been discussed below:

6.1 High Data Rate

MIMO antenna techniques with flexible sub channelization schemes and Advanced Coding and Modulation enable the Mobile WiMAX technology to support peak DL sector data rates up to 46 Mbps.

6.2 Quality of Service

Sub-channelization and MAP-based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency, and time resources over the air interface on a frame-by-frame basis. With high data rate and flexible scheduling, the QoS can be better enforced.

6.3 Scalability

802.16e technology is designed to be able to scale to work in different channelizations from 1.25 to 20 MHz to comply with varied worldwide requirements as efforts proceed to achieve spectrum harmonization in the longer term. This also allows diverse economies to realize the multi-faceted benefits of the Mobile WiMAX technology for their specific geographic needs such as providing affordable Internet access in rural settings versus enhancing the capacity of mobile broadband access in metro and suburban areas.

6.4 Tolerance to Multipath

In 802.16e, the sub-channels maintain their orthogonality in a multipath channel. The number of multipath components does not limit the performance of the system as long as the multipaths are within the cyclic prefix window. OFDMA systems therefore are robust to multipath effects. The sub-channel orthogonality within the cyclic prefix window also relaxes the time synchronization requirement.

6.5 Scalable Channel Bandwidth

One immediate advantage stemming from scalability is the flexibility of deployment. With little modification to air interface, OFDMA systems can be deployed in various frequency band intervals to flexibly address the need for various spectrum allocation and usage model requirements. Mobile WiMAX supports channel bandwidths of 5 MHz, 7 MHz, 8.75 MHz, and 10 MHz and can optionally support channel bandwidths ranging from 1.25 MHz to 20 MHz.

6.6 Orthogonal Uplink Multiple Access Interference

When considering multiple access benefits, sub-channel orthogonality provides OFDMA with a distinct advantage. Since with OFDMA, users are allocated different portions of the channel, there is no (or little) multiple access interference (MAI) between multiple users. OFDMA therefore, can support higher order uplink modulations and achieve higher uplink spectral efficiency.

6.7 Frequency Selective Scheduling

In broadband wireless channels, propagation conditions can vary over different portions of the spectrum in different ways for different users. IEEE 802.16e supports frequency selective scheduling to take full advantage of multi-user frequency diversity and improve QoS. With adjacent sub-carrier permutation makes it possible to allocate a subset of sub-carriers to mobile users based on relative signal strength. By allocating a subset of sub-carriers to each SS for which the SS enjoys the strongest path gains, this multi-user diversity technique can achieve significant capacity.

6.8 Fractional Frequency Reuse

IEEE 802.16e, supports frequency reuse one, i.e. all cells/sectors operate on one frequency channel to maximize spectrum utilization. There is always the possibility of heavy interference for the users at the edge of the cell. But since in 802.16e users operate on sub-channels, which only occupy a small fraction of the channel bandwidth, the cell edge interference problem can be easily addressed by reconfiguration of the sub-channel usage without resorting to traditional frequency planning.
The full load frequency reuse of one is maintained for center users to maximize spectral efficiency while fractional frequency reuse is achieved for edge users to improve edge user connection quality and throughput. The sub-channel reuse planning can be adaptively optimized across sectors or cells based on network load and interference conditions on a per frame basis. All the cells/sectors can operate on the same frequency channel and no frequency planning is required.

6.9 Advance Antenna Technology

With OFDM/OFDMA systems therefore, it is far easier to support smart antenna technologies. IEEE 802.16e supports a full range of smart antenna technologies to enhance performance including Beamforming, STC and SM. These technologies can improve both system coverage and capacity. It also supports dynamic switching between the smart antenna technologies to maximize the benefit based on channel conditions. It supports Adaptive MIMO Switching (AMS) between multiple MIMO modes to maximize spectral efficiency with no reduction in coverage area.

7. CONCLUSION

As many applications and extensions of the IEEE 802.16 standard unfold, the core that unites all of these remains the WirelessMAN MAC. This forward-looking and flexible design holds the promise of future multi tiered wireless metropolitan area networks that support fixed and mobile devices with data-centered multimedia services. It’s no wonder that independent observers are increasingly viewing IEEE 802.16 as the foundation of the Fourth Generation of wireless communications. If called to do so, the standards will serve well in that role.

This work has reviewed in detail MAC layer functionalities in various version of IEEE 802.16.

Practically, the major difference in MAC level functionality is found between 802.16a and 802.16e. This difference arises mainly due to consideration of advancement from fixed to portable and then to mobility in 802.16e. All the standards of the IEEE 802.16 technology follow the same path with some minor modifications. IEEE 802.16a brought the change by supporting Mesh network architecture in licensed and licensed exempt band.

An OFDM/OFDMA-based 802.16e system providing the mobility support has high granular resource allocation, better uplink efficiency, and can support a full range of advanced antenna technologies. These capabilities offer the potential for significant spectral efficiency advantages and better QoS in both the downlink and uplink direction.

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