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On IEEE 802.16: Worldwide Interoperability for Microwave Access

Rahul Singha Chowdhury[1], Sourangsu Banerji[2]
[1,2]Department of Electronics & Communication Engineering
RCC-Institute of Information Technology, Kolkata, WB 700015, India

ABSTRACT: Current wireless broadband technologies have now been providing omnipresent broadband access to wireless subscribers which were only confined to the wire line users till sometime ago. Traditionally, the wireless technologies have been categorized based on their area of coverage. The IEEE 802.11 and ETSI HiperLAN standards are the de facto standards of wireless access in local areas. Whereas IEEE 802.16 and 802.22, ETSI HiperACCESS and HiperMAN, WiBro, and HAP technologies has been predominantly used for providing service in metropolitan and cosmopolitan areas.

There have been many papers written in the recent past covering various types of wireless broadband access technologies, ranging from WLANs to satellite communications. But the study carried out previously never captured the entire spectrum of all such technologies, and even if one particular family of the wireless broadband access technology was scrutinized, the authors somehow concentrated only on certain aspects. In this paper, we aim to bridge that gap by summarizing one of the emerging wireless broadband access technologies i.e. IEEE 802. 16: WiMAX family in detail. Though some of the earliest versions of this family date back to the early decade and some are even out of practice, still we have included them in our study for the sake of completeness and a sense of insight.

Keywords: Wireless Communications, IEEE 802.16, WiMAX, WMAN, WWAN

1. Introduction

The introduction of cellular networks has made mobility an important issue in communications. Although cellular networks provide mobility support for voice communication they cannot support high bandwidth data transfer for numerous mobile users simultaneously [1]. Wire line networks on the other hand excel in high bandwidth data communication, but they do not support mobility [3-5]. The aim of emerging wireless data networks is to provide wireless service comparable to that of wire line networks for fixed and mobile users [2-6].

Wireless data networks can be categorized according to their coverage areas. Wireless Local Area Networks (WLANs) are designed to provide wireless access in areas with cell radius up to hundred meters and are used mostly in home and office environments. Wireless Metropolitan Area Networks (WMANs) [7] cover wider areas, generally as large as entire cities. Wireless Wide Area Networks (WWANs) [8-12] are designed for areas larger than a single city. Different network standards are designed for each of these categories. However, some of these standards fit into several of these categories [13-18].

While not as widely deployed as WLAN, WMAN networks are expected to be deployed with increasing numbers in 2007 and 2008. IEEE developed IEEE 802.16 standard to provide Broadband Wireless Access (BWA) to fixed Line of Sight (LOS) Subscriber Stations (SSs) from a Base Station (BS). IEEE 802.16-2005, the current version, also supports non-LOS (NLOS) SSs and Mobile Subscribers (MSs). Thus, accessibility in dense urban environments significantly increases. IEEE 802.16 is a cell based technology, in which multiple cells are used to cover urban areas. Average throughput of an IEEE 802.16 cell is expected to be between 75 and 100 Mbps. On the other hand, ETSI established the Broadband Radio Access Networks (BRANs) project in 1997 to develop standards that provide broadband radio access to business and residential users [19-25]. Two different WMAN standards are introduced under the BRAN project as of today; Hiper-ACCESS for LOS [26-33] and HiperMAN [34-38] for both LOS and NLOS user support. Furthermore, Wireless Broadband (WiBro) [39, 40] standard is developed by the TTA (Telecommunications Technology Association) of South Korea based on IEEE 802.16 [41, 42].

2. WirelessMAN

WMANs are designed to span whole cities with large numbers of LANs and WLANs. WLANs primarily provide indoor and hotspot coverage, but they can also be connected to the Internet via WMAN technologies. In the basic setting of a WMAN, there are two types of devices in the network; the BS and the subscribers. This type of connectivity represents a Point-to-Multipoint (PMP) network. Subscribers can be either buildings (for fixed access), or pedestrians and vehicles (for mobile access). In rural environments, each subscriber usually has LOS connection with the BS. However, in urban areas subscribers are connected to the BS in a NLOS manner. Since high frequency signals must have LOS connectivity to give acceptable service performance, WMANs do not work well at very high frequencies for urban settings. Generally, the transmission of a subscriber consists of the aggregate transmissions of local users. Thus, WMANs integrate similar types of transmissions (e.g., transmissions with similar QoS constraints) originating from different users in the LAN into a single connection.

In addition to the basic PMP setting, some WMAN standards support mesh connectivity. Mesh connectivity provides a more robust broadband access topology, eliminating the single point of failure problem, and enables direct communication between subscribers [16, 42]. Subscribers can relay their transmissions through other subscribers in mesh networks if they cannot directly reach a BS. Mesh connectivity is generally a better connectivity option for mobile users compared to PMP connectivity. Companies developing products for WMAN networks have formed a forum named Worldwide Interoperability for Microwave Access (WiMAX). Similar to the Wi-Fi alliance, WiMAX Forum aims overcoming interoperability problems between devices from different companies. In addition to IEEE 802.16, WiMAX Forum also supports ETSI HiperMAN standard. The current focus of the forum is NLOS communication instead of the earlier LOS communication systems [43].

2.1. IEEE 802.16 family

The IEEE 802.16 standard is developed based on two systems; Multichannel Multipoint Distribution System (MMDS) and Local Multipoint Distribution System (LMDS). Starting from 1996, some telephony companies started developing propriety wireless broadband access technologies as an alternative to DSL and cable data services. These services, called MMDS, target data rates of several Mbps. In 1998, FCC allocated frequency bands for these services [44]. In order to provide acceptable service quality in urban settings, MMDS works at the 2.1 GHz and 2.5–2.7 GHz frequency bands, which are very good against rain and vegetation attenuation. A typical MMDS cell has a radius of 50 km and gives 0.5–30 Mbps aggregate data rate per cell [17, 45].

Due to the ease of deployment, MMDS became a formidable technology in comparison to DSL and cable systems. However, the bandwidth of an MMDS cell is far from being adequate for all users in a 50 km radius. Thus, a new service type, called LMDS, is developed to work at higher frequencies [44]. Using 28–31 GHz in the U.S. and 40.5–42.5 GHz in Europe, LMDS is designed to provide high throughput. These frequency bands allow highly sectorized cells, to increase throughput in a given area. The cell size of an LMDS system is much smaller than its MMDS counterpart, ranging from 3 km to 5 km. Early LMDS cells support aggregate data rates of 34–38 Mbps per sector while later models increase this value to 36 Gbps [44, 46]. LMDS systems are asymmetric and favor downlink over uplink. Utilizing higher frequencies causes problems like LOS connectivity requirement, rain and vegetation attenuation. Another problem is the lack of standardization between LMDS systems from different companies, causing interoperability problems. To establish a standard for LMDS systems, IEEE formed The Work Group 16 which in turn developed the IEEE 802.16 standard in 2002 [44, 47].

The initial IEEE 802.16 standard provides connectivity for LOS subscribers in the PMP topology. The PHY layer works at the 10–66 GHz frequency band. The problems of LOS connectivity in urban settings forced the standard to develop another PHY layer for NLOS communications. This new PHY layer, developed as part of IEEE 802.16a, was introduced in 2003 [47]. In addition to the new PHY layer, IEEE 802.16a also introduced the Mesh topology support mode (Fig. 5). Since significant multi-path propagation is required for NLOS communication and in the 10–66 GHz frequency band there is little multi-path propagation, a lower frequency band, 2–11 GHz, is chosen for NLOS operation [48]. Thus, IEEE 802.16a uses licensed and license-exempt frequencies in the 2–11 GHz band. After some amendments (mainly named under IEEE 802.16d) for both the standard and the PHY layer, IEEE 802.16-2004, was introduced in 2004 [15, 49]. A recently finished standard, IEEE 802.16e, adds mobility support to the family [50]. The current version of the standard (IEEE 802.16- 2005) includes both LOS and NLOS communication at the 10–66 GHz and the 2–11 GHz bands, respectively. It also has mobility support for frequencies between 2 and 6 GHz. Being connection-oriented protocol, all transmissions in an IEEE 802.16 network are associated with connections. The connections are unidirectional and they can be uni-cast, multi-cast, or broad-cast.

2.1.1. Physical (PHY) layer

Initially, IEEE 802.16 supported a single PHY layer, Single Carrier PHY (WirelessMAN-SC PHY). Later, three additional PHY layers were developed for NLOS transmissions in the 2004 revision, one based on single carrier technology and two additional PHYs based on the OFDM technology (). Channel bandwidth can be 20, 25, and 28 MHz for WirelessMAN SC (). There are no fixed global channel bandwidth values for NLOS PHYs, but the available channel bandwidths are based on the frequency band that is used [49]. In LOS communication, aggregate raw data rate of the network is 36–135 Mbps based on the modulation and channel bandwidth used [49, 54]. However, IEEE 802.16 provides up to 75 Mbps of aggregate raw data rate in NLOS communication [49, 57–59]. According to a performance analysis regarding the actual bandwidth of NLOS communication, IEEE 802.16 supports 10 Mbps for a 5MHz-wide channel and 4.8–18.2 Mbps for a6MHz-wide channel [52]. In [53], studies were carried out on the PHY and MAC layer throughput of an IEEE 802.16

network working at 5 GHz frequency band and using a channel bandwidth of 20 MHz. According to this work, the PHY layer gives a throughput ranging between 7 and 62 Mbps based on the modulation and coding scheme used. Also, it is found that MAC layer reduces the PHY layer throughput by 10%. The effects of optional MAC layer mechanisms, such as ARQ and packing, are also studied in this work. In [52], the authors proposed various mechanisms to improve the current data rate, at least quadrupling the current data rate.

The WiMAX forum on the other hand expects 15 Mbps maximum throughput per sector using 3.5 MHz channel bandwidth and 35 Mbps using 10 MHz channel bandwidth [15, 51]. By using multiple adjacent channels, the bandwidth of the system can be improved up to 350 Mbps [57, 60]. IEEE 802.16 networks can also be deployed using sectorized antennas to further increase the overall bandwidth in a given area. In order to ensure interoperability between WiMAX devices produced by different vendors, the WiMAX forum defined a profile for IEEE 802.16 devices. Two different frequency bands are used in this profile: 3.5 GHz and 5.8 GHz. The channel bandwidth is defined for these frequency bands as 3.5 or 7 MHz in 3.5 GHz and 10 MHz in 5.8 GHz. Among the PHY layers available, the profile uses WirelessMAN-OFDM with 256 carriers with either Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD) [51].

IEEE 802.16 supports both TDD and FDD to separate downlink and uplink communication. While BSs support full-duplex FDD, SSs may support only half-duplex FDD to minimize the design cost. A continuous transmission of an IEEE 802.16 network is divided into fixed length parts called frames. In TDD mode, the frame consists of downlink and uplink subframes. In FDD operation mode, downlink and uplink subframes use different channels. IEEE 802.16 includes several modulation schemes and Forward Error Correction (FEC) mechanism to cope with the variation in radio link quality due to weather, terrain, etc. The modulation techniques allowed in the standard varies with the PHY layer used. While Quadrature Phase Shift Keying (QPSK), 16-state QAM and 64-state QAM are supported in all PHY layers, a more robust modulation scheme, Binary Phase Shift Keying (BPSK), and a less robust one, 256-state QAM, are also supported in WirelessMAN-SCa PHY layer. FEC rates of 1/2 and 3/4 can be used for error correction. Together these values form a burst profile and each connection (either uplink or downlink) is described with a burst profile. Available burst profiles in the network are described with the Uplink Interval Usage Code (UIUC) for uplink and Downlink Interval Usage Code (DIUC) for downlink connections.

Mapping of connections to these codes are broadcasted in Downlink Channel Description (DCD) and Uplink Channel Description (UCD) messages in each frame. In a single frame, an SS may have multiple connections with different burst profiles. Connections are associated with burst profiles upon connection establishment. When the link state changes an updated DCD or UCD message is sent by the BS in the next frame with new burst profiles for the connections. When the link state worsens, the connection switches to a more robust burst profile. On the other hand, if the link quality improves, the connection can switch to a less robust profile for higher bandwidth. Transmissions between BS and SSs in a single frame start from the connection with the most robust burst profile and continue with decreasing robustness of the burst profiles [49,48]). While this change in burst profile is defined in the standard, it is not defined how the change will be handled. A comprehensive work in [61] shows that MAC layer End-to-End (ETE) delay provides misleading information for handling the change in burst profile. However, network layer ETE delay can be used as a good metric for link adaptation purposes.

Broadcast and multicast connections in the uplink are essentially contention periods used for either bandwidth requests or initial ranging purposes. Each contenting SS randomly selects a transmission opportunity from the available transmission opportunities allocated to the connection in the uplink, and sends its request or message during the selected transmission opportunity. If more than one SS selects the same transmission opportunity, a collision occurs and these SSs retransmit their requests in the next frame until the transmission is successful or the timer expires. A more efficient ranging mechanism for Orthogonal Frequency Division Multiple Access (OFDMA) PHY layer is introduced in [62].

2.1.1.1. PHY in mesh mode

In the Mesh mode, a SS is called Mesh SS (MSS) and the BS is called Mesh BS (MBS). Unlike the PMP mode, transmissions are sent using the links between the nodes. These links are directional and are defined by 8-bit Link Identifiers (Link IDs). Upon initialization, a MSS establishes one link with each node in its range. In the Mesh mode, each MSS has a parent node. The parent node of a MSS is the node among the nodes in range that has less hop count to the MBS than that MSS. If the node is directly connected to the MBS, than the MBS is its parent node. The links between MSSs and their parent nodes form a scheduling tree. However the performance of the scheduling tree greatly depends on the parent node selection in the initialization. IEEE 802.16 standard describes a method for selecting the parent nodes. This method selects the node with the highest Signal to Noise Ratio (SNR) among candidate nodes as the parent node. This method does not guarantee that it finds the optimal scheduling tree. An analytical solution to find the optimal scheduling tree for the Mesh mode is described in [63]. In [65], an interference aware routing algorithm is introduced. This mechanism utilizes a Space Division Multiple Access (SDMA) approach in parent node selection during system initialization. The meaning of uplink and downlink is also different in the Mesh mode. Transmissions from a MSS to a parent MSS is called an uplink transmission. A transmission from a parent node to its child is called a downlink transmission [49]. In the Mesh mode each connection is associated with a link. Up to 64 connections can be defined on each link. Unlike the PMP mode, only TDD is supported in the Mesh mode.

2.1.1.2. Additional mechanisms in the PHY layer

IEEE 802.16 has an optional support for Adaptive Antenna Systems (AASs). Using multiple antennas, BS can increase the signal range and quality. Whether there are non-AAS SSs in the network or not, AAS BSs have the ability to support non-AAS SSs. When there are both AAS and non-AAS SSs in a network, the downlink and uplink parts are divided into two parts for both types of SSs. IEEE 802.16 also employs a DFS mechanism similar to the one used in HiperLAN. In case of a conflict with another network, an IEEE 802.16 BS initiates a frequency change mechanism. BS and SSs actively sense the air for other data transmissions and available frequencies.

2.1.2. Medium access control (MAC) layer

IEEE 802.16 MAC implements mechanisms such as bandwidth allocation, ARQ, etc. It also maps frames into connections. The MAC layer of WiMAX is designed with the link state of the PHY layer in mind. Thus, MAC layer may change the burst profile of a connection as a response to dynamic link variations. There are three sublayers in IEEE 802.16 MAC layer: Convergence Sublayer (CS), Common Part Sublayer (CPS), and Security Sublayer.

In the CS, network layer segments are acquired from CS Service Access Point (SAP) and converted into MAC Segment Data Units (SDUs). This sublayer also maps high-level transmission parameters into IEEE 802.16 service flow and connection couples, and utilizes mechanisms like Payload Header Suppression (PHS). Different high-level protocols are implemented in different CSs. Currently only two CSs exist: ATM CS for ATM networks and Packet CS for Ethernet, PPP, and TCP/IP. The second sublayer, the CPS, fetches MAC SDUs from CS sublayer via MAC SAP and converts them into MAC PDUs. This sublayer is responsible for system access, bandwidth allocation, connection related mechanisms, and packing multiple MAC SDUs into MAC PDUs. In the case of large MAC SDUs, the CPS also fragments the MAC SDUs into multiple MAC Packet Data Units (PDUs). With the help of PHS, packing, and fragmentation mechanisms, the standard tries to eliminate bandwidth waste due to repetitive information from higher layers. However, with the PHS mechanism, IEEE 802.16 deviates from the OSI model in which layer headers are assumed to be the part of the data. Therefore, layers are not always transparent to each other in IEEE 802.16 networks.

Last sublayer, the Security Sublayer, provides security and encryption in transmission. Security is maintained by encryption of data packets, secure key distribution via Privacy Key Management (PKM), authorization of PKM, and identification of nodes via X.509 profiles. Various security mechanisms are available for use in Security Associations (SAs). The BS assigns SA Identifiers (SAIDs) to SAs. Each connection can be assigned a different SAID, and one SAID can be assigned a number of connections [49]. Two types of SAs are defined: data SAs and authorization SAs. It has already been known that the security mechanisms defined in the IEEE 802.16 standard have many flaws especially regarding the authorization process, since there is no explicit definition for authorization SAs in the standard [66]. While the new security mechanisms introduced in IEEE 802.16-2005 provide better protection against attacks, the authorization problem still exists and must be addressed. The standard defines an optional use for ARQ that can be applied only to NLOS PHY interfaces. On connection establishment, nodes decide whether ARQ should be used or not. Once ARQ is selected for a connection, it cannot be changed during the lifetime of that connection. ARQ feedback messages can be either sent through management connections or piggybacked on other connections (). ARQ can also be used with the packing, fragmentation, and PHS mechanisms.

2.1.2.1. MAC in mesh mode

In the Mesh mode, distributed scheduling. While centralized scheduling can be used alone, distributed scheduling is used only with the centralized scheduling. Centralized scheduling is similar to the aforementioned PMP mode. Each MSS sends its request to the MBS and all the scheduling in the network is managed by the MBS. Nodes not directly connected to the MBS send their request messages through their parent nodes up to the MBS. Each MSS requests bandwidth on a link-by-link basis and only for the links on the scheduling tree. This mode is generally used for Internet traffic in the network. Distributed scheduling is composed of two methods: coordinated distributed scheduling and uncoordinated distributed scheduling. As opposed to centralized scheduling, none of these methods has a single point of scheduling control. Instead, every device distributes the scheduling information of its one-hop neighbors and its own scheduling information to its one-hop neighbors. Thus, each node knows the scheduling scheme in its two-hop neighborhood and makes its scheduling based on this information. Both of the methods use a three-way handshake mechanism for bandwidth allocation.

The difference between these two methods is that the scheduling information is sent in a collision-free manner in coordinated mode whereas in the uncoordinated method collisions are possible. Distributed scheduling is generally used for intranet traffic in the network. A recent work [54], shows the effects of different parameters in the performance analysis of distributed scheduling in the Mesh mode. If both scheduling methods are used, the data part of the frame is divided into two parts, one for centralized scheduling and one for distributed scheduling. In [55], Cheng et al. show that this partitioning results in unused data slots. The authors develop a combined scheme that allows either scheduling method to send its data using both parts of the data subframe.

2.1.3. Quality of service

In the PMP mode of IEEE 802.16, QoS is maintained through connections, service flows, and scheduling services. Higher layer QoS requirements are mapped to IEEE 802.16 QoS parameters in the CS sublayer based on the QoS requirements of the service flows. In Mesh mode, QoS is maintained in packet-by-packet basis and each packet has its own service parameters.

2.1.3.1. Connections

Connections are setup based on the services registered by the user during the initialization of a SS. If a user changes the services he is subscribed to, additional connections can be added to the network, a connection can be altered, or an existing connection can be terminated. More than one higher level transmission can be mapped to a single connection. Thus, a connection may represent many high level communications. In the PMP mode, each connection is identified with a 16-bit Connection Identifier (CID). Upon the initialization of a SS, two pairs of connections, Basic Management (BM) and Primary Management (PM), are set up. In the case of a managed SS, a third pair of connection, Secondary Management (SM), is set up. The use of these connections is specified in (). In [56], the authors studied the effect of number of connections on MAC layer performance. It is shown that as the number of connections increases, MAC layer efficiency decreases considerably. For connection establishment in the Mesh mode, the Link ID and four other link parameters are used to construct the CID. These four parameters are as follows: type, reliability, and priority/class and drop precedence. In this mode, each MSS also has a 16-bit Node Identifier (Node ID) acquired from the MBS when the MSS is initialized. The Link ID and Node ID pair is used in identifying data and control messages in the Mesh mode.

2.1.3.2. Service flows (SF)

Every connection in the network is associated with a SF that is composed of a set of QoS parameters, an SF Identifier (SFID), and a CID. SFs may or may not be active at a given time. SFs are associated with a connection when they are active. When an SF is established, a broad set of QoS parameters are selected. This broad set of parameters is called *ProvisionedQoSParamSet* (PQPS). When an SF is admitted for activation, a smaller set of PQPS, called the *AdmittedQoSParamSet* (AQPS), is selected. The admitted SF becomes active when the receiver accepts the flow. In this final step, the last parameter set, called *ActiveQoSParamSet* (ACQPS) is initialized. In addition to these parameter sets, there is also an authorization module for SFs.

Two types of authorization methods are available for SFs. In static authorization, parameter sets of an SF cannot be changed after SF establishment and additional SFs cannot be added. In dynamic authorization, there is a separate policy server in which the parameter sets are stored. The authorization module queries the policy server to check whether the admittance and activation of a new SF is appropriate. The policy server forwards this information to the authorization module in which establishment of dynamic SFs after SS initialization is done.

2.1.3.3. Scheduling services

Every SF is based on a scheduling service in the PMP mode of IEEE 802.16. These scheduling services define the nature of the data services supported, a rough QoS classification, and the set of allowed bandwidth request mechanisms for the connection. There are five different scheduling service classes available. Also, there are six QoS parameters defined in these scheduling services. The applicability of these parameters varies between scheduling service classes ().

UGS (Unsolicited Grant Service): This type of scheduling service supports real-time T1/E1 services and Constant Bit Rate (CBR) traffic. Upon connection establishment, the SS declares its bandwidth requirement to the BS for the connection. Then, the BS allocates exactly the requested amount of bandwidth to the connection in every frame. The bandwidth is always allocated to the SS regardless of the scheduler in the BS. The Poll Me Bit (PMB) in the grant subheader of UGS connections is used for non-UGS service requests. The bandwidth of the service is fixed and cannot be changed without restarting. With the exception of the traffic priority parameter, all remaining five QoS parameters are defined in UGS SFs.

rtPS (Real Time Polling Service): While UGS supports real-time CBR traffic, rtPS supports real-time Variable Bit Rate (VBR) traffic. For each rtPS connection of an SS, the BS assigns a periodic request opportunity in the uplink subframe. Thus, the connection never contends for bandwidth allocation. The size of the requested bandwidth varies from time to time, up to a limit set during the setup of the connection. Due to this request/grant mechanism, there are some overhead packets for a rtPS connection. The QoS parameters allowed in UGS SFs are also available in rtPS SFs with the exception of the tolerated jitter parameter.

nrtPS (non-Real Time Polling Service): nrtPS connections carry non-real-time traffic. The same polling mechanism used for rtPS connections is also used for nrtPS. Unlike rtPS, the connection may also enter contention for non-periodical bandwidth allocation request. Since these connections are not as important as rtPS connections and they have the ability to enter contention for bandwidth allocation requests, the polling periods of nrtPS connections are longer than that of rtPS connections. nrtPS SFs have the same QoS parameters as in rtPS SFs. However, since these SFs do not carry time critical packets, nrtPS SFs do not have the maximum latency parameter.

BE (Best Effort): This type of service can send bandwidth allocation requests only using contention. BS never allocates dedicated request opportunities to the SS for BE connections. Similar to nrtPS, BE SFs do not have the tolerated jitter and maximum jitter QoS parameters. BE does not have the minimum reserved traffic rate parameter as well. Both nrtPS and BE SFs have a special traffic priority parameter.

ertPS (Extended Real Time Polling Service): In [67], it is shown that current scheduling services are not appropriate for services like VoIP. Addressing this issue, the latest standard of IEEE 802.16 introduced ertPS scheduling service. ertPS is similar to UGS since it does not have any bandwidth request mechanism and in every frame the BS allocates bandwidth for the connection. However, the bandwidth allocated to the connection can change in time, similar to rtPS. An ertPS connection can decrease or increase its allocated bandwidth based on the traffic. ertPS SFs have the same QoS parameters with the rtPS SFs. The performance of these scheduling services is evaluated in [68]. In this work, it is shown that average uplink delay is greater than downlink delay because of the polling and request mechanisms. Also, the requirements of these scheduling service classes are satisfied with the current request and grant mechanisms stated in the standard. Application layer services use the most appropriate of these five scheduling service types for the given service.

2.1.4. New and upcoming standards

2.1.4.1. IEEE 802.16e.

The early standards of the IEEE 802.16 family do not support mobile users. In the literature, there are efforts to add mobility support to IEEE 802.16. The authors proposed a mechanism using a shortened initialization procedure for handovers [69]. In order to standardize similar mobility support mechanisms, IEEE 802.16 Task Group E was established and it finished development of the new standard in December 2005. The standard allow MSs working in the 2–6 GHz frequency band with vehicular speeds up to 60 kmph and is expected to support data rates up to 30 Mbps [70].

The standard addresses several issues regarding MSs and introduces mechanisms to tackle these problems. The most important difference between a SS and a MS is that a MS can change its BS during an active connection with a handover mechanism. In IEEE 802.16e, both the MS and its current BS may initiate a handover. The handover process is composed of two parts; breaking the connection with the current BS and establishing connection with the new BS. The second part is similar to the connection initialization of an SS with a BS. However, this process can be shortened by means of communication between the MS and the new BS while the MS is still connected to the old BS. IEEE 802.16e standard also supports soft handovers. The handover process of the standard is studied in [71], and a faster handover mechanism based on eliminating redundant work in the process is proposed. The simulation results show that the proposed handover mechanism greatly reduces handover delay compared to the original handover mechanism.

Another major problem regarding the mobile devices is the energy consumption. A sleep mode mechanism is implemented to reduce the overall energy consumption of MSs. The connection between a BS and a MS is established in two steps; interval of unavailability and interval of availability. During the interval of unavailability, the MS does not receive any transmission from the BS. Since the BS knows that the MS is sleeping, it buffers the packets destined to the MS. During the interval of availability, the BS sends the packets it buffered during the last interval of unavailability. If there are no packets destined to the MS during this period, the MS increases its sleep time and informs the BS about its new waking time. In [72–74], it is shown that this power saving mechanism is effective. A mobility profile is currently being defined by the WiMAX forum in addition to the fixed profile. The mobile profile is expected to use 2.3 and 2.5 GHz frequency bands utilizing the same channel bandwidth options available in the fixed profile. The PHY layer selection is different from the fixed profile. WirelessMAN-OFDMA is expected to be used to accommodate mobile users. Similar to the standard, the mobile profile allows both hard and soft handover between BSs [51].

2.1.4.2. IEEE 802.16j

A new task group Mobile Multihop Relay (MMR) also known as IEEE 802.16j, was formed to work on the PMP mode [75]. IEEE 802.16j allows the SSs not covered by the BS to connect to the network. In order to achieve this goal, Relay Stations (RSs) are introduced into the network. These RSs are directly connected to the BS, and SSs connect to the BS through these stations. RSs can only relay a transmission. Data allocations in both downlink and uplink are altered to enable relaying.

2.1.5. Problems and open issues

Similar to its WLAN counterpart IEEE 802.11, IEEE 802.16 has some problems on its own. Originally developed to standardize LMDS systems, current IEEE 802.16 standard also covers MMDS and mobile systems. While these improvements allow new user profiles to be used by the standard, they also introduce problems that were not considered while the standard was being developed at the first place.

2.1.5.1. QoS scheduler

QoS schedulers in both the BS and SS sides are left un-standardized in the original standard. These schedulers have a significant effect on the overall performance. The BS allocates bandwidth on SS basis rather than per connection. Thus, it does not specify for which connection the allocated bandwidth will be used. The SS decides the order in which the connections send their data. This distributed scheduling structure handles fairness between SSs, which in turn improves overall performance. In the literature, there are several proposals for SS and BS schedulers. In [76], SS schedulers in which connections with the same scheduling services are integrated and different queuing policies are applied to the queue of each scheduling service. The authors proposed method uses Wireless Packet Scheduling (WPS) for rtPS connections, Weighted Round Robin (WRR) for nrtPS connections and FIFO scheduler for BE connections. In the BS scheduler proposed in [77] the SS sends the arrival times of rtPS PDUs to the BS through the UGS connection. Also, the BS scheduler applies different queuing policies to different scheduling services; Earliest Deadline First (EDF) scheduling for rtPS connections and WFQ scheduling for nrtPS connections.

In [78], Jiang et al. develop another BS scheduler using token buckets to characterize traffic flows. In [68], a WRR scheduler is used for uplink bandwidth allocation in the BS scheduler and a Deficit Round Robin (DRR) scheduler is used in the SS scheduler. The DRR scheduler is also used for downlink bandwidth allocation in the BS scheduler. A queue-aware SS scheduler for polling service connections is proposed and its performance is analyzed in [79]. This scheduler informs the packet source of its queue status and tries to control the packet arrival rate. In [80], a BS scheduler for the Mesh mode is introduced. This scheduler introduces a node ordering mechanism among the nodes with same hop count from the MBS. Moreover, an SDMA mechanism is used to further increase the throughput in the network. Another SDMA-based BS scheduler for the centralized scheduling of the Mesh mode is introduced in [65]. This scheduler considers the interference of transmissions in links and makes scheduling decisions based on this information. Shetiya et al. propose a BS scheduler that is based on a dynamic programming framework that maximizes the total reward of the scheduler [64]. Various definitions regarding the meaning of the reward metric is introduced and their performances are evaluated.

2.1.5.2. MAC PDU size

Selecting an ideal MAC PDU size decreases the number of packed and segmented MAC SDUs. This decrease saves the network from unnecessary packing and segmentation subheaders. The size of a MAC PDU is not defined in the standard but a recent work on the optimum MAC PDU size shows that adaptive MAC PDU and Cyclic Redundancy Check (CRC) sizes, rather than fixed MAC PDU and CRC sizes, result in better link utilization [60]. This method uses the PMP mode with ARQ mechanism enabled and changes the MAC PDU size according to the wireless channel state to optimize the MAC PDU size for fewer retransmissions. In [53], optimal PDU sizes for given Bit Error Ratios (BERs) are calculated. This calculation also considers overhead due to retransmissions and packet headers. The MAC PDU size is calculated for the PMP mode only. In the Mesh mode, these optimal values could be different from those in the PMP mode.

2.1.5.3. Effects of contention periods

SFs with nrtPS or BE scheduling services contend with each other for bandwidth allocation. The number of collisions can be decreased by extending the contention windows, but this in turn generates unnecessarily long contention periods which decrease the system throughput. In [81] and [82], the effect of contention window size is analyzed. Both works assume that each SS sends one bandwidth request message in each frame instead of sending one bandwidth request for each active connection. According to these studies, contention window size should be selected close to the number of SSs in the network. When the bandwidth request messages, collide with each other; their SSs wait for several slots before retransmitting the request messages. This backoff mechanism is analyzed in [83] and [84]. These studies show that there are different optimal backoff values for different number of active SSs in the network.

2.1.5.4. Mesh QoS

Unlike the PMP mode, MAC PDUs are responsible for their own QoS constraints in the Mesh mode. There are not any QoS constraints associated with links and connections in this mode. Every MAC PDU carries its own QoS constraints. The standard does not introduce any mechanism for handling these QoS parameters. Mechanisms for handling these parameters should be developed for better QoS handling in the Mesh mode. Also these QoS parameters increase the MAC overhead in turn. Link by QoS schemes might also be used to decrease this overhead. In [85], a method for the centralized scheduling of the Mesh mode is proposed. Upon initialization, the MBS allocates five node IDs to each MSS. Each virtual node establishes one link with its parent node as in the default Mesh mode and sends a request message to the MBS. These five virtual nodes represent the five scheduling services in the PMP mode with similar request/grant mechanisms. By using this method the delay of time-critical packets decrease significantly.

2.1.5.5. Security

The authorization SAs is not defined in the IEEE 802.16 standard. Without any authorization module specified, the rest of the security mechanisms in the security sublayer cannot effectively protect the network against malicious users. In order to increase security in IEEE 802.16 networks, authorization SA definitions are needed. In [66], several changes are proposed to increase the security of IEEE 802.16.

3. Conclusion

The technical specifications of the standards presented in this survey have been summarized briefly in [56]. While WLAN supports connectivity in the range of 50–60 m radius, on the other hand WMAN provides connectivity with radius ranging from 1 to 4 km. From [56], we can see that WMANs provide data rates lower than WLANs, up to 135 Mbps in the case of only LOS users. As well as, if the standard has mobility support, the aggregate data rate of the cell drops drastically. WWAN technologies provide data rates much lower than that of WLANs and WMANs. Covering wider areas, families like IEEE 802.20 and 802.22 support 16–18 Mbps of data rate per cell. The frequency bands used by these standards depend on the area and user profiles. WLANs and WWANs use lower frequencies as compared to WMANs. Also, WMANs with mobility support and NLOS connectivity use low frequencies. LOS connectivity between the user and the central station is available, but then higher frequencies are used.

In this paper, we presented one of the emerging standards in broadband wireless data networks i.e. IEEE 802.16: WiMAX in detail. Some of the newer standards of the IEEE 802.16 family aim to improve the internet connectivity significantly by providing BWA for different areas and user profiles. However, we can say that with Integration such technologies will an omnipresent data access similar to what we have in voice communication networks. From what we have seen till now, some standards enhance older ones, others introduce new wireless access concepts.

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