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A survey on emerging broadband wireless access technologies

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Abstract

Wireless broadband technologies provide ubiquitous broadband access to wireless users, enabling services that were available only to wireline users. In this paper, we summarize emerging wireless broadband access technologies, ranging from WLANs to satellite communications. We explain the latest standards in the IEEE 802.11 and IEEE 802.16 families in detail. The MAC layer mechanisms of IEEE 802.11e, 802.11n, and 802.11s standards are explained as well as the point-to-multipoint and Mesh modes of IEEE 802.16. The recent mobility amendment to the WiMAX family, IEEE 802.16e, is also described. Though the earliest versions of some of these technologies date back to 1996 (such as IEEE 802.11) and some are obsolete (such as HiperLAN), they have been included in this survey for the sake of completeness.

Wireless technologies can be categorized based on their coverage areas. IEEE 802.11 and ETSI HiperLAN standards are considered for wireless access in local areas. IEEE 802.16 and 802.22, ETSI HiperACCESS and HiperMAN, WiBro, and HAP technologies can be used to provide service in metropolitan areas. Lastly, IEEE 802.20 and satellite systems provide service as wide area networks. Since the aim of this survey is to summarize wireless broadband technologies for data services, technologies such as Wireless USB are excluded. 3G and 4G systems have also been excluded since they are covered in detail in [C. Smith, D. Collins, 3G Wireless Networks, second ed., McGraw-Hill Osborne Media, 2006; S.G. Glisic, Advanced Wireless Networks: 4G Technologies, Wiley Publishing, 2005].

Keywords: WLAN; WMAN; WWAN; HiperLAN; HiperMAN; HiperACCESS; WiBro; IEEE 802.11; WiFi; IEEE 802.16; WiMAX; IEEE 802.20; IEEE 802.22; HAPs; Satellite

1. Introduction

Network technologies are traditionally based on wireline solutions. 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. Wireline networks on the other hand excel in high bandwidth data communication, but they do not support mobility. The aim of emerging wireless data networks is to provide wireless service comparable to that of wireline networks for fixed and mobile users.

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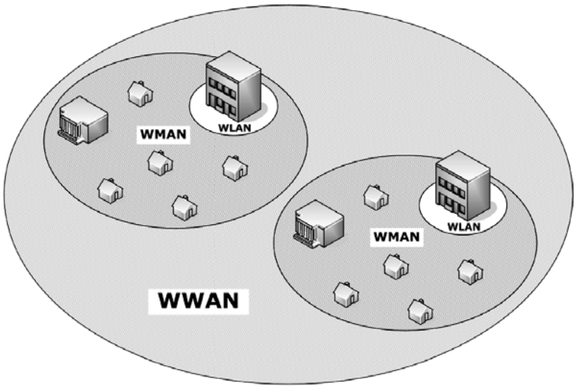

Fig. 1. Area coverage of different wireless access technologies.

Wireless data networks can be categorized according to their coverage areas (Fig. 1). *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*) cover wider areas, generally as large as entire cities. *Wireless Wide Area Networks* (*WWANs*) 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.

As of today, WLAN is the most widely deployed wireless technology. The most notable WLAN standard is IEEE 802.11 family. Another WLAN standard is the HiperLAN family by ETSI. These two technologies are united under the *Wireless Fidelity* (*WiFi*) alliance. Both technologies serve a local area with a radius of 50–100 m at most. A typical WLAN network consists of an *Access Point* (*AP*) in the center and *Stations* (*STAs*) connected to this AP. Communication to/from a STA is always carried over the AP. There is also a decentralized working mode of WLAN, in which all STAs can talk to each other directly in an ad-hoc fashion. While WiFi initially provided an aggregate throughput of 11 Mbps (per AP), the current standard provides a throughput of 54 Mbps. Also, in the market there are WiFi devices that support data rates up to 108 Mbps using various additional techniques. With the emerging IEEE 802.11n standard, WiFi is expected to standardize these improvements and provide throughput values up to 540 Mbps.

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* (*MS*s). 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 a 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. Two different WMAN standards are introduced under the BRAN project as of today; HiperACCESS for LOS and HiperMAN for both LOS and NLOS user support. Furthermore, *Wireless Broadband* (*WiBro*) standard is developed by the *TTA* (*Telecommunications Technology Association*) of South Korea based on IEEE 802.16.

A different approach for BWA support is *High Altitude Platforms* (*HAPs*). HAPs fill in the gap between WMANs and WWANs. In HAP systems, floating platforms (or air vehicles) serve as the BS over wide areas, and the cities are covered by multiple platforms. The most important aspect of HAP is the platform's ability to reach virtually all buildings within its LOS.

Satellite systems provide the widest coverage for WWAN environments. The satellites in current use are mostly capable of one sided (only downlink) broadcast communication. *Next Generation Satellite Systems* (NGSSs) are expected to have *Onboard Processing* (*OBP*) and on-board routing capabilities. Coupled with upload channel support, these satellites will have greater versatility and are expected to play an important role in future broadband systems.

Another WWAN technology is the emerging IEEE 802.20 standard. This new technology targets highly mobile vehicles with speeds up to 250 kmph (e.g., high speed trains) for BWA access. IEEE 802.20 is expected to cover large areas and will have versatile mobility support. Thus, mobile users with different speeds and profiles may connect to the same IEEE 802.20 BS. The aggregate throughput of the system is not expected to be as high as a WLAN AP or a WMAN BS due to the high speed of the mobile users.

Wireless data networks operating at different scales can be integrated to provide ubiquitous

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broadband access to users. In a simple integration environment, WLANs provide wireless access to indoor users. Traffic to/from multiple WLANs in the same building can be aggregated and transmitted over the local WMAN (e.g., through an IEEE 802.16 SS) to the Internet. WMANs covering different areas can be interconnected by a WWAN. Thus, a mobile user has ubiquitous connectivity in a wide area. Since this survey aims summarizing wireless broadband technologies for data services, technologies such as Wireless USB are excluded. 3G and 4G systems have also been excluded since they are covered in detail in [1,2].

In this paper, we summarize current and emerging BWA technologies. In Sections 2–4, we explain WLAN, WMAN, and WWAN technologies. We provide a comparison of these technologies and conclude our paper in Section 5.

2. Wireless LAN

Widespread use has helped WLANs to mature as an access technology in short-to-medium distances. As the importance of mobility and nomadic user profiles has increased, WLANs gained importance especially in home, office, and campus environments. Low infrastructure cost, ease of deployment and support for nomadic communication are among the strengths of WLANs. Deployment without cabling and ease of adding a new user to the network decrease the implementation cost of a WLAN dramatically.

The use of a wireless medium also brings its problems. Most importantly, the shared medium in a WLAN results in performance degradation with the increasing number of STAs. There are also various security problems regarding unauthorized access and eavesdropping in WLANs. Furthermore, the users access the medium in a contention-based manner. Contention for the shared medium results in probabilistic access to the wireless channel. Maintaining tight *Quality of Service* (*QoS*) constraints in WLANs are more troublesome due to the contention and variable link quality problems. Numerous methods have been introduced to remedy these problems in WLANs and more advanced methods are under development.

2.1. IEEE 802.11 family

First introduced in 1999, IEEE 802.11 standard targets home and office environments for wireless local area connectivity. While the initial standard [3] gives a maximum data rate of 2 Mbps per AP, the next standard in the family, IEEE 802.11b [4], increases the data rate to 11 Mbps. With the introduction of newer standards, IEEE 802.11a [5] and IEEE 802.11g [6], the data rate increases to 54 Mbps per AP. Additional mechanisms have been developed to remedy QoS support and security problems in the previous standards. These mechanisms are published as IEEE 802.11e [7] and IEEE 802.11i [8], respectively. Using various methods (e.g., Atheros SuperG) to boost up the data transmission rate, WLAN devices based on IEEE 802.11g currently offer data rates of 100–125 Mbps [9,10]. The next standard in the family, IEEE 802.11n, seeks to standardize these efforts and introduce new MAC enhancements to overcome MAC layer limitations in the current standards. Close to completion, IEEE 802.11n is expected to support very high data rates up to 540 Mbps[1] and use the QoS mechanisms introduced by IEEE 802.11e [11]. Another standard is the IEEE 802.11s, which adds mesh topology support to the IEEE 802.11. This work is expected to be finalized in 2008.

Chipset vendors that develop WLAN devices based on IEEE 802.11 standard have formed a consortium called WiFi alliance for interoperability between devices from different companies. WiFi also supports devices using HiperLAN standard. Currently, the terms IEEE 802.11 and WiFi are used interchangeably in the literature.[2] Standards that belong to the IEEE 802.11 family are summarized in Table 1.

2.1.1. Physical (PHY) layer

Various PHY layers are available in the IEEE 802.11 family. In order to increase the aggregate throughput of a IEEE 802.11 network, new PHY layer technologies are developed while preserving the MAC layer. The initial standard includes three PHY layers: *Frequency Hopping Spread Spectrum* (*FHSS*), *Direct Sequence Spread Spectrum* (*DSSS*), and *Infrared* (*IR*). IEEE 802.11b standard uses a new PHY layer, *High Rate DSSS* (*HR-DSSS*), based on DSSS. IEEE 802.11a and IEEE 802.11g use *Orthogonal Frequency Division Multiplexing* (*OFDM*) PHY layer that greatly increases the overall

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[1] WWise supports data rates up to 540 Mbps [11] while TGnSync supports data rates up to 630 Mbps [13].

[2] In this paper, we will follow the convention in the literature and use the terms WiFi and IEEE 802.11 interchangeably.

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Table 1
IEEE 802.11 family

Standard	Purpose	Publishing date
802.11	2 Mbps, 2,4 GHz standard (original standard)	1999
802.11a	54 Mbps, 5 GHz phy layer standard	1999
802.11b	11 Mbps, 2,4 GHz phy layer standard	1999
802.11d	International roaming extensions for 5 GHz Band	2001
802.11e	QoS enhancements	2005
802.11g	54 Mbps, 2,4 GHz PHY layer standard (current standard)	2003
802.11h	Spectrum managed 802.11a for satellite and radar compatibility	2004
802.11i	Security enhancements	2004
802.11j	Extensions for Japan	2004
802.11k	Radio resource measurement extensions (for areas with multiple APs)	Expected 2007
802.11n	Up to 540 Mbps, 2,4 GHz higher throughput	Expected 2007
802.11p	Wireless access for the vehicular environment (WAVE)	Expected 2008
802.11r	Fast roaming between WLANs	Expected 2007
802.11s	Mesh topology support	Expected 2008
802.11u	Internet working between different WLANs	Preliminary
802.11v	Wireless network management	Preliminary
802.11w	Protected management frames	Expected 2008
802.11y	3.65–3.7 GHz PHY layer standard	Preliminary

throughput at the AP. Modulation techniques available in OFDM are summarized in Table 2. In the upcoming IEEE 802.11n standard, the use of OFDM modulation coupled with a *Multiple Input Multiple Output* (*MIMO*) mechanism is planned.

Most of the IEEE 802.11 PHY layers work in the 2.4 GHz frequency band (2.414–2.484 GHz) with 14 distinct channels. The availability of these 14 channels vary from country to country. The last channel is designed specifically for Japan (with the IEEE 802.11j extension). IEEE 802.11 does not have a fixed channel bandwidth but the standard dictates several rules about signalling such as the center frequency of these channels must be at least 5 MHz apart from each other and the power levels of the signals for nearby frequencies cannot exceed certain thresholds. A typical APs signal does not extend more than 22 MHz from center frequency of the selected frequency. Thus, the channel bandwidth of IEEE 802.11 is in effect 22 MHz [12]. As a result only three of the 14 channels do not overlap. IEEE 802.11a, on the other hand, works in the 5 GHz (5.15–5.825 GHz) frequency band with a fixed channel center frequency of 5 MHz. The number of channels varies from 36 to 161 depending on the frequency band. There are 12 non-overlapping channels (with center frequencies 20 MHz apart from each other) in the frequency band used by IEEE 802.11a [4,5] in the US and 19 non-overlapping channels in Europe [14]. IEEE 802.11n is expected to use non-overlapping channels with channel bandwidths of 20 and 40 MHz. While 20 MHz channel bandwidth will be supported by every IEEE 802.11n device, support for 40 MHz channel will be optional.

A typical WLAN AP uses one omnidirectional antenna and has a range of 30–50 m indoors and 100 m outdoors. This range (especially indoors range) is greatly affected by the obstacles between the AP and the STA, link condition, and the security measures used in the WLAN. Using directional antennas, directed *peer-to-peer* (*P2P*) WLAN links can be established within a few km range. Working at a higher frequency band, IEEE 802.11a networks suffer more from increased range and attenuation compared to IEEE 802.11b/g networks. In [15], it is shown that using sectored antennas instead of omnidirectional antennas greatly increases the aggregate WLAN data rate in a given area two to three times.

Table 2
OFDM PHY layer modulation techniques [12]

Data rate (Mbps)	Modulation	Coding rate	Coded bits/subcarrier	Code bits/OFDM symbol	Data bits/OFDM symbol
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

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2.1.2. Medium access control (MAC) layer

MAC layer of IEEE 802.11 utilizes a contention-based scheme called *Distributed Coordination Function* (*DCF*). STAs associated with the AP sense the air interface for channel availability. If the interface is idle, the source STA sends its data to the destination through the AP. If more than one STA try to access the air interface simultaneously a collision occurs. The standard uses *Carrier Sense Multiple Access/Collision Avoidance* (*CSMA/CA*) mechanism to avoid collisions [3].

IEEE 802.11 also defines a centralized MAC technique, the *Point Coordination Function* (*PCF*), which is partially contention-based and partially centralized. In PCF, transmission is divided into two parts. In the first part, AP polls each STA in a round robin fashion to check if they have packets to send. Any STA that is not polled till the end of the polling period, will be queued for polling during the next polling period. The second part of the transmission is contention-based and is same as DCF.

DCF is the default MAC technique used in a IEEE 802.11 networks. If the network device supports PCF, the AP has the option to enable PCF anytime (e.g., when one or more STAs need to send/receive time-bounded data). PCF can only be used in infrastructure operating mode. However, due to the polling mechanism, using PCF decreases the aggregate throughput of an IEEE 802.11 network [12]. While the standard includes both MAC techniques, PCF is not included in the WiFi alliance's interoperability standard, and therefore not widely implemented. These two methods are used in all IEEE 802.11 standards.

In both MAC techniques, an *Automatic Response Request* (*ARQ*) mechanism is used. Any device in the network receiving a frame will send an *Acknowledgment* (*ACK*) frame to the sender.

2.1.2.1. RTS/CTS. In case two STAs cannot communicate directly, using CSMA/CA may result in incorrect medium information. This problem is called the *Hidden Node* problem, in which collisions cannot be detected by some part of the network. When there is at least one pair of STAs that cannot directly communicate, the AP enables the use of the *Request To Send* (*RTS*)/*Clear To Send* (*CTS*) mechanism. For each transmission, the source STA transmits a RTS message. The destination STA responds this request with a CTS message. When the source STA receives the CTS message, it starts its data transmission. All other STAs assume that the medium is in use for the duration given in the message when they receive the RTS and/or CTS messages. Like PCF, using RTS/CTS mechanism greatly reduces the network throughput. In networks with STAs supporting different PHYs (e.g., devices with IEEE 802.11b and IEEE 802.11g), STAs using the old PHY may be considered as hidden nodes unless special protection mechanisms are used, and RTS/CTS mechanism must be used in order to avoid collisions [12].

2.1.2.2. Authentication and encryption. Security is also handled in the MAC layer. In order to avoid eavesdropping from unauthorized STAs, several security mechanisms have been introduced. Initially the only available encryption method was *Wired Equivalent Privacy* (*WEP*). Due to security problems in WEP, WiFi alliance developed another encryption method named *WiFi Protected Access* (*WPA*). With the completion of IEEE 802.11i [8] an improved version of WPA, (WPA2)**,** is integrated in the standard. Likewise, the authentication methods defined in the original standard, open system and shared key authentication, are proved to be insecure. IEEE 802.11i also addressed this issue and incorporated IEEE 802.1X authentication method which is used in all IEEE 802 family standards. Using this method, the users can authenticate their identities by a RADIUS or a Diameter server [16].

2.1.2.3. Operating modes. The standard introduces two operating modes. The infrastructure operating mode is a network with an AP, in which all STAs must be associated with an AP to access the network. STAs communicate with each other through the AP. The second operating mode, the independent mode or the ad hoc mode, is used if there are no APs in the network. In this mode, STAs form an ac hoc network directly with each other.

2.1.3. Quality of service

The original IEEE 802.11 standard was developed with only best effort traffic in mind. Thus, maintaining QoS is cumbersome using either of the two MAC techniques, DCF or PCF. In the literature, several solutions have been proposed to tackle the QoS provisioning problem induced by these MAC techniques [17,18]. In 2005, IEEE developed a new standard, IEEE 802.11e, to standardize the QoS enhancement efforts [7]. While not a final solution, the MAC techniques introduced in IEEE 802.11e significantly enhance QoS support in WiFi.

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Two new MAC techniques are described in IEEE 802.11e. These two techniques, *Hybrid Coordination Function* (*HCF*) and *Enhanced Distributed Coordination Function* (*EDC*F),[3] are based on PCF and DCF, respectively. In addition to these techniques, the standard includes two additional MAC enhancements to increase MAC layer throughput. Block acknowledgement enables sending a single ACK for more than one MAC frame (a block of frames). The other mechanism, *Direct Link Protocol* (*DLP*), enables direct communication between two STAs in the same WLAN cell [19]. An AP with IEEE 802.11e support is called *QoS Enhanced AP* (*QAP*). Likewise, an STA with IEEE 802.11e support is called *QoS Enhanced STA* (*QSTA*). These techniques and enhancements are summarized below.

2.1.3.1. HCF. The main MAC technique in IEEE 802.11e, *Hybrid Coordination Function* (*HCF*), is based on the PCF mechanism in the original standard. Unlike PCF, HCF is mandatory for devices that support IEEE 802.11e. Similar to DCF periods in PCF, there are EDCF periods in HCF. The contention free period of HCF is called *HCF Controlled Channel Access* (*HCCA*). In HCF, there are several EDCF periods for random access and several HCCA periods for contention free access. The main difference from PCF is that packets with different QoS levels are mapped into different MAC queues, *Traffic Classes* (*TC*), which have different polling priorities. The QAP polls the TCs of the QSTAs using a priority-based round-robin scheduler starting with the first QSTAs highest TC queue. In effect, the QAP considers each queue of a QSTA as a separate WLAN node [19,20].

2.1.3.2. EDCF. EDCF is used only as a part of the first technique. Similar to the DCF, EDCF is a contention-based medium access technology. Also similar to HCCA, packets are queued in different *Access Categories* (*ACs*) in EDCF similar to the TCs. Using EDCF, a QSTA acts like a virtual STA for each different QoS level. Medium access parameters of ACs of a given STA depend on their respective priorities. ACs are different from TCs; a given type of packet has one AC and one TC in a WiFi network.

2.1.3.3. Block acknowledgement. After sending a MAC frame, the destination sends an ACK for every MAC frame according to the IEEE 802.11 standard. ACKs cause high overhead and waiting time for the network. IEEE 802.11e uses frame blocks and sends one ACK for one frame block. The disadvantage of this mechanism is that the loss of an ACK causes retransmission of the whole frame block.

2.1.3.4. DLP. Traditionally, two STAs in the same WLAN can communicate only through the AP. Thus, the amount of bandwidth consumed in the cell is twice the actual data rate of the transmission. DLP is a mechanism that enables STAs in the same WLAN to communicate directly with each other, avoiding excessive use of resources.

Unlike DCF and PCF, the MAC techniques in IEEE 802.11e divide the transfer time into *Transmission Opportunities* (*TO*). A QSTA (or QAP) can use the medium for a number of TOs. This limitation eliminates timing problems in PCF. Both in EDCF and HCF, the QSTA sends an information packet regarding QoS specifications for each communication request before the start of the transmission. If the QAP can handle this transmission subject to requested QoS parameters, it accepts the request. Otherwise, the request is denied but can be retried with lower QoS constraints [19].

The performance of the new MAC techniques and enhancements in IEEE 802.11e have been studied in [19–21]. The results clearly show that EDCF and HCF provide lower delay for time-critical packets and increase overall MAC layer throughput.

In the literature, Additional mechanisms to further improve MAC throughput and QoS support, have been proposed. In [19,23], it is shown that using adaptive contention window, *Inter-Frame Space* (*IFS*) parameters based on the link condition improve the overall performance of IEEE 802.11e. In [22,21], TCP unfairness in WLANs is stated. They proposed using the highest queue level for ACKs, which increases TCP fairness drastically according to analytical and simulation results. In [24], the polling mechanism in the HCCA period is replaced with a request based scheduler. Each QSTA sends requests for their queues to the QAP, and then the QAP schedules these uplink packets with its own downlink packets using a modified *Weighted Fair Queuing* (*WFQ*).

2.1.4. Mobility

IEEE 802.11 is developed as the wireless counterpart of Ethernet. Since mobile user profiles are not

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[3] EDCF is also called *Enhanced Distributed Channel Access* (*EDCA*).

defined in the original standard, seamless transition between WLAN cells cannot be accomplished. The upcoming IEEE 802.11s standard addresses the issue of intra-AP communication, but it does not provide a solution for roaming users either. The Cellular IP architecture provides a solution for seamless transition between different WLANs. In this architecture, several WLAN cells are connected to the Internet and each other by a single gateway. This gateway keeps record of routing paths to all STAs in the network. In the case a STA changes its serving AP, a new path is established between the gateway and the STA [25].

2.1.5. Other standards

In addition to the standards described previously, there are other standards in IEEE 802.11 family.

2.1.5.1. IEEE 802.11d. IEEE 802.11a defines the operation parameters at the 5 GHz frequency band, but it only covers North America, Europa, and Japan. IEEE 802.11d defines the specifications to which an AP working in the other parts of the world must conform to operate at the 5 GHz [26].

2.1.5.2. IEEE 802.11h. In addition to IEEE 802.11a signals, there are satellite and radar signals at the 5 GHz frequency band in Europe. IEEE 802.11h adds two mechanisms to IEEE 802.11, *Dynamic Frequency Selection* (*DFS*) and *Transmit Power Control* (*TPC*). With DFS, the AP detects other networks operating at the same frequency band in the same region and changes the operating frequency of the WLAN to prevent collision. TPC is used to keep the signal level below a threshold if a satellite signal is available in nearby channels. This mechanism can also be used to improve link condition by changing the working frequency to a more clear channel and also to reduce power consumption [14].

2.1.6. New and upcoming standards

2.1.6.1. IEEE 802.11k. This standard enables management of the air interface between multiple APs. This standard specifically targets environments with many APs. An AP can order an STA to make a site survey and report the results. Then, the AP takes admission control decisions based on this information. Normally, an STA searching for an AP connects to the AP with the strongest signal. Using IEEE 802.11k, a congested AP may reject a new STA and force it to connect to a less congested AP within the STAs range.

2.1.6.2. IEEE 802.11n. Unlike the earlier enhancements, the goal of this new standard is to increase the MAC layer throughput of IEEE 802.11, instead of simply increasing the data rate of the PHY layer. A MAC layer throughput of at least 100 Mbps is planned [13]. To reach this goal IEEE 802.11n introduces new MAC layer mechanisms to increase overall throughput. Unifying three proposals, IEEE 802.11n is expected to be published in 2006. The three major proposals, *Worldwide Spectrum Efficiency* (*WWise*), *Task Group N Synchronization* (*TGnSync*), and *Mac and mImo Technologies for MOre Throughput* (*MITMOT*) employ similar mechanisms.. All of these proposals use MIMO and new modulation and coding mechanisms to increase data rate [27,28]. Using the MIMO mechanism, these proposals use two receiving and two transmitting (2X2) antennas. They also have additional antenna coupling schemes (e.g., 2X3, 2X4) for higher data rate and better signal quality. Different modulation and coding schemes are allowed in the proposals; WWise and MITMOT allows 64-state *Quadrature Amplitude Modulation* (*QAM*) with 5/6 encoding while TGnSync allows 256-state QAM with 7/8 encoding [29]. The proposals use a fixed channel bandwidth of 20 MHz, which is useful for backward compatibility with older standards. They also have optional support for 40 MHz channel bandwidth similar to some unofficial methods used to increase the data rate (e.g Atheros Super-G) [11,13].

In order to increase the MAC layer efficiency in WLANs, several mechanisms are proposed, using methods similar to IEEE 802.11n to increase overall throughput in WLAN [30,31]. The two mechanisms that are expected to be in the final version of the standard are frame aggregation and block acknowledgement. In the current IEEE 802.11 MAC layer, an STA waits for a while after sending a MAC frame. When the frames are small, the waiting time results in severe underutilization. The frame aggregation mechanism enables STAs to aggregate small frames into larger ones to minimizes this problem. Also, to maximize the efficiency of this method, the maximum frame size is increased, allowing longer frames. The second enhancement, block acknowledgement, is similar to the mechanism with the same name in IEEE 802.11e.

2.1.6.3. IEEE 802.11p. Also known as the *Wireless Access for Vehicular Environments* (*WAVE*), the standard deals with inter-vehicular communication for *Intelligent Transportation System* (*ITS*) support.

Using this protocol, vehicles send information about their traffic parameters (speed, distance from other vehicles, etc.) to nearby vehicles. Thus, each vehicle knows the current traffic status and acts accordingly. IEEE 802.11p is planned to work at the 5.9 GHz frequency band, which is not compatible with IEEE 802.11a/b/g.

2.1.6.4. IEEE 802.11r. This standard allows seamless handover for STAs between APs. The handover delay is not small enough to support voice communication but can support data communication. The main target application for IEEE 802.11r is *Voice over IP* (*VoIP*). In order to decrease the handover delay, the STA keeps track of the nearby APs and communicates with them before making the actual handover.

2.1.6.5. IEEE 802.11s. In the infrastructure mode, each WLAN is composed of a single cell. The communication between two WLAN cells can only be performed through a wireline network. The range of APs can be extended using wireless repeaters. Thus, two WLANs can be connected through a wireless bridge, but multiple WLANs cannot form a unified network composed of multiple WLAN cells (Fig. 2). Addressing this issue, IEEE formed Task Group S to develop a standard for inter-WLAN communication. This work is also called "support for mesh topology" in IEEE 802.11. IEEE 802.11s is not a solution for a complete *P2P* networking [32]. It tries to form a mesh topology between APs, not a mesh including STAs.

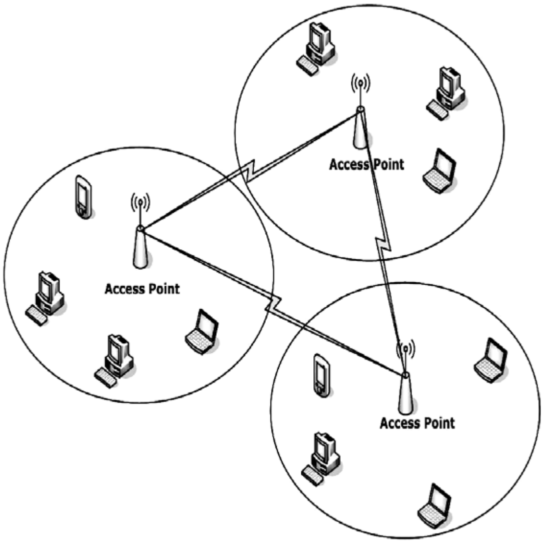

Fig. 2. Mesh topology in the backbone of a number of WLANs.

In the market different techniques are used by the products in the market to provide wireless connectivity between APs. Some of these solutions use the same frequency for AP–STA and AP–AP communication while others use different frequencies for AP–STA and AP–AP communication [32,33]. IEEE 802.11s is expected to be a universal solution and will remedy interoperability problems between different mesh support mechanisms. IEEE 802.11s has broadcast, multicast, and unicast support and is expected to include multiple routing algorithms between APs. Petar et al. developed a mesh support solution for IEEE 802.11a networks using the MAC layer of the Mesh mode of IEEE 802.16 [34]. In [35], a proposal for a routing algorithm is introduced targeting the use of a space diversity method in mesh WLAN networks. Still in preliminary stages, there are currently four proposals for the standard. Most notable ones are *Simple, Efficient, and Extensible Mesh* (*SEEMesh*) supported by Intel, Nokia, and Motorola, and the proposal of Wi-Mesh Alliance supported by Nortel including IEEE 802.11e support for handling QoS. Expected to be finalized in 2008, IEEE 802.11s is under development with IEEE 802.11g and IEEE 802.11n support.

2.1.6.6. IEEE 802.11u. In an IEEE 802.11 network, an STA can be associated with an AP if the STA is authorized priorly by the AP. IEEE 802.11u focuses on on-the-fly authorization between APs and STAs. With the usage of external network authorization, an AP provides service to previously unknown STAs.

2.1.6.7. IEEE 802.11y. Since the current frequency channels at the 2.4 and 5 GHz frequency bands are occupied by current WLANs, a new frequency band (3.65–3.7 GHz) is defined in the US. Targeting this new frequency band, IEEE 802.11y adapts current PHY layers to the new frequency band.

2.1.7. Problems and open issues

Although numerous new standards have been introduced after the publication of the original standard in 1999, there are still some problems in IEEE 802.11 networks.

2.1.7.1. Data rates. The current IEEE 802.11g standard can give a maximum data rate of 54 Mbps. This is still too low when compared to wireline solutions (such as IEEE 802.3). The upcoming IEEE

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802.11n standard addresses this issue and is expected to support much higher data rates. The WWise proposal supports data rates up to 540 Mbps, while TGnSync proposal supports a higher data rate of 630 Mbps. However, the 40 MHz channel bandwidth required for 540 and 630 Mbps data rates is not available in every country (e.g., Japan) [13]. This data rate is still low when compared to the 10 Gbps capacity of the upcoming IEEE 802.3an standard. Thus, more advanced PHY layers are needed in IEEE 802.11 networks.

2.1.7.2. MAC layer throughput. While the maximum data rate of IEEE 802.11g is 54 Mbps, the MAC layer throughput is far from this value. A recent detailed study shows that at higher data rates, the MAC layer throughput drops to 40–50% of the raw data rate[36]. If the RTS/CTS mechanism is used or there are legacy IEEE 802.11b devices, the network cannot attain even this data rate. Besides the link condition, the overhead of the MAC layer control headers also contribute to the decrease in MAC throughput. In [30], it is shown that using the current MAC layer, there is a theoretical throughput limit of 75 Mbps in IEEE 802.11 networks. Increasing the PHY layer data rate alone cannot solve the throughput problem; but the MAC layer must also be changed. IEEE 802.11e and IEEE 802.11n both introduce new mechanisms to increase the MAC layer throughput, they are far from providing ultimate solutions. Thus, additional MAC layer mechanisms are required to increase the throughput of IEEE 802.11 networks.

2.1.7.3. Security. Since the communication in WLAN is conducted over a shared medium, security is a major concern in wireless networks. Signals can be overheard by unauthorized people and critical information can be accessed with the usage of powerful receivers. The initial standard (WEP) provides some protection, but its weaknesses have been found and exploited [37]. Another security measure, WPA by WiFi alliance, provides significant improvement, but does not provide a final solution. More complex security measures are required for WLAN security without decreasing MAC throughput.

2.2. ETSI HiperLAN family

High PErformance Radio Local Area Network (HiperLAN) is a part of ETSIs BRAN project, targeting wireless local area access. The initial standard, HiperLAN/1, was developed in 1996 and supports data rates up to 20 Mbps. A second standard, HiperLAN/2, was developed in 2000 to support data rates up to 54 Mbps [38]. HiperLAN/2 aims competing with IEEE 802.11a. HiperLAN is developed with more detailed MAC layer mechanisms than IEEE 802.11, especially in QoS and mobility support.

While the initial HiperLAN standard was available earlier and offered higher data rates than the initial IEEE 802.11 standard, HiperLAN did not achieve a market success like its IEEE counterpart. Currently, no additional HiperLAN standards are reported to be under development. However, we have included HiperLAN in this survey for the sake of completeness.

2.2.1. Physical (PHY) layer

Both HiperLAN standards are designed to work at the 5 GHz frequency band (5.15–5.35 GHz and 5.47–5.725 GHz). Unlike IEEE 802.11, HiperLAN has a fixed channel bandwidth of 20 MHz. HiperLAN and IEEE 802.11a has similar number of non-overlapping channels. A HiperLAN network chooses its own channel using the DFS mechanism. DFS changes the operating frequency of the network if the current frequency is being used by another network (e.g., another WLAN).

The PHY layer of HiperLAN uses OFDM and has several modulation and coding values for different data rates (see Table 3). The range of a typical HiperLAN network is 30 m indoors and 150 m outdoors [39]. The antennas of a HiperLAN BS or STA can be either omnidirectional or sectorized.

2.2.2. Data link control (DLC) layer

There are two operating modes in HiperLAN; the centralized mode and the direct mode. The centralized mode is similar to the infrastructure mode of IEEE 802.11. In this mode, all traffic in the

Table 3
HiperLAN PHY layer modulation techniques

Data rate (Mbps)	Modulation	Coding rate	Coded bits/ subcarrier
6	BPSK	1/2	1
9	BPSK	3/4	1
12	QPSK	1/2	2
18	QPSK	3/4	2
27	16-QAM	9/16	4
36	16-QAM	3/4	4
54	64-QAM	3/4	6

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WLAN is transmitted through the AP. In the second mode, if both the source and destination for a given transmission is in the same WLAN, the traffic is directly sent from the source node to the destination node. Similar to the centralized mode, there is a *Central Controller* (*CC*) in the direct mode that is responsible for the management of all traffic in the WLAN.

DLC layer of HiperLAN employs a *Time Division Multiple Access* (*TDMA*) scheme. The traffic is strictly controlled by the AP/CC (e.g., the duration of the downlink and uplink phases). Each MAC frame is divided into five phases. The first phase is called the broadcast phase and contains broadcast messages in the network. The frame structure information, which contains the time information of the downlink and the uplink phases of the current frame, is also sent in this phase. The downlink and uplink phases contain messages originated from the AP/CC and from a WLAN node, respectively. If there is a connection that is specified to be a direct link connection, frames belonging to this connection are sent in the Direct Link Phase. Finally, association messages and resource allocation messages is transmitted in the Random Access Phase (Fig. 3).

In HiperLAN, each transmission belongs to a connection. When an STA needs to establish a connection, a request for a new connection is sent to the AP/CC. If the AP/CC accepts the new connection based on the current network load and the QoS constraints of the connection, it establishes the connection and reserves its resources accordingly. Otherwise, the connection request is denied. In the case of a rejected connection request, the STA can respecify and retransmit its request. QoS constraints for connections are set up during connection establishment. There is no MAC layer throughput limit in HiperLAN networks as is IEEE 802.11 networks, as analytically shown in [40].

Another major difference between IEEE 802.11 and HiperLAN is the HiperLAN's plane-based protocol stack. Two planes exist in the protocol stack of HiperLAN, one for user data and the other for control messages. All data packets are sent over the user plane, and the control packets (e.g., association, connection establishment) are sent over the control plane [38,41].

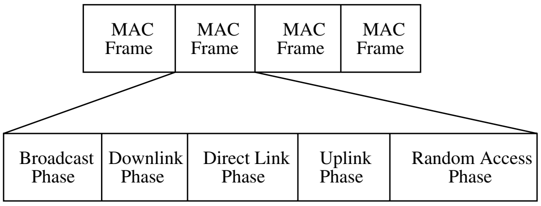

Fig. 3. HiperLAN frame format [38].

3. Wireless MAN

WMANs are designed to span whole cities with large numbers of LANs and WLANs. While WLANs provide indoor and hotspot coverage, they can 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 as shown in Fig. 4. 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.

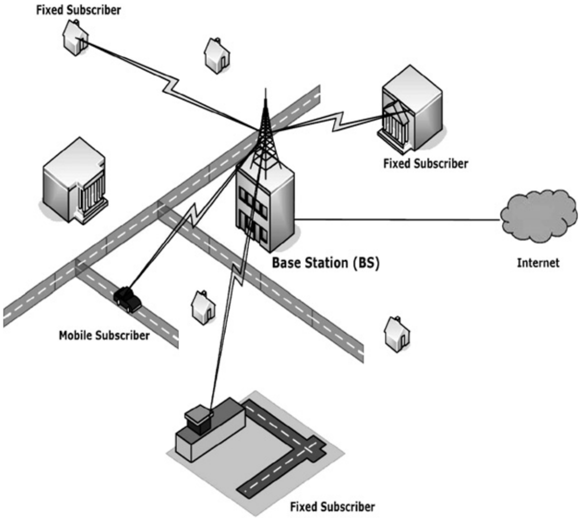

Fig. 4. WMAN point-to-multipoint configuration.

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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 [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 WiFi 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].

3.1. 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 [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 licenced 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 [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.[4] It also has mobility support for frequencies between 2 and 6 GHz.

As a connection-oriented protocol, all transmissions in a IEEE 802.16 network are associated with connections. The connections are unidirectional and they can be unicast, multicast, or broadcast.

3.1.1. 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

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[4] We will refer to IEEE 802.16-2004 and IEEE 802.16-2005 as IEEE 802.16 in this paper, as generally done in the literature.

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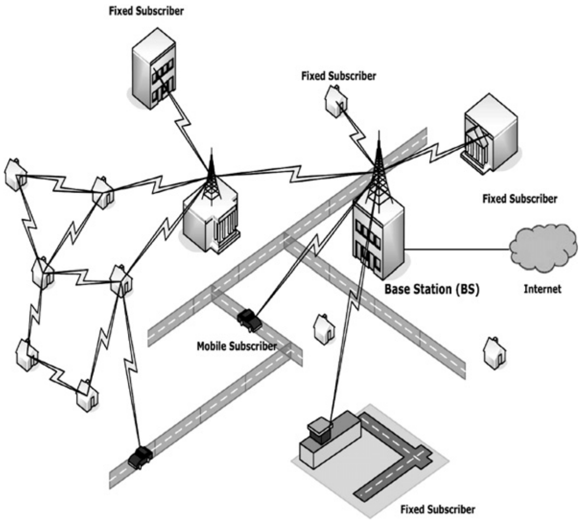

Fig. 5. 802.16 Mesh mode configuration [89].

based on single carrier technology and two additional PHYs based on the OFDM technology (see Table 4). Channel bandwidth can be 20, 25, and 28 MHz for WirelessMAN SC (see Table 5). 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 5 MHz-wide channel and 4.8–18.2 Mbps for a 6 MHz-wide channel [52]. In [53], Hoymann study 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], Ghosh et al. propose 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 [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].

Table 5
802.16 WirelessMAN-SC data rates (Mbps) [49]

Channel bandwidth (in MHz)	QPSK	16QAM	64QAM
20	32	64	96
25	40	80	120
28	44.8	89.6	134.4

Table 4
IEEE 802.16 PHY layer specifications [49]

Specification	Frequency band	Optional mechanisms	Description	Duplexing
WirelessMAN-SC	10–66 GHz		Main PHY specification of IEEE 802.16	TDD, FDD
WirelessMAN-SCa	<11 GHz	AAS, ARQ	Single carrier specification for NLOS transmission	TDD, FDD
WirelessMAN-OFDM	<11 GHz	AAS, ARQ, Mesh	OFDM support for NLOS transmission, also used in Mesh topology	TDD, FDD
WirelessMAN-OFDMA	<11 GHz	AAS, ARQ	OFDM support for NLOS transmissions	TDD, FDD
WirelessHUMAN	<11 GHz	AAS, ARQ, Mesh, DFS	Main PHY specification for mesh topology	TDD

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 a 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].

3.1.1.1. 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.

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3.1.1.2. Additional mechanisms in the PHY layer.

IEEE 802.16 has an optional support for *Adaptive Antenna Systems* (*AAS*s). 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.

3.1.2. 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. (Fig. 6).

In the CS, network layer segments are acquired from CS *Service Access Point* (*SAP*) and converted into MAC *Segment Data Units* (*SDU*s). 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.

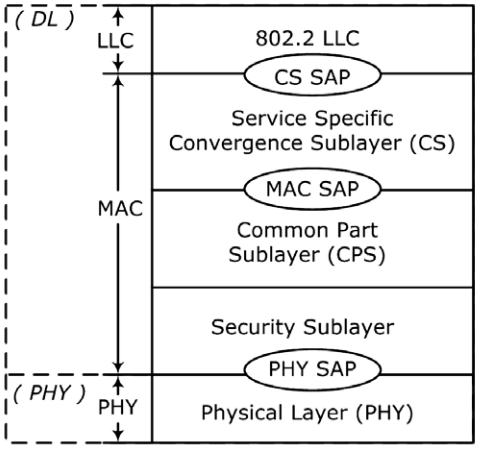

Fig. 6. Layers of IEEE 802.16.

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* (*SA*s). The BS assigns *SA Identifiers* (*SAID*s) 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. Johnston et al. state 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 (Table 6). ARQ can also be used with the packing, fragmentation, and PHS mechanisms.

3.1.2.1. MAC in mesh mode.

In the Mesh mode, there are two types of scheduling: centralized and

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Table 6
Usage of management connections

Message description	Management connection used
Ranging messages	BM
Downlink burst profile change messages	BM
SS basic capability messages	BM
AAS management messages	BM
ARQ Management Messages	BM
registration messages	PM
Dynamic service messages	PM
Multicast assignment messages	PM
Simple network management protocol (SNMP) messages	SM
Dynamic host configuration protocol (DHCP) messages	SM
Trivial file transfer protocol (TFTP) messages	SM

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 devices distributes the scheduling information of its one-hop neighbours 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.

3.1.3. 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.

3.1.3.1. 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 are specified in Table 6. In [56], Xhafa et al. study 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, 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.

3.1.3.2. 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

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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.

3.1.3.3. 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 vary between scheduling service classes (see Table 7).

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.

Table 7
Scheduling services of IEEE 802.16

	UGS	rtPS	nrtPS	BE	ertPS
Preferred traffic type	CBR	VBR	VBR	ABR	VoIP
Periodic polling allowed	–	+	+	–	+
Usage of PMB allowed	–	+	+	+	+
Usage of contention periods Allowed	–	–	+	+	–
Max. sustained traffic rate	+	+	+	+	+
Max. latency	+	+	–	–	+
Tolerated jitter	+	–	–	–	–
Request/transmission policy	+	+	+	+	+
Min. reserved traffic rate	+/–	+	+	–	+
Traffic priority	–	–	+	+	–

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

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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.

3.1.4. New and upcoming standards

3.1.4.1. 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. Leung et al. propose 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].

3.1.4.2. IEEE 802.16j. Recently, a new task group, *Mobile Multihop Relay* (*MMR*) also known as IEEE 802.16j, has been 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.

3.1.5. 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.

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3.1.5.1. QoS scheduler. QoS schedulers in both the BS and SS sides are left unstandardized 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], a SS scheduler 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 propose using *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.

3.1.5.2. 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* (*BER*s) 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.

3.1.5.3. 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 decreases the system throughput. In [81] and [82], the effect of contention window size is analyzed. Both work 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 bandwidth request messages collide, 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.

3.1.5.4. 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. Using this method, the delay of time-critical packets decrease significantly.

3.1.5.5. 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 can not 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.

3.2. ETSI HiperACCESS

High Performance Radio Access (*HiperACCESS*) was standardized by ETSI in 2002 to provide broadband wireless access for LOS SSs. HiperACCESS is a part of ETSIs BRAN project. It uses frequencies between 11 and 43.5 GHz [86–88] and targets *Small-to-Medium Size Enterprise* (*SME*) and residential customers in the urban areas. HiperACCESS also provides backbone support for other cellular networks such as GSM (Fig. 7). HiperACCESS has the following properties:

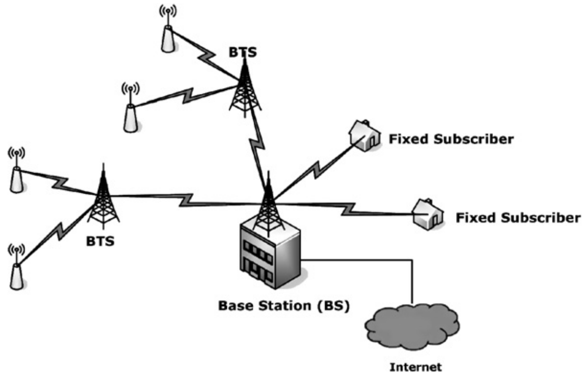

Fig. 7. HiperACCESS architecture serving both as a metropolitan area system and the backbone of a cellular network.

- HiperACCESS uses a PMP topology with the AP at the center and *Access Terminals* (*AT*s) as the end nodes.
- It is a connection-oriented protocol with detailed QoS mechanisms.
- It supports both FDD and TDD duplexing schemes (Half-FDD support is also available for cheaper ATs).
- A variety of PHY layer modulation schemes are available for different link conditions.
- It has CSs to support both packet-switched (e.g., IP, Ethernet) and cell-switched (e.g., ATM) technologies.

The differences between IEEE 802.16 and HiperACCESS are summarized in Table 8. HiperACCESS is similar to IEEE 802.16 unless noted below.

3.2.1. Physical (PHY) layer

PHY layer of HiperACCESS is based on OFDM with a channel bandwidth of 28 MHz for both downlink and uplink channels. The aggregate data rate of one HiperACCESS cell is 25–100 Mbps. Cell sizes are different for city and urban settings. A HiperACCESS cell has a radius up to 5 km [86].

Different modulation schemes in HiperACCESS are available for uplink and downlink connections. 4-state QAM modulation with no FEC and 2/3 FEC rate are available in both directions. Also, 16-state QAM with no FEC and 7/8 FEC rate can be used in both directions. 64-state QAM with no FEC and 5/6 FEC rate are available for only downlink. Burst profiles must be in decreasing robustness order, but unlike IEEE 802.16, there can only be four different burst profiles in a given frame. All frames have a fixed length of 1 ms in HiperACCESS [89].

Table 8
Comparison between HiperACCESS and 802.16

	IEEE 802.16	ETSI HiperACCESS
Operating mode	PMP, Mesh	PMP
Subscriber type	LOS, NLOS	LOS
Packet length	Fixed, Variable	Fixed
Operation frequency	2–66 GHz	11–43.5 GHz
Mobility support	Yes	No
PHY layer	SC, OFDM, OFDMA	OFDM
Channel bandwidth	Variable	28 MHz

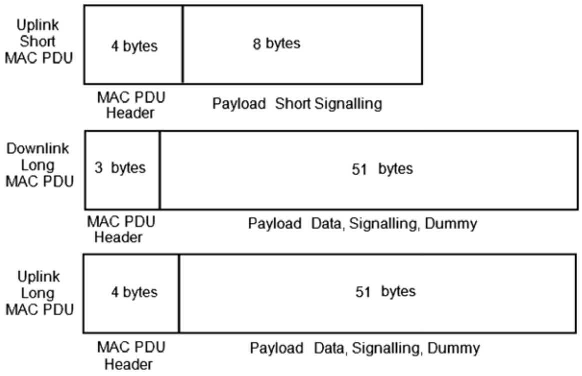

Fig. 8. HiperACCESS packet formats.

3.2.2. Data link control (DLC) layer

HiperACCESS MAC PDUs have fixed sizes and they are used to relay data and control messages. These MAC PDUs are 54-bytes long in downlink and 55-bytes long in uplink (Fig. 8). There is also a 12-byte control MAC PDU type used in ranging, bandwidth request messages, and queue status messages. These short messages can be used only in the uplink [89]. The ARQ mechanism is supported only for uplink transmissions and can be set up on connection basis. Similar to its IEEE counterpart, long packets from the CSs are split into multiple MAC PDUs.

In addition to the CIDs and MAC addresses of ATs, there are a few additional identifiers in HiperACCESS.

- *Terminal Identifier* (*TID*): After initialization, every AT is given a 10-bit TID, and henceforth the AP distinguishes ATs using these TIDs (e.g., grant allocation in UL-MAP). The AT MAC address is used only in initialization and authentication. Theoretically, 1024 ATs per carrier can be supported by one AP, but due to noise floor limitations the maximum number of AT available per carrier is 254.
- *Connection Aggregate Identifier* (*CAID*): In an AT, connections with the same QoS class can be aggregated using a 16-bit CAID by the AP during initialization. This identifier is used in bandwidth requests and queue status request messages. A connection can be moved from one CAID to another after initialization.

QoS classes are similar to IEEE 802.16 scheduling services. There are four QoS classes for different types of traffic:

PRT (*Periodic Real Time*). Similar to UGS scheduling service, PRT class is used for CBR data traffic.

RT (*Real Time*). This is the HiperACCESS QoS class counterpart of rtPS scheduling service. It is used for VBR real time traffic with bandwidth, delay, and jitter constraints.

NRT (*Non-Real Time*). This is the HiperACCESS QoS class counterpart of nrtPS scheduling service. It is used for non-real time traffic and has a minimum bandwidth constraint.

BE (*Best Effort*). Also similar to the BE scheduling service in IEEE 802.16, there are no QoS constraints for this class.

The resource requesting and granting mechanisms in HiperACCESS are similar to IEEE 802.16. The AP polls ATs by their TIDs. The requests are sent on connection aggregate basis and grants, are sent on TID basis. There is an additional resource allocation mechanism in HiperACCESS. The AP can ask the ATs to send their queue status regarding the ATs connection aggregate queues. The AP takes the queue status information from the ATs into consideration when generating the next UL-MAP.

3.3. ETSI HiperMAN

Published in 2003, *High Performance Radio Metropolitan Access Network* (*HiperMAN*) is another ETSI standard in the BRAN project, targeted for residential and *Small Office Home Office* (*SOHO*) users [89]. HiperMAN works at frequency bands under 11 GHz and serves mainly NLOS ATs as in IEEE 802.16a. One of the main advantages of HiperMAN is the ease of deployment like WLAN technologies. HiperMAN is developed using IEEE 802.16 and IEEE 802.16a as a baseline. Thus, the standard is very similar to IEEE 802.16 unless noted below.

3.3.1. Physical (PHY) layer

Though a variety of frequency bands are available for HiperMAN, it is optimized to work at 3.4–4.2 GHz frequency band. HiperMAN supports aggregate data rates up to 25 Mbps for each sector of an AP. Channel bandwidth is mainly multiples of 3.5 MHz but there are exceptions based on the available frequencies in different European countries (e.g., 20 MHz in United Kingdom). Similar to HiperACCESS, the PHY layer of HiperMAN is based on OFDM. The size of a HiperMAN cell

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varies from 2 to 15 km depending on the settings of the environment; 2–2.5 km for NLOS urban settings and 4 km for NLOS for rural settings. In the case of LOS operation, the range increases up to 15 km. While PMP is the main topology, the standard allows optional use of the Mesh topology as well.

HiperMAN allows various modulation schemes to be used by its PHY: BPSK with 1/2 FEC rate, QPSK with 1/2 and 3/4 FEC rates, 16-state QAM with 1/2 and 3/4 FEC rates, and optionally 64-state QAM with 2/3 and 3/4 FEC rates. The frame duration is chosen from a list of available frame durations ranging from 2.5 to 20 ms. There is also AAC support in HiperMAN [90].

3.3.2. Data link control (DLC) layer

Most of the features of the DLC layer are similar to IEEE 802.16. Optional ARQ support is also available on a connection basis. Channel information is sent via the DCD, UCD, DL-MAP, and UL-MAP messages. Three QoS service classes are available in HiperMAN [90]. These classes are the same with the classes defined in the DiffServ model.

EF (*Expedited Forwarding*). The EF class is used for time and jitter critical VBR traffic.

AF (*Assured Forwarding*). The AF class has more tolerance to fluctuations than EF class in delay and jitter parameters like nrtPS in IEEE 802.16.

BE (*Best Effort*). The BE class is similar to the service class with the same name in IEEE 802.16.

Since the main user profile is home and SOHO users, there is no CBR service class in HiperMAN [91].

3.4. WiBro (wireless broadband)

Another recently developed WMAN solution by TTA of Korea, WiBro, is designed to provide broadband wireless access to stationary and mobile *Personal SSs* (*PSS*s) (low to medium mobility users up to 60 kmph). Also known as Portable Internet Service, development of WiBro started in 2003 in South Korea. and finished its first phase in 2004. The second phase that enables WiBro's collaboration with IEEE 802.16e is also finished in 2005. WiBro Phase 1 products and services have already been started to appear in the mobile market in South Korea. Based on IEEE 802.16 and IEEE 802.16e Draft 3, WiBro includes all mandatory parts of IEEE 802.16 and some of its optional parts. The major advantage of WiBro is that it is designed with mobile users in mind, as opposed to IEEE 802.16.

Similar to IEEE 802.16e, WiBro operates at 2.3–2.4 GHz frequency band with a channel bandwidth of 9 MHz. Unlike IEEE 802.16, however, it only supports TDD scheme with a fixed frame length of 5 ms. Regarding the modulation and coding issues, WiBro uses a physical layer based on OFDMA with different modulation schemes (QPSK, 16-state QAM, and 64-state QAM) much like IEEE 802.16. A typical WiBro cell has a radius of 1 km, cell sectorization can be utilized to support large numbers of users. Aggregate data rate per sector is expected to be 18 Mbps for downlink and 6 Mbps for uplink; per user data rate is much lower (see Table 9) [92,93]. These aggregate data rates are increased in the second phase of WiBro to 50 Mbps for downlink.

There are few differences between IEEE 802.16 and WiBro regarding the MAC layer. The ARQ support, the PHS mechanism, packing, fragmentation and QoS service layers of IEEE 802.16 are also available for WiBro. Since WiBro targets mostly mobile users, CBR QoS service layer is not present in the standard, but the rest of the QoS service layers are available. Furthermore, a handover mechanism is included in the standard [92]. The system architecture of WiBro is similar to cellular technologies rather than IEEE 802.16. The BS is called *Radio Access Station* (*RAS*) in WiBro (Fig. 9).

WiBro is expected to be used in notebook computers as well as PDAs in South Korea. This product range may extend the use of WiBro into cellular telephone sector in the future. After the standardization of WiBro Phase 2, WiMAX forum and TTA declared that WiBro products will be interoperable with WiMAX devices.

3.5. HAP (High altitude platform)

HAP constitutes a new type of wireless access technology. Initially mentioned in [95], HAPs utilize quasi-stationary aerial platforms in the stratosphere at 17–22 km altitude as the base stations of the network [96]. The platform is a solar-panelled airship or airplane with a long mission flight duration.

Table 9
WiBro per user data rates

Throughput	Minimum	Maximum
Downlink	1 Mbps	3 Mbps
Uplink	128 Kbps	512 Kbps

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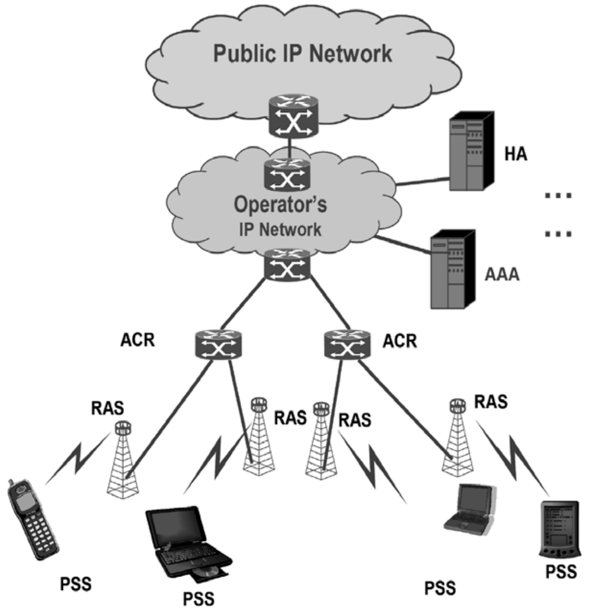

Fig. 9. WiBro system architecture [94].

HAPs merge several advantages of both terrestrial and satellite systems. Located at the stratosphere, the ETE delay of HAPs is comparable to terrestrial networks. Also, similar to satellite systems the platform has a LOS connectivity with most terrestrial user terminals in its coverage area. LOS connectivity enables the use of millimeter frequencies in HAPs. ITU has assigned frequency bands of 47–48 GHz to HAPs worldwide. Frequency band (28–31 GHz) is also assigned to HAPs in various countries [96,98,99]. The frequency band usage is summarized in Table 10. HAPs are designed not as an alternative to terrestrial and satellite systems but to be a complementary part of a terrestrial and/or satellite networks [100].

Table 10
Frequency band allocation of HAPs [99]

Frequency band	Link direction	Region
1885–1980 MHz	Uplink and downlink	1, 2, 3
2010–2025 MHz	Uplink and downlink	1, 3
2110–2160 MHz	Uplink and downlink	2
2110–2170 MHz	Uplink and downlink	1, 3
27.5–28.35 GHz	Downlink	40 countries worldwide
31.0–31.3 GHz	Uplink	40 countries worldwide
47.2–47.5 GHz	Uplink and Downlink	Global
47.9–48.2 GHz	Uplink and Downlink	Global

The most important advantage of a HAP network over a terrestrial network is the LOS connectivity of the platform with the users. As mentioned in IEEE 802.16, LOS connectivity cannot be attained in urban settings via terrestrial networks due to high-rise buildings. Thus, the use of NLOS connectivity, which in turn hinders the use of millimeter frequency bands, is a better option. Transmitting signals from the stratosphere, the radio channel is more clear than that in terrestrial networks. Similar to using sectorized antennas in terrestrial networks, HAPs utilize multiple transmitters to form cells for different areas to increase capacity.

HAPs also remedy some problems inherent in satellites. Due to lower development costs, launching and maintenance cost of HAPs are lower than satellite systems. Technologies used in satellites become partly obsolete at development due to long development phases. Simpler design of HAPs allow the use of cutting-edge technologies. Since airships and airplanes are able to land on earth, maintenance of HAPs are also less costly.

In the literature various scenarios are proposed for the deployment of HAPs [96,99,101]:

3.5.1. Broadband data network scenario

According to this scenario, terrestrial users are connected to the HAP that acts as the BS of a broadband wireless data network (Fig. 10). There are ground stations for every HAP which connects the HAP to the global network. Multiple HAPs can be deployed for better coverage and intra-HAP links enable communication between multiple HAPs. Thus, the backhaul connection is not used for a connection between two users served by different HAPs. For backup purposes and broadcast services, the HAPs can also be connected through satellites.

The *High Altitude Long Operation* (*HALO*) network is a pioneer work among the broadband wireless metropolitan area networks [97]. The key significance of HALO is that it is a practical system. The development of the HALO network started in 1997, and in 1998 the first HALO airplane flight was accomplished. HALO utilizes a piloted airplane at an altitude of 16 km as the HAP to cover an area of 7200 km^2. An aggregate data rate of 10 Gbps can be supported by each HAP and data rates up to 100 Gbps is planned. The system uses an ATM-based cellular architecture (Fig. 12). A HALO cell covers an area of several km^2. A typical footprint of an airplane consists of 125 cells, which utilizes

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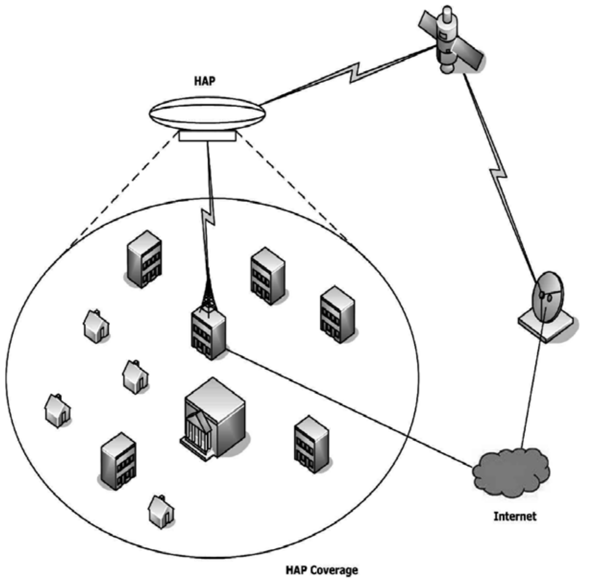

Fig. 10. HAPs data network.

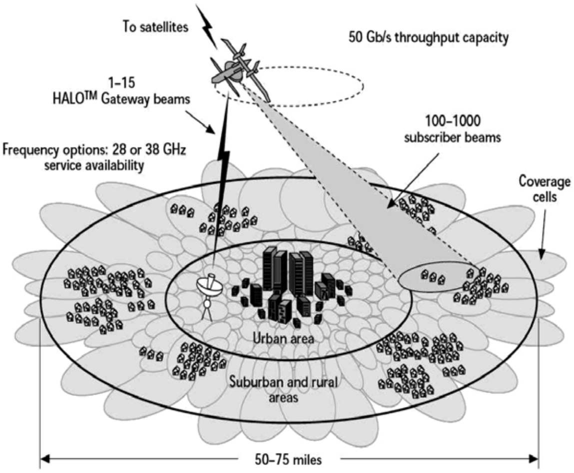

Fig. 12. HALO network system architecture [97].

frequency reuse mechanisms similar to cellular networks. Each HALO airplane can communicate with nearby HALO airplanes directly. Also, transmissions between HALO airplanes and satellites are supported. Broadband data and voice services can be supported by HALO network including various multimedia applications.

The CAPANINA project by the European Commission is another broadband data network that aims to serve fixed users as well as mobile users with speeds up to 300 kmph [98]. This HAP system is developed as a complementary system to terrestrial wireless and satellite systems. A CAPANINA HAP provides a data rate of 120 Mbps for an area of 60 km wide. In [100], the CAPANINA system is simulated using a modified version of the WirelessMAN OFDM PHY layer of IEEE 802.16, and the data rate specification of the network is met using 256-QAM modulation with 3/4 coding rate with a channel bandwidth of 28 MHz.

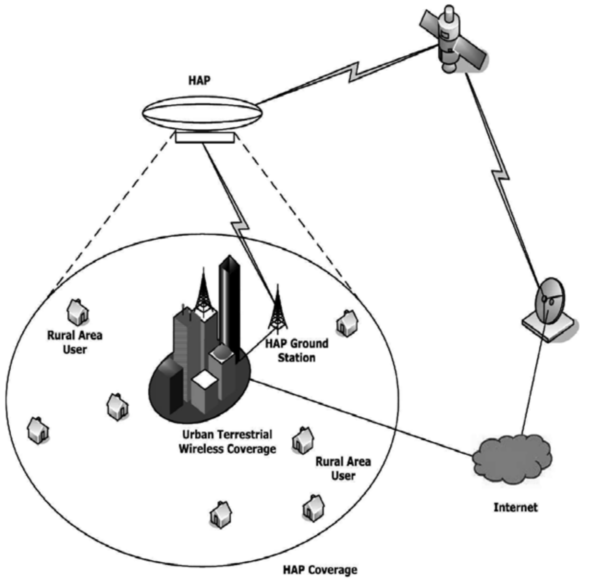

Fig. 11. HAPs rural data network.

3.5.2. Rural broadband data network scenario

Terrestrial networks need many BSs to cover sparsely populated rural areas. In this scenario, the terrestrial network serves the urban areas, but it relies on HAPs for suburban and rural area coverage where deploying fixed BSs is infeasible. Similar to the previous scenario, the HAP serves as the BS for terrestrial users, but it works as a complementary part of a the terrestrial wireless broadband network rather than being the only BS in the network (Fig. 11).

3.5.3. Communication network scenario

HAPs can also be used as the BS of communication networks. Utilizing SDMA, highly cellular networks can be formed under the coverage of one HAP. These cells can be used to form a cellular communication network. A backhaul link is also required between the HAP and the core network. Another scenario uses both terrestrial BSs and HAPs. In this scenario, the terrestrial BSs are the microcells, and the HAP cells act as macrocells of

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a two-tier cellular communication network [99]. The European network HeliNet is a good example of this kind of communication network scenario [102].

3.5.4. Satellite HAP network scenario

HAPs can also be used as a stepping stone for satellite networks. The path loss model in the satellite-HAP connection is quite different than the path loss model for the link between the HAP and the terrestrial stations. Placing a HAP between the user and the satellite, these two different environments can be served by two different systems, which in turn increase the overall performance of the system. In [101], this scenario is considered for *Interactive Digital Broadcast Systems* (*IDBS*s). Simulation results show that increased system performance is attained with the use of HAPs. The same scenario can also be applied to other satellite systems.

3.6. IEEE 802.22

A recently started work, IEEE 802.22 *Wireless Regional Area Network* (*WRAN*), targets rural and remote areas for fixed broadband access. It uses unoccupied TV channels in the 54–862 MHz range, depending on the region of operating. The standard is expected to be finalized in Q1 2008.

As a network that targets rural areas, the cell size of a typical WRAN BS is expected to be 20–40 km. The channel bandwidth is 6 MHz, and a BS is expected to support data rates up to 18 Mbps. The PHY layer modulation is adaptive and different modulation and coding techniques will be based on the location and the link state information of the subscribers [103].

4. Wireless WAN

Broadband WWAN access technologies mainly consist of satellite networks that cover the world completely or partially. While they can be used as separate data networks, they can also act as a backbone network for multiple WMANs in physically distant areas as well as less populated places not covered by WMANs. Different WMANs can communicate with each other via these backbone WWANs. Current satellite networks generally have broadcast capabilities. On the other hand, NGSSs are planned to have unicast and multicast capabilities as well.

A terrestrial WWAN technology, the IEEE 802.20, is also under development. This technology is similar to WMAN technologies but is expected to have wider coverage area and better mobility support.

4.1. IEEE 802.20

In the process of bringing mobility support to IEEE 802.16, some experts argued that it would be better to design a special standard for mobility support. Based on this idea, IEEE approved Task Group 20 to develop a standard based on mobile user support. So, IEEE 802.20, *Mobile Broadband Wireless Access* (*MBWA*) or *mobileFI,* was born in December 2002. Since the main concern of IEEE 802.20 is to provide mobility to vehicles with speeds up to 250 kmph, the bandwidth considered is much lower than IEEE 802.16 and IEEE 802.11. IEEE 802.20 targets a cell radius more than 15 km [104]. In order to utilize NLOS signaling, the standard amends working in licensed frequencies below 3.5 GHz and supporting both FDD and TDD duplexing. To avoid the latency problems, IEEE 802.20 does not include any connection establishment mechanism, unlike IEEE 802.16. The standard was first planned to be available by the end of 2004, but the current schedule of the working group aims the end of 2006. However, the activity of the working group was suspended for a few months in the third quarter of 2006. Thus, the standardization of IEEE 802.20 will not be completed until 2007 or 2008.

Based on providing broadband access to mobile users, IEEE 802.20 seems sharing the same goal with IEEE 802.16e. Because of sharing the same wireless market, some companies (notably Intel) claim that only one of the two technologies will achieve wide market availability. IEEE 802.16 is an older and more complete technology than IEEE 802.20. Furthermore, IEEE 802.16e is recently standardized whereas the standardization of IEEE 802.20 is expected to be 2007 or 2008. Therefore, this argument seems to hold value. However, market targets of these two technologies are far from each other since IEEE 802.16e can only give mobile support to vehicles with speeds up to 60 kmph, but IEEE 802.20 supports devices with speeds up to 250 kmph.

4.1.1. Physical (PHY) layer

At the moment IEEE 802.20 standard supports only one type of PHY layer with a channel bandwidth of 1.25 MHz or 5 MHz. The data rates for

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Table 11
Bandwidth parameters of IEEE 802.20

	1.25 MHz bandwidth	5 MHz bandwidth
Peak user data rate (Downlink)	>1 Mbps	>4 Mbps
Aggregate data rate (Downlink)	>4 Mbps	>16 Mbps
Peak user data rate (Uplink)	>0.3 Mbps	>1.2 Mbps
Aggregate data rate (Uplink)	>0.8 Mbps	>3.2 Mbps

different channel bandwidths are summarized in Table 11. The aggregate data rates for uplink and downlink severely limit the number of active users in a IEEE 802.20 cell. To overcome this problem channels with higher bandwidth (up to 40 MHz) are also considered. The standard will also include multi-antenna capability for BSs and MTs [105].

4.1.2. Medium access control (MAC) layer

To avoid lengthy connection establishment procedures and better manage mobility IEEE 802.20 will be a connectionless network. The group plans mechanisms to establish, monitor, and enforce the established QoS levels but these mechanisms are yet to be designed. Similar to the QoS mechanisms, handover mechanisms will also be developed [106].

4.2. Next generation satellite networks (NGSN)

Traditional satellite networks are generally used for one-way TV broadcast, military, and telephony applications. They consist of 1–3 *Geostationary Earth Orbit* (*GEO*) satellites, which are capable of only repeating a signal. The main advantages of using a satellite network are global coverage, high mobility support, and broadcast capabilities [107]. Utilizing these aspects satellite technology is a very good candidate for supporting ubiquitous Internet access. However, a satellite network is not feasible as an isolated system, mainly due to its high delay values. A satellite network can greatly increase the connectivity of a terrestrial network by complementing it in places where building infrastructure is either too costly or practically impossible [108].

The NGSN will also include new mechanisms like OBP, *Intersatellite Links* (*ISL*), and utilization of *non-GEO* (*NGEO*) satellites, *Low Earth Orbit* (*LEO*) and *Medium Earth Orbit* (*MEO*) satellites, to provide effective data and communication access. While each satellite system is system-wise unique, there are several guideline standards available for NGSNs (Table 12).

4.2.1. DVB

Designed to provide digital television and data services, ETSI developed the *Digital Video Broadcast* (*DVB*) standard in 1993. The standard supports a variety of applications such as TV broadcasting and Internet access. The initial standard of the project is *DVB-Satellite* (*DVB-S*). This standard supports data rates up to 45 Mbps using QPSK modulation in downlink using GEO satellites. An improved standard, DVB-S2, was published in 2003. DVB-S2 allows additional modulation techniques for higher throughput. 8-state QPSK, 16-state *Amplitude Phase Shift Keying* (*APSK*), and 32-state APSK can be used in DVB-S2. These new modulation techniques and additional mechanisms introduced in DVB-S2 improve the throughput in the original standard by 30% (up to 60 Mbps) [109]. Satellite links are used for only downlink transmission DVB-S and DVB-S2.

4.2.2. DVB-return channel satellite (DVB-RCS)

In order to allow DVB uplink transmission via satellites, a return channel standard, DVB-RCS,

Table 12
Current NGEO satellite systems [112]

System	Organization	Constellation type	# of Satellites	Altitude (km)	Min. elevation angle	OBP	Coverage (%)	ISL
NeLS	Japan NiCT	LEO	120	1200	20	Yes	79	Yes
Iridium	Motorola	LEO	66	780	8.2	Yes	100	Yes
Skybridge	Alcatel	LEO	80	1469	10	No	86	No
Celestri	Motorola	LEO	63	1400	16	Yes	73	Yes
Spaceway	Hughes	GEO & MEO	16 GEO, 20 MEO	35.786, 10.352	20	No	86	Yes
Quasi-GEO	–	Quasi-GEO	Varies	35.786	40	Varies	96	Yes
Globalstar	Global Star Co.	LEO	48	1406	10	Yes	83	Yes

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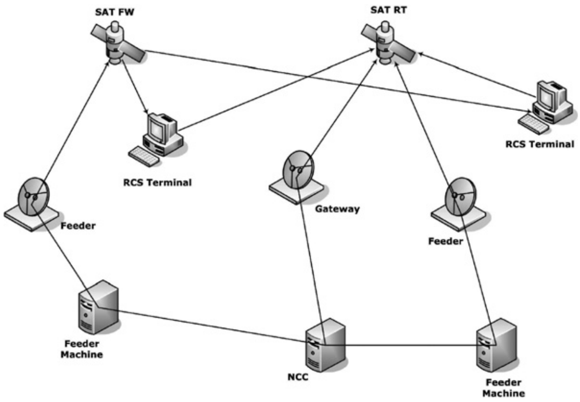

Fig. 13. DVB-RCS architecture.

was introduced in 2004. Using DVB-RCS, data rates up to 2 Mbps can be attained using QPSK modulation. DVB-RCS can be used with any forward channel technique defined in DVB-S and DVB-S2. In DVB-RCS, another satellite, responsible for handling return channels, is introduced to the network (Fig. 13). The two satellites in the DVB-RCS architecture can also be merged into one satellite with multiple transmitters. In this scenario, the uplink information is forwarded to the *Network Central Controller* (*NCC*) and necessary changes are made in the broadcast channel. With the introduction of DVB-RCS, Internet services can be supported with DVB without using any other non-satellite technology [110].

In DVB-RCS, the RCS terminals access the return channel using a *Multi Frequency* (*MF*) TDMA scheme. Each user is given a time slot in one of the frequencies of the return channel. The provisioning of these time slots and frequencies is managed by the NCC. This provisioning can be either fixed or dynamic. In the fixed allocation mode, the time slot and frequency allocated by the NCC does not change during the connection. On the other hand, in the case of dynamic allocation mode, the RCS terminal may request alterations in bandwidth allocation. Requests can be sent during both contention or non-contention periods [111]. Unlike DVB-S standards, DVB-RCS uses IP over ATM instead of IP over MPEG for data transmission.

4.2.3. Problems and open issues

Due to the differences between satellite and terrestrial wireless networks, there are several problems exclusive to satellite networks such as choosing appropriate multiple access technique to satellite channels, dynamic routing in NGEO satellites, and the behaviour of transport layer of TCP/IP to satellite networks.

4.2.3.1. Multiple access techniques. One of the main problems regarding the design of a satellite system is the choice of multiple access technique. Current multiple access techniques can be categorized in three groups: *Fixed Assignment Multiple Access* (*FAMA*), *Random Assignment Random Access* (*RAMA*), and *Dynamic Assignment Multiple Access* (*DAMA*). FAMA techniques consist of FDMA, TDMA, and *Code Division Multiple Access* (*CDMA*). While these methods provide optimized solutions for fixed traffic patterns, they do not perform very well in the bursty traffic of Internet. The second category consists of random access techniques in which all the users contend to access the medium. This contention results in long delays for some users and causes unfair resource allocation among the users. The last category, DAMA, usually offers better medium usage due to of its dynamic nature, though the transmission of resource requests are sent in contention periods. There are many variations of RAMA and DAMA, but each one is appropriate for a different type of application. Thus, currently there is no ultimate multiple access scheme appropriate for satellite networks. The selection of the multiple access technique that will be used depends on the applications that will be supported by the satellite system.

4.2.3.2. Dynamic routing. The physical location of a NGEO satellite with respect to the earth change with time. Thus, a terrestrial fixed user may be served by different satellites during a connection. Since the entire topology is changing, classical routing algorithms provide infeasible results. In order to solve this problem, several different routing algorithms are proposed. There are two main routing algorithm approaches regarding NGEO satellite systems: *Dynamic Virtual Topology Routing* (*DVTR*) and *Virtual Node* (*VN*) [107,108].

In the DVTR approach, the system divides the total time period of the constellation into time slots during which the same satellite illuminates a given region on earth. Since the movement of the satellites is known a priori, classical routing algorithms can be run for different time slots. This routing information can be loaded on the satellites before launch. Satellites switch between different routing table at the beginning of each time slot. Although this

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Table 13
Comparison between wireless access technologies

Standard name	Access type	Status	Data rate (aggregate per cell)	Cell radius	User type allowed	Handover capability	Frequency band
IEEE 802.11g/WiFi	WLAN	Available	54 Mbps	50–60 m	Fixed (LOS and NLOS), Nomadic	No	2.4 GHz
IEEE 802.11n/WiFi	WLAN	Expected 2007	540 Mbps	50–60 m	Fixed (LOS and NLOS), Nomadic	No	2.4 GHz
ETSI HiperLAN/2	WLAN	Available	54 Mbps	50–60 m	Fixed (LOS and NLOS), Nomadic	No	5 GHz
IEEE 802.16/WiMAX	WMAN	Available	36–135 Mbps for LOS, 75 Mbps for NLOS	Up to 70–80 km	Fixed (LOS and NLOS)	No	2–66 GHz
IEEE 802.16e/WiMAX	WMAN	Available	30 Mbps	Up to 70–80 km	Fixed (LOS and NLOS), Nomadic, mobile	Yes	2–6 GHz
ETSI HiperACCESS	WMAN	Available	25–100 Mbps	1.8–2.5 km	Fixed (LOS)	No	11–43.5 GHz
ETSI HiperMAN	WMAN	Available	25 Mbps	2–4 km	Fixed (LOS and NLOS)	No	<11 GHz
WiBro	WMAN	Available	18 Mbps	1 km	Fixed (LOS and NLOS), Nomadic, mobile	Yes	2.3–2.4 GHz
HAP	WMAN–WWAN	Available	Varies	Varies	Varies	Varies	28–31 GHz and 42–43 GHz
IEEE 802.20	WWAN	Expected 2007–2008	16 Mbps	>15 km	Fixed (LOS and NLOS), Nomadic, mobile, highly mobile	Yes	3.5 GHz
IEEE 802.22	WMAN–WWAN	Expected 2008	18 Mbps	40 km	Fixed (LOS and NLOS)	No	54-862 MHz
Satellite (GEO)	WWAN	Available	Up to a few Gbps	Four satellite gives global coverage	Fixed (LOS), Nomadic, mobile	Varies	4–8 GHz (C Band), 10–18 GHz (Ku Band), 18–31 GHz (Ka Band), 37–50 GHz (Q/V Band)
Satellite (MEO)	WWAN	Available	Up to a few Mbps	11 satellite gives global coverage	Fixed (LOS), Nomadic, mobile	Varies	Same as GSO satellites
Satellite (LEO)	WWAN	Available	Up to a few Mbps	Varies	Fixed (LOS), Nomadic, mobile	Varies	Same as GSO satellites

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method performs well under static traffic, it cannot adapt to the variations in the traffic load.

The VN approach constructs a fixed virtual topology using VNs and runs classical routing algorithms on this virtual topology. The algorithm is implemented based on the VNs and each satellite assumes the role of one VN at any time. When a satellite moves to an arc on its planar orbit that corresponds to another VN, it assumes the role of that VN.

4.2.3.3. Satellite transport layer. TCP was designed with wireline networks in mind. Thus, TCP assumes that the problems occur as a result of the congestion in the network. This assumption is not valid for wireless terrestrial and satellite networks. The long ETE delays in GEO satellites and high jitter values in dynamically routed LEO satellites are incorrectly interpreted as congestion by TCP. Thus, the source decreases its window size, which in turn causes underutilization of the satellite link. In the literature, there are a number of solutions developed to overcome this problem. These solutions, including *Performance Enhancing Proxies* (*PEP*) and TCP enhancements are summarized in [107] and [108].

5. Comparison and conclusion

The technical specifications of the standards presented in this survey are summarized in Table 13. These networks can be classified according to the size of their coverage areas. While WLAN supports connectivity in 50–60 m radius, WMAN provides connectivity with radius ranging between 1 and 4 km. IEEE 802.22 supports higher ranges, targeting to fill the gap between WMANs and WWANs. IEEE 802.20 cell radius is expected to be greater than 15 km, but no upper bound on the cell radius is specified. The coverage area of a satellite system varies, greatly depending on the configuration. Satellite systems have the capability to provide global coverage outdoors, but they fail in indoors coverage. The whole globe can be covered with four GEO satellites, while it takes dozens of LEO and MEO satellites for the same coverage.

From Table 13, one can observe that the aggregate data rate tends to drop as the cell size increases. This inverse proportion is expected since the signal quality is adversely affected by the distance. Tough current WLANs provide data rates up to 54 Mbps, this value is expected to increase at least tenfold with the emerging IEEE 802.11n standard. WMANs provide data rates lower than WLANs, up to 135 Mbps in the case of only LOS users. On the other hand, 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, 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 than WMANs. Also, WMANs with mobility support and NLOS connectivity use low frequencies. LOS connectivity between the user and the central station is available, higher frequencies are used.

Wireless access technologies can be categorized by their coverage areas. For home and office environments, WLANs provide internet connectivity using HiperLAN and IEEE 802.11 standards. Multiple WLANs can be covered and intra-WLAN communication can be attained via WMANs. IEEE 802.16 is an important emerging WMAN technology. ETSI HiperACCESS, ETSI HiperMAN, WiBro, and HAP also provide broadband access in metropolitan areas. HAPs and IEEE 802.22 technologies extend the city wide coverage to rural areas. Together with satellite technology, IEEE 802.22 provides intra-city connectivity for global coverage.

In this paper, we presented the emerging standards in broadband wireless data networks. These upcoming standards improve Internet connectivity significantly by providing BWA for different areas and user profiles. Integration of these technologies will enable a ubiquitous data access as in voice communication networks. While some standards enhance older ones, others introduce new wireless access concepts. IEEE 802.11n improves the data rate of WiFi ten folds to make it an alternative for wireline technologies in the local area. While WiMAX and HAP systems provide broadband wireless data access throughout cities, MBWA enables access for highly mobile users. IEEE 802.22 and Satellite networks allow data network connectivity to rural users.

Abbreviations

Abbreviations	open form
AAS	adaptive antenna system
AC	access category
ACK	acknowledgement
ACQPS	active QoSParamSet
AF	assured forwarding
AP	access point

APSK	amplitude phase shift keying
AQPS	AdmittedQoSParamSet
ARQ	automatic response request
AT	access terminal
BE	best effort
BER	bit error rate
BM	basic management
BPSK	binary phase shift keying
BRAN	broadband radio access network
BS	base station
BWA	broadband wireless access
CAID	connection aggregate identifier
CBR	constant bit rate
CC	central controller
CDMA	code division multiple access
CID	connection identifier
CPS	common part sublayer
CRC	cyclic redundancy check
CS	convergence sublayer
CSMA/CA	collision sense multiple access/collision avoidance
CST	clear to send
DAMA	dynamic assignment multiple access
DCD	downlink channel description
DCF	distributed control function
DFS	dynamic frequency selection
DIUC	downlink interval usage code
DLC	data link control
DLP	direct link protocol
DRR	deficit round robin
DSSS	direct sequence spread spectrum
DVB	digital video broadcast
DVB-RCS	DVB-return channel satellite
DVB-S	DVB-satellite
DVTR	dynamic virtual topology routing
EDCA	enhanced distributed channel access
EDCF	enhanced distributed coordination function
EDF	earliest deadline first
EF	expedited forwarding
ertPS	extended real time polling service
ETE	end to end
FAMA	fixed assignment multiple access
FDD	frequency division multiplexing
FEC	forward error correction
FHSS	frequency hopping spread spectrum
GEO	geostationary earth orbit
HALO	high altitude long operation
HAP	high altitude platform
HCF	HCF controlled channel access
HiperACCESS	high performance radio access
HiperLAN	high performance radio local area network
HiperMAN	high performance radio metropolitan area network
HR-DSSS	high rate DSSS
IDBS	interactive digital broadcast system
IFS	inter-frame space
IR	infrared
ISL	intersatellite link
ITS	intelligent transportation system
LEO	low earth orbit
LMDS	local multipoint distribution system
LOS	line of sight
MBS	mesh base station
MBWA	mobile broadband wireless access
MEO	medium earth orbit
MF	multi frequency
MIMO	multiple input multiple output
MITMOT	mac and mimo technologies for more throughput
MMDS	multichannel multipoint distribution system
MS	mobile subscriber
MSS	mesh subscriber station
NCC	network central controller
NGEO	non GEO
NGSS	next generation satellite system
NLOS	non LOS
NRT	non-real time
nrtPS	non-real time polling service
OBP	onboard processing
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
P2P	point to point
PCF	point control function
PDU	packet data unit
PEP	performance enhancing proxies
PHS	payload header suppression
PKM	privacy key management
PM	primary management
PMB	poll me bit
PMP	point to multipoint
PQPS	ProvisioneQoSParamSet
PRT	periodic real time
PSS	personal SS
QAM	quadrature amplitude modulation
QAP	QoS enhanced AP
QoS	quality of service
QPSK	quadrature phase shift keying
QSTA	QoS enhanced STA
RAMA	random assignment multiple access
RAS	radio access station
RS	relay station
rtPS	real time polling service

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RT	real time
RTS	request to send
SA	security association
SAID	security association identifier
SAP	service access point
SDMA	space division multiple access
SDU	segment data unit
SEEMesh	simple, efficient, and extensible mesh
SF	service flow
SFID	SF identifier
SM	secondary management
SME	small to medium sized enterprise
SNR	signal to noise ratio
SOHO	small office home office
SS	subscriber station
STA	station
TC	traffic class
TID	terminal identifier
TDD	time division duplexing
TDMA	time division multiple access
TGnSync	task group N synchronization
TO	transmission opportunity
TPC	transmit power control
TTA	telecommunications technology association
UCD	uplink channel description
UGS	unsolicited grant service
UIUC	uplink interval usage code
VBR	variable bit rate
VN	virtual node
VoIP	voice over IP
WAVE	wireless access for vehicular environments
WEP	wired equivalent privacy
WFQ	weighted fair queuing
WiBro	wireless broadband
WiFi	wireless fidelity
WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network
WMAN	wireless metropolitan area network
WPA	WiFi protected access
WPS	wireless packet scheduling
WRAN	wireless regional area network
WRR	weighted round robin
WWAN	wireless wide area network
WWise	worldwide spectrum efficiency

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