Chapter 2
MAC Protocols for High Data-Rate Wireless Networks

The ever-growing demand for multimedia services anywhere, anytime has fostered the development of high data-rate wireless networks, and various standards have emerged. In this chapter, we briefly introduce three categories of wireless networks, the wireless local area networks (WLANs), wireless personal area networks (WPANs), and wireless body area networks (WBANs). Their coverage scales down from over a building to a house/home and finally to a body. Their resource management and MAC protocols have distinct features due to different data rates, capacity, radio ranges, and application scenarios. The enabling physical-layer radio frequency (RF) transmission technologies, MAC schemes, and standardizations of the three kinds of networks are summarized, with the objective to provide readers with a preliminary understanding of the design philosophies and implementation requirements.

2.1 Wireless Local Area Networks

(1) Overview of IEEE 802.11 WLANs

IEEE 802.11 is a set of PHY and MAC specifications to implement WLANs among terminals, with or without APs that are connected to wide area networks. The radio communications in the 2.4, 5, and 60 GHz frequency bands are utilized in the physical layer and a set of MAC protocols are defined for channel access and resource management. The IEEE Local and Metropolitan Area Networks (LAN/MAN) Standards Committee (IEEE 802) is responsible for creating and maintaining the PHY and MAC specifications.

The US Federal Communications Commission (FCC) opened the 2.4–2.5 GHz spectrum for individual non-licensed usage in the late 1980s. IEEE, the world's largest technical professional organization, recognized the need for a standard that

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fulfilled the demand for wireless communications and networking infrastructures. Work began on creating such a standard in September 1990, and the first approved and adopted version of IEEE 802.11 was released in June 1997. When the work to develop IEEE 802.11 started, the goal was to develop inter-operable wireless products reaching a data rate of over 1 Mbps. Then the working group has made a series of 802.11 enhancements, such as the IEEE 802.11e for QoS support, 802.11ac for data rate as high as 1 Gbps, and IEEE P802.11ax for dense deployments (e.g., those in stadiums and shopping malls).

Due to the low-cost chipsets and the convenient setup, IEEE 802.11 has been widely deployed and it impacts our daily lives and industry. Nowadays, consumer electronics and portable devices such as laptops, tablets, TV sets, and smart phones are typically equipped with an IEEE 802.11 radio, often branded as "WiFi". The IEEE 802.11 technologies have been globally popular in providing wireless access to the Internet from offices, homes, airports, hotels, restaurants, trains, and aircraft.

IEEE celebrated the 25th anniversary of IEEE 802.11, which has become the standard for the world's premier WLAN products, on September 10th, 2015. The evolution of the IEEE 802.11 family has promoted technology improvement and enabled a wide range of applications. Today the IEEE 802.11 Wireless LAN Working Group continues to evolve the standard to support new applications such as smart grid and Internet of Things (IoT).

(2) Evolution of IEEE 802.11 Standards

The 802.11 family includes a series of half-duplex communication techniques based on the same basic protocol specified in the first IEEE 802.11 standard which was published in 1997 and clarified in 1999. The great success in the market and the perceived capacity limits of the basic 802.11 standard have driven a prolific technology improvements and extensions. The revisions are denoted by an alphabet set of amendments. The first widely accepted one was 802.11b that appeared in 2000 and was followed by the major standards of 802.11a, 802.11g, 802.11n, and 802.11ac. The other specifications in the family, using the alphabets such as from c to f, h, and j, are corrections to the previous standards or service extensions and amendments.

After the release of 802.11-1997, a lot of feedbacks have been received by the IEEE 802 working group that the compatibility among the products from different vendors was not supported well. For example, the default encryption scheme, called wired equivalent privacy (WEP), could not work among different products. Thus, a certification program to ensure the compatibility and inter-operability among the commercial products is needed. In order to solve the issue of compatibility among different vendors, the wireless ethernet compatibility alliance (WECA) was founded in 1999 and renamed as the WiFi alliance (WFA) in 2003. The WFA was formed as a trade association and the products certified by WFA hold the WiFi trademark. Nowadays almost every wireless product using the IEEE 802.11 air interface has the WiFi certification and is labeled by the brand.

The history of the evolution of IEEE 802.11 specifications and the amendments in progress are listed in Tables 2.1 and 2.2, respectively. The key standards and amendments are summarized as follows.

1. 802.11-1997 (Initial 802.11 Standard) [65]
   The first version, IEEE 802.11-1997 (802.11 legacy), specifies three solutions in the PHY layer: frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), and infrared PHY schemes. The first two schemes use the S-band radio frequency (RF) transmission, operating in 2.400–2.500 GHz (referred to as the 2.4 GHz band) which belongs to the industrial scientific medical (ISM) frequency band under the FCC Part 15 Rules and Regulations [3]. The last one uses the infrared band at 316–353 THz. It is defined in the standard that all the three PHYs provide a basic data rate of 1 Mbps and an optional 2 Mbps mode. However, the commercial products of the infrared PHY scheme in 802.11-1997 actually do not exist in the market.

   The spectrum is sub-divided into 14 channels and each channel spans 5 MHz. The center frequency of the first channel is 2.412 GHz. In addition, a spectral mask is specified in 802.11 and it regulates the power distribution allowed over the channels. According to the mask, the signals are required to be attenuated by a minimum of 20 dB compared with the peak amplitude of the power spectrum of a channel when the frequency is ± 11 MHz away from the center of the band. Hence the bandwidth of the signal over the 802.11 air interface is effectively 22 MHz. As a result, the center frequencies of stations of two geographically overlapped 802.11 WLANs must be separated by at least four channels. In other words, for multiple WLANs to operate at the same location, the stations should use every fourth or fifth channel to avoid signal frequency overlapping.
2. 802.11a (OFDM Scheme in 5 GHz Band) [73]
   The PHY layer based on the orthogonal frequency-division multiplexing (OFDM) signaling method was originally described in the 1999 specification, but was later defined in the 2012 specification which used the 4.915–5.825 GHz (referred to as the 5 GHz band). By following the original standard (802.11 legacy), 802.11a adopts the same MAC protocol and frame format. However, 802.11a specifies transmission and reception at the data rates from 1.5 to 54 Mbps (the rate is higher if the error correction code is counted), which yields effective throughput up to 20–30 Mbps. The vendors began to ship 802.11a products in 2001 due to the development of the commercial radio devices working at the 5 GHz band. Nowadays the term "802.11a" is used by most WiFi products (interface cards and routers) to indicate inter-operability at the 5.8 GHz band with 54 Mbps data rate.

   The advantage of using the 5 GHz band is that there may be less interference because fewer other systems may operate in this band. However, this higher carrier frequency brings a disadvantage: signals are absorbed more severely by the solid objects such as walls in their propagation due to the smaller wavelength compared with 802.11b/g in 2.4 GHz. Consequently, 802.11a can only penetrate over shorter distance and provide a smaller effective coverage range.

Table 2.1 The IEEE 802.11 standard and its amendments

Number	Approval date	Title	Comment
802.11-1997	1997/6/26	IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	Initial standard. 1 and 2 Mbps, 2.4 GHz RF and infrared (IR) standard
802.11-1999	1999/3/18	Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	Superseded by ISO/IEC 8802.11-1999
ISO/IEC 8802.11-1999	2003	IEEE Std 802.11-1999 (R2003)	International standard
802.11a	1999/9/16	High Speed Physical Layer in the 5 GHz band	54 Mbps OFDM PHY @ 5 GHz
802.11b	1999/9/16	Higher Speed PHY Extension in the 2.4 GHz Band	11 Mbps DSSS PHY @ 2.4 GHz
802.11b-cor1	2001/10/10	Corrigenda to IEEE 802.11b-1999	Clarify Amendment 2
802.11c	2001	Media Access Control (MAC) Bridges	Bridging in wireless bridges or access points, included in IEEE 802.1D standard
802.11d	2001/7/13	Operation in Additional Regulatory Domains	Allow devices to comply with regional requirements
802.11e	2005/9/22	MAC Enhancements	Support for QoS
802.11f	2003/8/4	Inter-Access Point Protocol Across Distribution Systems Supporting IEEE 802.11 Operation	Released as 802.11.1 and withdrawn by IEEE-SA Standards Board on 2006/2/3
802.11g	2003/6/12	Further Higher Data Rate Extension in the 2.4 GHz Band	54 Mbps OFDM PHY @ 2.4 GHz
802.11h	2003/10/10	Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe	In Europe, 5 GHz devices must implement 802.11h
802.11i	2004/6/24	MAC Security Enhancements	MAC security enhancements, known as WPA and WPA2 from WiFi Alliance
802.11j	2004/9/23	4.9 GHz to 5 GHz Operation in Japan	Compliance with Japanese 5 GHz spectrum regulation
802.11k	2008/6/12	Radio Resource Measurement of Wireless LANs	Discover the best available access point
802.11ma	2007/3/8	802.11 Standard Maintenance Revision	Prepared for 802.11-2007 that supersedes 802.11-1999

(continued)

Table 2.1 (continued)

Number	Approval date	Title	Comment
802.11mb	2011/3/31	802.11 Accumulated Maintenance Changes	Second maintenance, prepared for 802.11-2012
802.11n	2009/10/29	Enhancements for Higher Throughput	Increase the maximum net data rate to 600 Mbps using MIMO, frame aggregation, etc. @ 2.4 and 5 GHz
802.11p	2010/7/15	Wireless Access for the Vehicular Environment	Car to car communication, closely related to IEEE 1609
802.11r	2008/7/15	Fast Basic Service Set (BSS) Transition	Permit continuous connectivity handoffs in a seamless manner
802.11s	2010/9/30	Mesh Networking	Transparent multi-hop operation
802.11t	2009/12/31	Recommended Practice for the Evaluation of 802.11 Wireless Performance	Develop 802.11.2, administratively withdrawn by IEEE-SA on 2006/2/3
802.11u	2011/2/25	Interworking with External Networks	Convergence of 802.11 and GSM
802.11v	2011/2/9	Wireless Network Management	Allow client devices to exchange information about network topology
802.11w	2009/9/30	Protected Management Frames	Increase the security of management frames
802.11y	2008/11/6	3650–3700 MHz Operation in USA	High powered equipment to operate using the 802.11a protocol on a co-primary basis
802.11z	2010/10/14	Extensions to Direct Link Setup (DLS)	AP independent DLS
802.11-2012	2012/3/29	New Release	Include Amendments k, n, p, r, s, u, v, w, y, and z
802.11aa	2012/5/29	Video Transport Streams	MAC enhancements for robust audio and video streaming
802.11ac	2013/12/11	Very High Throughput <6 GHz	Enhancements for >1 Gbps throughput below 6 GHz
802.11ad	2012	Very High Throughput 60 GHz	Enhancements for >1 Gbps throughput @ 60 GHz band
802.11ae	2012/4/6	Prioritization of Management Frames	Communicate management frame prioritization policy
802.11af	2013/11/11	TV White Spaces	Geolocation-based spectrum databases and channel sensing

Table 2.2 The IEEE 802.11 amendments in progress

Number	Approval date	Title	Comment
802.11mc	2016	Standard Maintenance	Roll-up of 802.11-2012 with the aa, ac, ad, ae & af amendments, prepared for 802.11-2016
802.11ah	2016	Sub 1 GHz band, Machine-to-Machine communications	Enhanced power saving mechanisms and efficient small data transmissions
802.11ai	2016/9	Fast Initial Link Setup	Reduce link setup time to below 100 ms
802.11aj	2016/6	China Millimeter Wave	Very high throughput WLAN using mmWave MI MO @ 45 GHz
802.11ak	2016/5	General Links	Support IEEE 802.11 links for transit use in bridged networks
802.11aq	2016/7	Pre-association Discovery	Further discover the services running on a device or provided by a network
802.11ax	2019	High Efficiency WLANs	Dynamic channel bonding, multi-user uplink MIMO, and full-duplex wireless channel
802.11ay	TBD	Enhancements for Ultra High Throughput in and around the 60 GHz Band	Extension of 802.11ad to extend throughput, range, and use-cases by channel bonding, MIMO and higher modulation schemes
802.11az	TBD	Enhancements for Positioning	Enables determination of absolute and relative position with better accuracy

3. 802.11b (DSSS Scheme in 2.4 GHz Band) [74]
   The 802.11b standard directly extended the modulation technique of the initial 802.11 in the PHY and employs the same media access method in the link layer. 802.11b adopts DSSS modulation and a channel has the bandwidth of 22 MHz, resulting in three "non-overlapping" channels (channel indexes of 1, 6, and 11). Compared with the 802.11-1997 which provides the mandatory data rate of only 1 Mbps, the maximum raw data rate in 802.11b is 11 Mbps. Due to the significant throughput increase and price reduction, 802.11b received rapid acceptance and became popular when it was released in 2000.

Meanwhile, other products operating in the 2.4 GHz ISM band, such as microwave ovens, cordless telephones, baby monitors, Bluetooth, ZigBee, and some amateur radio equipments, cause severe interference to 802.11b devices. In order to control the susceptibility, the DSSS scheme is adopted in the physical layer to mitigate the interference.

4. 802.11g (OFDM Scheme in 2.4 GHz Band) [75]
   The 802.11g standard was ratified in June 2003 and it specifies the third modulation standard, i.e., the same OFDM-based scheme as 802.11a, but works in the 2.4 GHz band (same as 802.11b) with the channel bandwidth of 20 MHz. In the physical layer, besides the forward error correction codes, a maximum bit rate of 54 Mbps can be provided. Working in the same frequency band, the hardware of 802.11g is fully backward compatible with that of 802.11b. However, due to this legacy issue, the throughput of 802.11g is reduced by 21 % compared to 802.11a. In addition, when an 802.11g network and an 802.11b network co-exist, the data rate of the former will be reduced due to the activities of the latter. Similarly to 802.11b, 802.11g devices experience interference from other products that also operate in the 2.4 GHz ISM band, and the OFDM signaling method provides the ability to mitigate the interference.

   The 802.11g standard was rapidly accepted by the market thanks to its high data rates and manufacturing cost reductions. By summer 2003, most products of mobile adapter cards and access points became dual-band/tri-mode, which means that they can work in 802.11a and 802.11b/g networks.
5. 802.11-2007 (Base Standard) [76]
   In order to "roll up" a series of amendments to the 802.11-1999 version, the task group made a single specification that merged the eight amendments including 802.11a, b, d, e, g, h, i, and j with the initial standard. The merged version was approved on March 8, 2007 and became the new base standard, named as IEEE 802.11-2007.
6. 802.11n (MIMO Enhancement) [77]
   The amendment, 802.11n, was published in October 2009, and improved the previous 802.11 standards by introducing multiple-input multiple-output (MIMO) antennas. It is mandatory that 802.11n devices can work in the 2.4 GHz band, and they can optionally operate in the 5 GHz bands. Modifications have been defined to both the PHY and MAC layers so that operation modes can be enabled to support a net data rate from 54 Mbps to as high as 600 Mbps. A maximum throughput above 100 Mbps can be provided as measured at the MAC data service access point (SAP).
7. 802.11-2012 (Base Standard) [79]
   A single document was created to merge the ten amendments (802.11k, r, y, n, w, p, z, v, u, and s) with the 802.11-2007 base standard. The task group made much cleanup and reordered many clauses. The merged version was published on March 29, 2012, which became the new base standard and is referred to as IEEE 802.11-2012.

8. 802.11ac (High-rate in 5 GHz Band) [80]
IEEE 802.11ac-2013 was an amendment based on 802.11n in the 5 GHz band and published in December 2013. Compared with 802.11n, 802.11ac employs several advanced new technologies. The channel bandwidth is increased to 80 or 160 MHz from the original 40 MHz. Up to eight spatial streams can be supported instead of four streams. It also adopts the modulation of up to 256-QAM, which has a higher order than the original 64-QAM. In addition, 802.11ac introduces the multi-user MIMO (MU-MIMO). By October 2013, the 802.11ac products have appeared, which could support 80 MHz channels, 256-QAM modulation, and three spatial streams in the 5 GHz band. The implementation yielded a data rate of up to 433.3 Mbps for each spatial stream and 1.300 Gbps in total. It has been expected to support four spatial streams, channel bandwidth of 160 MHz, and MU-MIMO in 2015, which can provide multi-gigabit throughput.
9. 802.11ad (High-rate in 60 GHz Band) [81]
IEEE 802.11ad specifies a new physical layer which operates in the 60 GHz millimeter wave (mmWave) spectrum. The channel propagation characteristics in this frequency band are drastically different from the 2.4 and 5 GHz bands (which will be discussed in details in Sect. 2.2). The peak transmission rate of 802.11ad is expected to achieve 7 Gbps. The WiFi Alliance is now developing the certification for 802.11ad.
10. 802.11af (High-rate in VHF and UHF Bands) [82]
Approved in November 2013, IEEE 802.11af is a new amendment that specifies the operation of WLAN in TV white space spectrum in the VHF and UHF bands from 54 to 790 MHz. Hence this standard is called "White-Fi" and "Super Wi-Fi". The primary users in this band include analog TV channels, digital TV channels, and wireless microphones. In order to transmit through the unused channels within this spectrum, the cognitive radio technology is used in 802.11af to measure the interference and ensure that the interference to the primary users is limited. Furthermore, APs and stations may use a positioning method such as GPS to determine their positions and then query a geolocation database (GDB) through the Internet. The GDB is usually provided by a regional regulatory agency. According the GDB, the 802.11af devices can determine the available frequency channels that can be used at a given location and time.

    The modulation technique in the physical layer of 802.11af uses OFDM, based on 802.11ac. The advantages of working in the UHF and VHF bands are that, compared with the 2.4 and 5 GHz bands, the attenuation by brick, concrete, and other construction materials is smaller and thus the propagation path loss is reduced. Consequently, the coverage range may be increased.

    According to the regulatory domain, the allowed frequency band of 802.11af ranges from 6 to 8 MHz. Furthermore, in order to increase the channel bandwidth, at most four channels can be aggregated to form one or two contiguous blocks. In 802.11af, MIMO operation is supported. By using either multi-user (MU) or space-time block code (STBC), up to four streams are possible in the MIMO operation mode. Each spatial stream can achieve the data rate of

26.7 Mbps (if the channel bandwidth is 6 and 7 MHz) and 35.6 Mbps (if 8 MHz channels are used). The maximum data rates of 426.7 Mbps (6 and 7 MHz channels) and 568.9 Mbps (8 MHz channels) can be achieved by utilizing four bonded channels and four spatial streams.

11. 802.11ah (High-rate in sub 1 GHz Bands)
    A WLAN working at sub 1 GHz license-exempt bands is specified in IEEE 802.11ah which is planned to be approved in 2016. Different from the conventional 802.11 WLANs operating in the 2.4 and 5 GHz bands, 802.11ah can achieve a wider coverage range thanks to the favorable propagation characteristics (such as smaller path loss) in the low frequency spectrum. Because the available bandwidth is relatively narrow, the applications can be supported by 802.11ah include range-extended hotspots, large-scale sensor networks, and outdoor WiFi to offload the cellular traffic.
12. 802.11ax (High Efficiency WLANs)
    The IEEE 802.11ax amendment was initiated by the high efficiency WLANs (HEW) task group in 2014, and is expected to be released in 2019. 802.11ax is proposed to support future dense networks where multiple WLANs co-exist and each of them may have many stations. In order to address this challenge, spatial reuse of the channel resources is adopted. Furthermore, as the successor to 802.11ac, 802.11ax further increases the network resource utilization and efficiency. It is supposed to be able to increase the throughput of 802.11ac by four times. New technologies such as MU-MIMO and OFDMA are employed in both downlink and uplink to improve the network throughput. To be backward compatible with the current 802.11 WLANs, the legacy PHY preamble is adopted and EDCF is the basic MAC protocol.

As an amendment to the 802.11 standard, IEEE 802.11ai plans to introduce new techniques to setup initial links quickly. In order to use WLANs in the 45 GHz spectrum which is unlicensed in China and some other regions, the standard 802.11ad is rebanded in this band in the amendment of 802.11aj. The amendment 802.11u [78] defines the mechanisms for device discovery, and it is extended in 802.11aq that can perform the pre-association discovery of services. By using 802.11aq, a device may discover the services running on another device or provided by a network. On the other hand, for the support of multimedia services, the amendment 802.11e [54] defines the MAC procedures to support applications with QoS requirements, including the transport of voice, audio, and video over IEEE 802.11 WLANs.

(3) Medium Access Mechanisms

The contents of IEEE 802.11 standard mainly include the specification of the physical layer and the MAC sublayer. The basic 802.11 MAC sublayer defines two mechanisms for channel access: the *distributed coordination function (DCF)* and *point coordination function (PCF)*. The hybrid coordination function (HCF) is further defined in 802.11e. The MAC architecture can be illustrated in Fig. 2.1, where the functionalities of PCF and HCF are provided through the services of DCF.

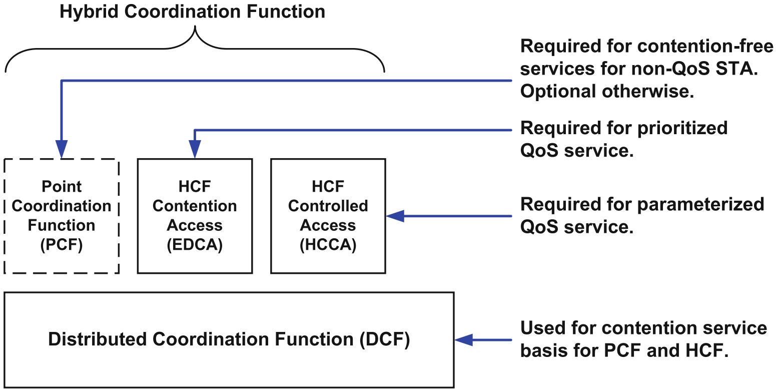

Fig. 2.1 MAC architecture defined in IEEE 802.11e

(a) IEEE 802.11 DCF

DCF is the fundamental protocol for the 802.11 WLANs [65]. It is mandatary and the basic medium access mechanism for both ad hoc and infrastructure modes. It employs the carrier sense multiple access with collision avoidance (CSMA/CA) algorithm. In DCF, stations contend for the transmission opportunities (TXOPs) in a distributed manner. A TXOP is a time interval when a particular station has the right to initiate transmissions. Using a backoff mechanism, each station should wait for a random backoff interval before transmitting or retransmitting a frame for collision avoidance. DCF is well known to provide best-effort service for asynchronous data transmission. However, since the application QoS requirements are not considered, traffic classes are not differentiated and the channel access priority is not supported. The description, analytical model, and performance evaluation of the basic DCF protocol will be discussed in details in Chap. 3.

Different from the wired networks such as Ethernet, wireless networks may suffer from the hidden terminal problem. In a WLAN with an AP, the stations communicating with the AP may not hear each other (such as the stations on the opposite edge of the geographical coverage area of the AP). This is because the wireless signal may attenuate too much before it can reach that far. In order to avoid the hidden terminal problem, DCF introduces a virtual carrier sense mechanism which is optional for a WiFi device. In this mechanism, the source and destination stations exchange short request-to-send (RTS) and clear-to-send (CTS) frames with the network allocation vector (NAV) to block the neighboring stations including the hidden terminals from transmitting simultaneously. The RTS/CTS scheme can solve the hidden terminal problem, but at the same time it introduces the exposed terminal problem, i.e., it may unnecessarily block other transmissions that will not interfere with the ongoing one.

(b) IEEE 802.11 PCF

PCF is an optional MAC technique defined in the IEEE 802.11 standards by which the channel access control is centralized. PCF adopts a centrally controlled polling method and an AP in a WLAN serves as the point coordinator to coordinate the frame transactions within the network. Therefore, with PCF, the network is operated in the "infrastructure" mode. PCF is performed based on DCF in the 802.11 MAC sublayer architecture. An AP waits for a PCF interframe space (PIFS) duration instead of the DCF interframe space (DIFS) duration to access and occupy the channel. Since PIFS is shorter than DIFS, the AP is granted a higher priority to access the wireless channel. The AP sends contention-free-poll (CF-Poll) frames to the stations that are able to operate in the PCF mode, and permits one of them to transmit a frame.

Due to the priority of PCF over DCF in channel access, the DCF-only stations might not gain access to the medium. To ensure that all stations have transmission opportunities, alternative intervals have been designed to provide both (contention-free) PCF access and (contention-based) DCF access. The AP sends beacon frames with fixed intervals, for example every 0.1 s. The time between two beacon frames is divided into two periods, the contention free period (CFP) and the contention period (CP), which are repeated continuously. When stations hear a beacon frame, they start their NAVs for the CFP period to halt the channel access. During the CFP time, the AP sends CF-Poll frames to all of the stations. It sends one frame to a station at a time in order to provide it an opportunity to send a frame. Then during the CP, DCF is used and stations can contend for the channel.

PCF allows for a better management of QoS by the centralized control. However, although PCF is more suitable to support synchronous data transmissions in a WLAN, classes and priorities of traffic which are usually adopted in other QoS mechanisms are not defined. PCF is optional and not required in the interoperability standard by the WiFi Alliance. Consequently, it is rarely implemented in the 802.11 network interface cards in practice.

(c) IEEE 802.11e EDCA in HCF

As discussed in Chap. 1, multimedia applications such as video and audio have QoS requirements such as bandwidth, delay, jitter, and packet loss which are different from data service. Wireless multimedia extensions (WME) is an interoperability certification of the WiFi Alliance, and also known as WiFi multimedia (WMM). WME proposed the IEEE 802.11e-2005 standard [54] which defines the fundamental QoS support in an IEEE 802.11 network. The 802.11e amendment specifies a set of modifications to the MAC layer to enhance QoS provisioning.

A new coordination function, named *hybrid coordination function (HCF)*, has been added in 802.11e to enhance the MAC protocols of DCF and PCF. HCF is similar to the mechanisms specified in the legacy 802.11 MAC and has defined the contention-based and reserved contention-free channel access schemes: *enhanced distributed channel access (EDCA)* and *HCF controlled channel access (HCCA)*, respectively. In order to support QoS provisioning in 802.11 WLANs, HCF introduces a number of QoS-oriented mechanisms and frame subtypes.

Four access categories (ACs) of traffic are prioritized by WME, which are voice, video, best effort, and background. Table 2.3 lists the mapping from the eight user priorities (UPs) defined in 802.1D to the four ACs. The primary principle to provide QoS in EDCA is to give the multimedia traffic a high priority and the best-effort data traffic a low priority in channel access. For example, emails are assigned with a low priority (best effort), and voice over wireless LAN (VoWLAN) and streaming videos are usually assigned to a high priority (voice and video). The channel access of each AC follows DCF but uses a set of differentiated EDCF channel access parameters. If a frame from a higher-priority flow is to be sent, it waits for less time on average than that with a lower priority. As a result, the traffic with a higher priority has a better chance of accessing the channel and being sent. This is accomplished through the modification of the backoff parameters in the traditional CSMA/CA. Thus, delay-sensitive data are protected and QoS is better supported.

Figure 2.2 illustrates the parallel backoff entities in a single IEEE 802.11e station. The traffic flows belonging to the four ACs are handled by four independent backoff entities, and an arbitration is performed inside a station to handle the internal collision among the entities.

In EDCA, a station can access the channel without contention during the period of its TXOP. Within the bounded time period of a TXOP, a station can send a number of frames given that the transmissions do not exceed the duration limit of the TXOP. In the case that a frame is too large to be transmitted within a single TXOP, the station should fragment the frame into multiple frames with a smaller size. By using the time limit of TXOPs, it can be avoided that a low-rate station occupies too much channel time to transmit frames in an 802.11 WLAN.

In addition, block acknowledgment (B-ACK) is adopted which can acknowledge an entire TXOP by using a single ACK frame. This scheme can reduce the overhead of the acknowledgment especially when TXOPs are long and multiple frames are delivered within one TXOP. Furthermore, in supporting QoS, the class of service is defined with two values: QoSAck and QoSNoAck. QoSNoAck is used to inform that a frame is not acknowledged. Thus, retransmissions of highly time-critical data (such as real-time VoWLAN), which are unnecessary, can be avoided.

The released IEEE 802.11-2007 standard has included this amendment to provide statistical instead of hard QoS support. The channel access mechanism of the EDCA protocol will be analyzed and evaluated in details in Chap. 3.

(d) IEEE 802.11e HCCA in HCF

HCCA is similar to PCF. However, there are several critical differences between them as listed below.

- In PCF, the time duration between two adjacent beacon frames is partitioned into two intervals, CFP and CP. In HCCA, CFPs are allowed to start at anytime inside a CP. Such CFP is referred to as the controlled access phase (CAP) in 802.11e. An AP can initiate a CAP any time when it wants to transmit a frame to or receive a frame from a station by contention-free channel access. During a CAP, the access to the wireless channel is controlled by the hybrid coordinator (HC), i.e., the AP. On the other hand, inside a CP, all stations contend for the channel access via EDCA.

Table 2.3 Priority to access category mappings

Priority	User Priority (UP)	AC Index (ACI)	Access Category (AC)	Designation (informative)	Minimum CW Size	Maximum CW Size	AIFSN
Lowest ↓ Highest	1	0	AC_BK	Background	aCW_{min}	aCW_{max}	7
	2	0	AC_BK	Background			
	0	1	AC_BE	Best Effort	aCW_{min}	aCW_{max}	3
	3	1	AC_BE	Best Effort			
	4	2	AC_VI	Video	$\frac{aCW_{min}+1}{2} - 1$	aCW_{min}	2
	5	2	AC_VI	Video			
	6	3	AC_VO	Voice	$\frac{aCW_{min}+1}{4} - 1$	$\frac{aCW_{min}+1}{2} - 1$	2
	7	3	AC_VO	Voice			

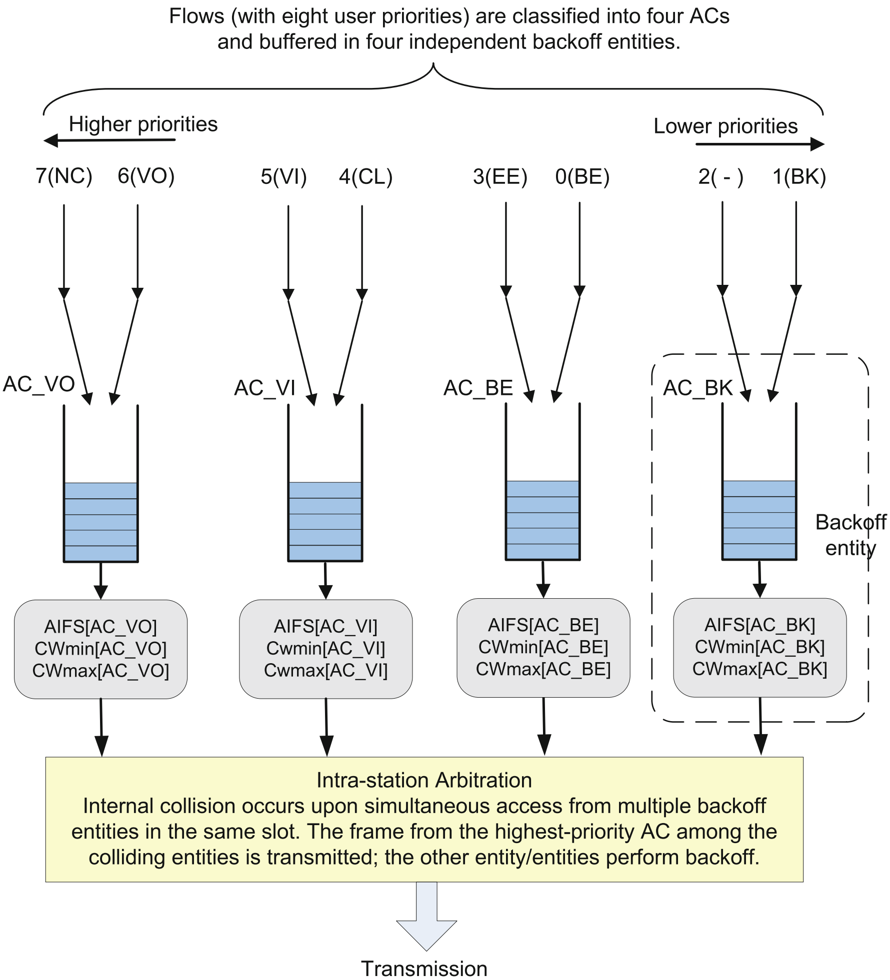

Fig. 2.2 Four parallel backoff entities for the ACs with different EDCA parameter sets and intra-contention in one IEEE 802.11e station

- As mentioned earlier, PCF does not define prioritized classes. HCCA specifies ACs and traffic streams (TS). Thus an HC can construct a queue for each session (stream), rather than for each station. In addition, HCF can coordinate these streams or sessions in any fashion (not just round-robin). Meanwhile, the stations report their queue lengths of all ACs to the HC, and then the HC may adjust the scheduling accordingly.
- In HCCA, a station may send multiple frames in a burst inside a given period of time determined by an HC, while this mechanism is not provided in PCF.
- During a CAP in HCCA, stations can also send CF-Poll frames to the HC to request data transmissions.

It is considered that HCCA is the most advanced (and complex) coordination function in the IEEE 802.11 standard family. In HCCA, QoS for each individual traffic flow can be specified with high accuracy by specific transmission parameters (such as data rate, jitter, etc.). Therefore, multimedia applications can be supported more effectively in a WLAN. However, since HCCA functionality is not mandatory in 802.11e, there are few (if any) AP products that implement HCCA at present.

2.2 Wireless Personal Area Networks

(1) Overview of WPANs

A personal area network (PAN) is used for the interconnection of devices inside the space of an individual person (intra-personal communications), sometimes with connection to a wide area network such as the Internet or cellular networks. The functionality of a PAN is to realize the inter-operation and data exchange among devices and systems at home or in a business workplace, for data and multimedia services. In addition to consumer services, WPAN applications include industrial automation and control, medical monitoring, etc. "Plug-in" is a key principle in wireless PAN (WPAN) technology. The objective is that, when two or more WPAN devices are inside the proximity of each other, they are able to communicate as if they were connected by cables. The proximity of a device is usually within several meters. Therefore, WPAN is regarded as a short-range networking technology.

WPANs are mainly standardized by the 802.15 working group of the IEEE 802 standardization committee. The 802.15 working group includes seven task groups (TGs), and they have worked out a series of specifications for the lower network layers (PHY and MAC) for various communication technologies and applications. The standards are briefly listed below, and the important ones, such as low-rate WPANs based on Bluetooth and high-rate WPANs based on ultra wideband and millimeter-wave technologies, will be discussed in details later in this section.

- TG 1: *Bluetooth*. It defines the WPAN specifications based on the Bluetooth technology for wireless connection among fixed and portable devices. The standards were approved in 2002 [83] and 2005 [84].
- TG 2: *Coexistence*. Released in 2003, the IEEE 802.15.2-2003 specification [85] addressed the coexistence issue of WPANs and other wireless networks, such as WiFi, which also operate in the same unlicensed frequency bands.
- TG 3: *High Rate WPAN*. The standard IEEE 802.15.3 defines the high-rate (11–55 Mbps) WPANs, and has three subdivisions of 802.15.3 [86] (usually called 3a), 3b [87], and 3c [88]. They employ the ultra-wideband (UWB)-based and mmWave-based PHYs.
- TG 4: *Low Rate WPAN*. The standard IEEE 802.15.4-2003 [89] specifies the WPAN that operates at low data rate, has very long battery life (e.g., for months or even years), and has low system complexity. The 1st edition was released in May 2003. A number of standardized protocols and proprietary protocols have been

developed to work on top of the 802.15.4-based wireless networks, including IEEE 802.15.4-2015 [97], ZigBee, IPv6 over low power wireless personal area networks (6LoWPAN), wireless highway addressable remote transducer protocol (WirelessHART), and international society of automation (ISA) 100.11a. The low-rate WPAN will be discussed in details in the next section.

- TG 5: *Mesh Networking*. IEEE 802.15.5 [98] defines the architecture for WPAN devices to form an inter-operable, steady, and flexible wireless mesh network. The standard consists of two divisions: mesh-less WPAN with low data rate and mesh WPAN with high data rate. The former is established on the MAC mechanism of IEEE 802.15.4-2006 [90], while the latter is based on IEEE 802.15.3b MAC [87].
- TG 6: *Body Area Networks*. IEEE 802.15.6 TG approved the standard for body area network (BAN) technologies in December 2011 [99]. It is a wireless standard for low-power and short-range devices which operate on, in, or around an individual body. The wireless BAN (WBAN) enables a spectrum of applications including medical care, consumer electronics, and personal entertainment. The BAN will be discussed in details in the next section.
- TG 7: *Visible Light Communication*. The IEEE 802.15.7 [100] draft was completed in December 2011 for visible light communications (VLC). It is especially used for optical communications using visible light in free space.

(2) Low-Rate WPAN: IEEE 802.15.4

(a) Overview and Physical Characteristics

IEEE 802.15.4 defines the PHY scheme and MAC protocol for low-rate WPANs (LR-WPANs). The MAC protocols in the standards, including ZigBee, ISA100.11a, WirelessHART, and MiWi (designed by Microchip Technology), are based on 802.15.4 and each of them further defines different upper layers such as packet routing and applications. For example, 6LoWPAN utilizes 802.15.4 (for lower layers) and the standard Internet protocols (for higher layers) to build a wireless embedded Internet. The key feature of 802.15.4 is to provide low-rate, low-cost, short-range communications among nearby devices, contrasted to the high-rate, more power-intensive wireless solutions such as WiFi. The target capacity of 802.15.4 is a link of 10 m at a transmission rate of only 250 Kbps or even lower (such as 20, 40, and 100 Kbps) to achieve extremely low power consumption. It also emphasizes the need for little to no underlying infrastructure for low operation costs and easy and flexible network setup.

In IEEE 802.15.4, PHY is composed of the physical signal transceiver in the radio frequency (RF) band, and also selects appropriate channel for networking and managing energy consumption. The original version of the standard released in 2003, IEEE 802.15.4-2003 [89], specifies the PHY utilizing the direct sequence spread spectrum (DSSS) technique which operates in three unlicensed frequency bands.

- 868.0–868.6 MHz: Europe, one communication channel, transfer rates of 20 and 40 Kbps;

- 902–928 MHz: North America, up to ten channels (2003) and extended to thirty (2006), transfer rates of 20 and 40 Kbps;
- 2400–2483.5 MHz: worldwide use, up to sixteen channels, transfer rates of 250 Kbps.

The 2006 revision, IEEE 802.15.4-2006 [90], improves the maximum data rates up to 100 and 250 Kbps in the frequency bands of 868 and 915 MHz. A series of amendments following the original versions are briefly listed below.

- *IEEE 802.15.4a-2007: WPAN Low Rate Alternative PHY [91].* This amendment specifies two additional PHYs, one using direct sequence (pulse radio) UWB (operating in the unlicensed UWB spectrum, including below 1, 3–5, and 6–10 GHz) and the other using chirp spread spectrum (operating in the unlicensed 2450 MHz spectrum). The radio pulse-based PHY schemes are able to perform localization and ranging with high precision (e.g., the accuracy can be one meter or even smaller), large aggregate throughput, and scalability in the tradeoff between longer range and higher data rates. They also provide lower power consumption options with reduced cost.
- *IEEE 802.15.4-2006: Revision and Enhancement [90].* Approved in June 2006 and published in September 2006, 802.15.4-2006 specifies enhancements and clarifications to the IEEE 802.15.4-2003 standard. The enhancements include resolving ambiguities, reducing complexity if not needed, increasing scalability in the use of security key, considering frequency bands that are newly available, and others.
- *IEEE 802.15.4c: PHY Amendment for China [92].* It was approved in 2008 and published in January 2009. It adds the newly opened RF spectrum bands in China for WPAN use, including the 314–316, 430–434, and 779–787 MHz bands.
- *IEEE 802.15.4d: PHY and MAC Amendment for Japan [93].* It defines a new PHY and the necessary MAC modifications to operate in the newly allocated frequency bands from 950 to 956 MHz in Japan. Meanwhile, it ensures the coexistence between 802.15.4 WPANs and passive tag systems in this band.
- *IEEE 802.15.4e: MAC Amendment for Industrial Applications [95].* It was approved in February, 2012. As the industrial markets increase, 802.15.4e defines a new amendment to the MAC scheme in the existing standard 802.15.4-2006. Channel hopping strategy is employed to improve the signal robustness against external interference and continual multipath fading.
- *IEEE 802.15.4f: PHY and MAC Amendment for Active RFID [94].* It defines new wireless PHY and improvement to the 802.15.4-2006 MAC to enable the localization applications of active RFID systems.
- *IEEE 802.15.4g: PHY Amendment for Smart Utility Networks (SUN) [96].* Released in April 2012, the 802.15.4g standard creates a PHY amendment that is capable of supporting large, geographically diverse networks. This standard can facilitate very large-scale process control. For example, the utility smart grid network may have millions of fixed terminals with minimal infrastructure.

(b) MAC and Network Topology

The MAC layer manages the physical channel access for frame transmissions, network beaconing, time slot scheduling, frame validation, and node associations. Note that the majority of the IEEE 802.15.4 PHYs only allow a frame size of up to 127 bytes and do not provide the exchange of standard Ethernet frames to upper layers. Therefore, the adaptation layer (like in 6LoWPAN) is needed to provide frame fragmentation for network-layer packets in the protocol stack. For the channel access mode, 802.15.4 includes both guaranteed time slots by reservation and transmission opportunities by contention with collision avoidance (following the CSMA/CA mechanism).

Network nodes in the 802.15.4 standard are defined as two types. The first kind is the full-function device (FFD) which operates as the coordinator of a PAN as well as a common node. An FFD node can also forward/relay packets. On the contrary, the reduced-function devices (RFDs) have much less complexity. They typically have limited resource and communication capacity, and can talk with FFDs only. An RFD cannot operate as a coordinator.

The 802.15.4 WPAN can work in either the peer-to-peer mode or the star mode. An 802.15.4 network requires at least one FFD to serve as the coordinator which is in charge of the establishment of the whole network. Every device is assigned a unique identifier. Within each PAN domain, short 16-bit identifiers may be used. Peer-to-peer networks can work in the ad hoc mode and are able to perform self-organization and management. Furthermore, the network can be extended to become a generic mesh network. The network nodes are organized in clusters. There is a local coordinator (an FFD node) in every cluster and a global coordinator in charge of the whole network. The cluster-based network topology is illustrated in Fig. 2.3. The cluster-tree topology of ZigBee supports power-saving operations and light-weight tree routing protocol, and hence is suitable for low-power low-rate WSNs. However, events in the sensing area may trigger sensors to generate much higher data traffic. Due to the restricted routing protocol, the cluster-tree networks may not be able to deliver the increased traffic. Huang et al. [52] have proposed an adoptive-parent based framework to increase the bandwidth utilization. The throughput optimization is formulated as a convex-constraint maximum flow, and a distributed pull-push-relabel (PPR) algorithm compatible with the existing standard is designed to maximize the throughput. On the other hand, the 802.15.4 standard also supports the star topology which is more structured. In this case, the coordinator of a star-like network is required to be the central node.

Frames are the basic unit for data transfer in 802.15.4. There are four fundamental types of frames, which are data, acknowledgment, beacon, and MAC command. Based on the definition of the four frame types, a reasonable tradeoff can be made between network simplicity and robustness. The superframe structure which is limited with two beacons sent by the coordinator is used for node synchronization and channel access management. In peer-to-peer networks, the communications between any two devices are possible. The channel access can be coordinated in

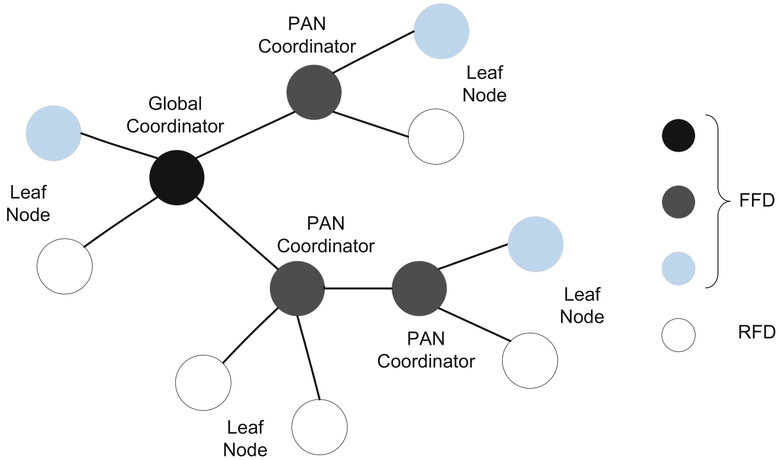

Fig. 2.3 IEEE 802.15.4 cluster-tree based network topology

two ways, by either unslotted CSMA/CA based on contention or synchronization mechanisms. However, in the star topology, nodes cannot communicate with each other except with the network coordinator.

(3) Low-Rate WPAN: Bluetooth

(a) Overview and Physical Characteristics

Bluetooth uses short-range radio communications for exchanging data over approximately 10 m from fixed and mobile devices and building WPANs. Bluetooth is managed by the Bluetooth special interest group (SIG), which was formally created on May 20th, 1998, and now has more than 20,000 member companies. Although Bluetooth used to be specified as IEEE 802.15.1, it is not maintained any more by IEEE 802 group but by the SIG. Bluetooth is defined for low-rate, short-range, low-power, and low-cost wire-replacement communications. Moreover, by simplifying the discovery and setup of services between devices, Bluetooth operates well with simple setup in the scenario that two devices can be connected with minimum configuration, contrasted to the WiFi technology which requires client configuration and provides high speeds. The WPAN devices using Bluetooth including keyboards, pointing devices, audio head-sets, laptops, printers, smart phones, and game consoles have become very popular today.

Bluetooth works in the spectrum band of 2400–2483.5 MHz, the globally unlicensed ISM band. The range is divided into 79 designated channels, and the frequency-hopping spread spectrum (FHSS) scheme is adopted in the PHY layer. The original data stream is partitioned into packets and every packet is sent in one channel. The bandwidth of a channel is 1 MHz (note that 2 MHz spacing is used in Bluetooth 4.0, resulting in 40 available channels). When adaptive frequency-hopping (AFH) is enabled, PHY usually executes 1600 hops in 1 s.

The development of the Bluetooth technology is briefly reviewed below.

1. Bluetooth v1.0 and v1.0B contain a number of issues, which led to much difficulty in the inter-operation among products from different manufacturers.
2. Bluetooth v1.1 was approved as the IEEE Standard 802.15.1-2002 and many problems existing in the v1.0B standard were fixed. In addition, the non-encrypted channels and received signal strength indicator (RSSI) were added.
3. Bluetooth v1.2 made great improvement. The fast discovery and connection mechanism was added. The AFH in the FHSS, which excluded the crowded frequencies in the hopping frequency sequence, was introduced. Thus the resistance to radio interference from other devices in the unlicensed band was enhanced. Higher transmission data rates up to 721 Kbps were provided. v1.2 was released as the IEEE standard 802.15.1-2005.
4. Bluetooth v2.0+EDR was released in 2004, which defined an optional enhanced data rate (EDR) up to 3 Mbps for faster data transfer (the practical data transfer rate is 2.1 Mbps).
5. Bluetooth v2.1+EDR was accepted by the SIG on July 26th, 2007, which provides secure simple pairing (SSP) to achieve enhanced security.
6. Bluetooth v3.0+HS was approved by the SIG on April 21st, 2009. The key enhancement was to support high-speed (HS) transport by employing 802.11, which was an alternative MAC/PHY (AMP) for Bluetooth. The link negotiation and establishment were done by Bluetooth communications, while a collocated 802.11 link was used to carry high-rate data traffic. Thus, the data rate could theoretically achieve 24 Mbps.
7. Bluetooth v4.0 [15], also named as Bluetooth Smart, was approved on June 30th, 2010. The Classic Bluetooth (legacy Bluetooth protocols), Bluetooth HS (based on WiFi), and Bluetooth low energy protocols are included in this release.
8. Bluetooth v4.1 [16] was formally released by the SIG on December 4th, 2013. The update adds new features which improve co-existence support for LTE, transfer speed for bulk data, and simultaneous multiple role support of a device which can be used for developer innovation.

(b) MAC and Network Topology

Bluetooth is a packet-based protocol with a master-slave structure and one master may communicate with up to seven slaves. Therefore, the eight devices including the master form a PAN called a *piconet* (the prefix "pico" means very small or one trillionth). The range of a piconet is typically 10 m. In a piconet, the first Bluetooth device plays the role as the master, and then other devices which communicate with the master are slaves. All devices in a piconet use the common clock of the master. The master typically selects a slave device to interact with and it switches rapidly among the devices in a round-robin fashion.

Furthermore, as specified in the Bluetooth standards, two or more piconets can inter-connect with each other and form a scatternet. In this case, a device may need to be the master in one piconet and at the same time a slave in another piconet, in order to realize the inter-connection of multiple piconets.

(4) **High-Rate WPAN:** 3.1–10.6 **GHz UWB**

(a) Overview and Physical Characteristics

The frequency band from 3.1 to 10.6 GHz has been issued by FCC for the unlicensed use of UWB devices [40]. In addition, the transmission power must be below the power spectrum mask (−41.25 dBm/MHz for indoor deployment), in order to allow physically coexistence with other 802.15 devices which also operate in this band. For the purpose of communications, a UWB system is defined in either one of the two ways. The first way is that the −10 dB fractional bandwidth of the communication system should be at least 20 %. The second is that −10 dB bandwidth needs to be equal to or more than 500 MHz. As a promising technology for short-range, high-rate, and low-power wireless communications, UWB technology has received significant interests from both academia and industry [118, 162]. Due to the very high-data rate over 100 Mbps, UWB networks are able to support simultaneously several isochronous streaming flows, such as voice over IP (VoIP), high-definition television (HDTV), and massive data download [35].

The IEEE 802.15.3 working group is responsible for specifying the PHY and MAC standards for high-rate WPAN. It has three subgroups, IEEE 802.15.3a [86], 3b [87], and 3c [88]. Since 3c specifies the UWB technology operating in the mmWave band, it will be discussed in the next subsection. The works of 3a and 3b are summarized as below.

- *IEEE 802.15.3a* provides a high speed UWB PHY enhancement amendment for applications involving streaming multimedia and massive data. There were two proposals for the UWB technologies, multi-band orthogonal frequency division multiplexing (MB-OFDM) and direct sequence UWB (DS-UWB). They were proposed by two industry alliances comprising of different companies. However, an agreement on choosing which technology proposal could not be achieved among the task group members. Consequently, the group was dissolved in January 2006. The UWB-based high-rate WPAN will be introduced in details later in this section.
- *IEEE 802.15.3b-2006* amendment was issued on May 5, 2006. The amendment enhanced the implementation and inter-operability of the MAC, which included minor optimizations, error corrections, ambiguity resolution, and editorial improvement.
- *IEEE 802.15.3c-2009* was released on September 11, 2009. The TG3c was organized in March 2005 and developed an alternative PHY for WPAN based on mmWave. This mmWave PHY works in the unlicensed frequency band from 57 to 64 GHz, which is a clear band as defined by FCC 47 CFR 15.255. Operating in this mmWave band, a very high speed over 2 Gbps is possible. The targeted applications include high-data rate Internet access, massive data download, real-time streaming (high-definition IPTV, video on demand, etc.), and cable replacement (e.g., wireless home theater).

As a very wide band radio technology, UWB transmission has several unique merits, for example, very low transmission power, capability in mitigating multipath effect, high-data rate, and ability in precise positioning. The UWB technology is expected to fully exploit the very large bandwidth in transmitting information, and thus tries to provide a data rate higher than 100 Mbps. By restricting the transmission power under the appropriate level required by FCC, UWB is able to coexist with other wireless systems and share the spectrum.

UWB was originally employed as "pulse radio" in radar for positioning. For high-rate data communications ($>$ 100 Mbps), the UWB system can be implemented by a pulse-based approach [136, 146, 162] or an MB-OFDM based approach [7, 114]. In the former approach, information is modulated on very short pulses. The duration of a pulse is typically in the order of a nanosecond. In the latter approach, the combination of frequency hopping and OFDM is adopted. For the data transmissions in a multipath wireless channel, either of the two UWB proposals has its pros and cons.

- In the pulse-based UWB, the multipath diversity can be exploited effectively by utilizing the rich resolvable multipath components (MPCs).
- A long channel acquisition time is needed for channel estimation in the pulse-based approach. Also, high-speed analog-to-digital conversion (ADC) is required in processing the received pulse signals.
- MB-OFDM has the advantage in spectral flexibility and efficiency. It has also the robustness against narrowband interference.
- MB-OFDM needs a slightly more complicated transmitter compared with the pulse-based UWB system.

In addition, the pulse-based UWB technology is also flexible in providing low-rate data transfer ($<$ a few Mbps) over moderate or long distances (from 100 to 300 m) [107, 111].

(b) WiMedia WPAN MAC

The function of MAC in WPANs is similar to that in WLANs, i.e., coordinating the channel access from the competing stations in order to transmit data efficiently and fairly. The major MAC specifications for UWB-based WPANs include IEEE 802.15.3 [86] and WiMedia-368 [69] which is specified by the Multiband OFDM Alliance (MBOA).

Based on the MB-OFDM technology, the WiMedia Alliance has released the standards for both the PHY scheme and the MAC protocol [49]. WiMedia UWB has been promoted for personal computers, consumer electronics, mobile devices, and automotive networks. In order to achieve ad hoc connectivity, two distributed channel access mechanisms are defined by the WiMedia specification: the prioritized channel access (PCA) and the distributed reservation protocol (DRP).

PCA is a contention-based approach and it adopts the mechanisms that are similar to EDCA in IEEE 802.11e to provide differentiated channel access. A device senses the channel before transmitting frames. To prioritize traffic channel access, the parameters in the backoff and channel contention are selected depending on the traffic class and priority. Only statistical QoS provisioning is realized in the EDCA-like MAC protocols. Therefore, the QoS requirements of isochronous traffic, such as the stringent delay bound, are difficult to be satisfied in PCA [21]. The detailed performance analysis on the PCA protocol can be found in [63] and [138]. The analysis and performance evaluation of EDCA will be presented in details in Chap. 3, which is readily applicable to PCA.

DRP is a distributed TDMA protocol, by which users reserve channel access time in superframes and then transmit frames within the reserved time slots without interruption. However, different from the original TDMA scheme, the stations in a WPAN first negotiate the channel reservation in a distributed manner. The advantage of DRP is that the transmission opportunities and time for isochronous traffic are guaranteed by the channel reservation. Since the QoS requirements such as the stringent delay bound is satisfied, DRP is preferable for streaming multimedia applications. However, isochronous data flows such as compressed video traffic have bursty data rates. The packet inter-arrival time is random (i.e., the instantaneous data rate varies significantly). The difference between the reserved bandwidth and the time-varying requirement from the traffic results in the difficulty in resource reservation. To accommodate the burstiness of the traffic flow, over-reservation is usually adopted which leads to considerably inefficient utilization of the network bandwidth when fixed channel time is reserved (*hard reservation*). This inefficiency in resource reservation can be improved via the *soft reservation*. In the latter, the unused reserved time can be released by the owner and other stations which have backlogged frames can contend for channel access following the PCA protocol.

Another important aspect of DRP is that the allocation of the reserved time slots for one flow is more flexible. The main feature of DRP different from the traditional TDMA scheme is in the reservation pattern. To limit the delay variation, it is desirable to reserve contiguous or evenly spaced time slots with constant interval in each scheduling cycle (i.e., a superframe in the MAC protocol). Such reservation pattern can be realized by a centralized coordinator. However, in DRP, because the locations of the available time slots within a superframe are arbitrary, there can be multiple reserved time slots which may be non-uniformly distributed inside a superframe for one traffic flow, resulting in a random reservation pattern in a scheduling cycle. The reservation algorithms for multimedia traffic in DRP will be discussed in details in Chap. 4.

(5) High-Rate WPAN: 60 GHz PHY

(a) Overview and Physical Characteristics

With the hope that all cables in home networks for indoor information delivery are replaced by high-rate wireless data bus, FCC issued the frequency band from 57–64 GHz that became available in FCC 95-499 [3] and CFR 15.255. Japan declared the 59–66 GHz band and the European Telecommunications Standards Institute (ETSI) allocated the 57–66 GHz band too. Thus, a common, contiguous 5 GHz band is available around 60 GHz in major markets around the world [9] (see Fig. 2.4). Since the signal wavelength at 60 GHz is about 5 mm, this spectrum is referred to as the mmWave band. In July 2003, with the increasing interests in developing an mmWave PHY within the IEEE 802 family, an interest group belonging to the

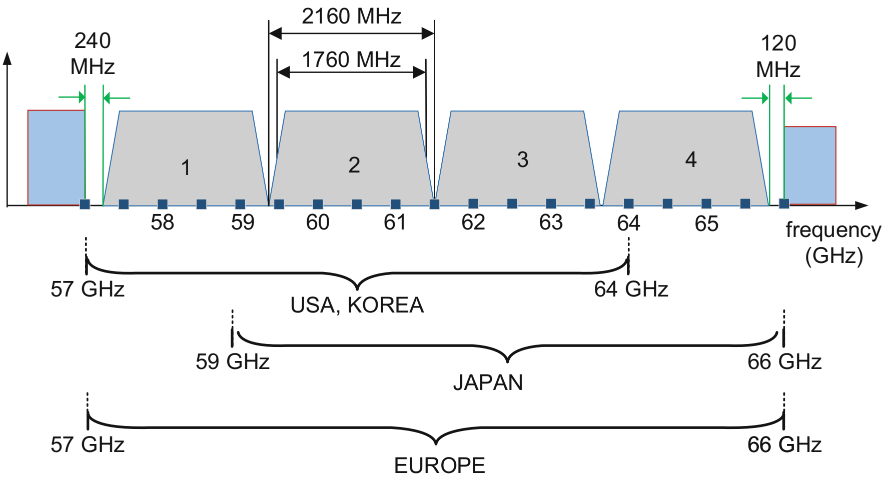

Fig. 2.4 Channelization of 802.15.3c and unlicensed bands around the globe

802.15 working group was formed for WPANs and a study group was formally established in March 2004. The members of this group developed an mmWave-based alternative PHY to support 1 Gbps or higher data rates for the existing 802.15.3 WPAN standard. It was decided by the IEEE 802 Working Group to adopt the existing MAC protocol (IEEE 802.15.3b), and necessary modifications and extensions should be done to improve implementation and interoperability of the MAC. The task group started by concentrating on the application models, an indoor wireless channel model at 60 GHz, and the evaluation criteria for PHY proposals. After 2 years of hard work, three PHY schemes and a number of MAC enhancements were proposed to realize different usage scenarios. Finally, the IEEE 802.15.3c-2009 [88] was released in September 2009, approved by the IEEE-SA standards board.

The mmWave WPAN operating in 60 GHz band allows the physical coexistence with other microwave devices communicating within this band. It also allows high data rate over 2 Gbps to support applications including massive content transfer, high-speed Internet access, real-time streaming, and wireless cable replacement. By analyzing in details the potential applications by consumers, the 802.15.3c Task Group defined five usage models (UMs) in the 60 GHz band [115].

- UM 1) *Uncompressed video streaming:* The very wide bandwidth enables sending high-definition television (HDTV) traffic flow from HD video cameras to display screens to replace video cables. The HD video signals have at least 1920 × 1080 pixel resolution, 24 bits for each pixel and a rate of 60 frames per second. Hence the uncompressed video streaming bit rate is more than 3.5 Gbps.
- UM 2) *Uncompressed multivideo streaming:* A home network gateway may deliver several video signals to multiple TV sets or a TV can show a couple

of channels side by side on a screen. One stream may require 720 × 480 pixels per frame. Thus the gateway should be able to provide at least two streams with 0.62 Gbps each simultaneously.

- UM 3) *Office desktop:* This UM considers the data communication between a personal computer and multiple external peripherals, such as one or more screens, printers, and hard disks. The data flows can be unidirectional or bidirectional. For reliable data delivery, retransmissions may be needed.
- UM 4) *Conference ad hoc operation:* Many computers are communicating with each other in an ad hoc, bi-directional, and asynchronous mode. The conference operation range is usually larger than the office desktop.
- UM 5) *Kiosk file downloading:* The portable devices will be equipped with transceivers with low complexity and power consumption to enable large data uploads and downloads. For example, downloading video files and large amount of pictures from smart phones at 1.5 Gbps within 1 m range will be possible.

(b) 60 GHz Channel Model

Different from the radio systems within unlicensed ISM bands such as 2.4 and 5 GHz, 60 GHz signals have much smaller wavelength, resulting in significantly higher propagation loss. Hence the efficient PHY technologies and MAC protocols adapting to the new features are needed. For example, directional transmission and reception are usually needed to increase the signal power in the target direction. The conventional Saleh-Valenzuela (S-V) channel model [116], which is suitable for the signal transmission/reception by the IEEE 802.11 and IEEE 802.15 specifications in the ISM band, cannot be applied for the 60 GHz propagation. Therefore, a new channel model has been proposed by the IEEE 802.15.3c channel modeling subcommittee. It adopts the two-path model which incorporates a line-of-sight (LOS) component and NLOS reflective clusters similar to the S-V model [56, 125].

The new model is illustrated in Fig. 2.5. In order to cover all the possible scenarios, the model is determined by a set of different parameters (e.g., path loss coefficients, shadowing effect [151], etc.). These parameters have been extracted from field measurements for different scenarios.

(c) MAC in IEEE 802.15.3c

The IEEE 802.15.3c standard [88] defines the PHY and MAC specifications for mmWave-based high-rate WPANs. In the standard, a group of devices (DEVs) exchange data in an ad hoc fashion and form a *piconet*. In order to ensure piconet synchronization and manage the channel access among DEVs, one DEV would play the role as the *piconet coordinator (PNC)*. Time is divided into sequential *superframes* and each superframe contains three segments: a beacon period, a contention access period (CAP), and a channel time allocation period (CTAP). Beacons are broadcast periodically by the PNC which bear the necessary control information, for example, the time and opportunities a DEV can access the channel. When a DEV hears a beacon, it would know the presence of a piconet.

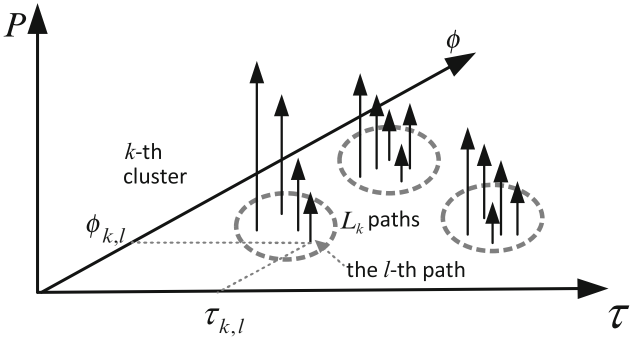

Fig. 2.5 Graphical representation of the 60 GHz channel model

The CAP is mainly used for the PNC and DEVs to exchange command and control messages. Because the packet-based data transfer is mostly asynchronous, the contention-based access scheme is adopted, i.e., the prioritized CSMA/CA such as IEEE 802.11e. The analytical model and performance analysis of CAP with the existence of the CTAP within a superframe will be presented in details in Chap. 5.

The rest of the superframe includes the CTAP which adopts reservation-based channel access such as TDMA. The CTAP comprises multiple channel time allocations (CTAs). The CTAs are time slots granted by the PNC and each CTA is used by a certain pair of DEVs for data exchange. By TDMA, time-sensitive applications such as multimedia streaming can utilize CTAs for guaranteed data delivery and the delay can be bounded.

Based on the fundamental architecture of the MAC protocol for WPANs, the task group has also developed enhancements in three major areas to define an efficient and well-structured MAC layer [9].

- *Coexistence among 802.15.3c PHYs:* For the purpose to make devices using various PHY schemes physically coexist with each other, sync frames are employed. It is mandatory that a PNC-capable DEV should transmit a sync frame in each superframe as specified by the 802.15.3c rules. A PNC is also capable of receiving and decoding sync frames regardless operating with what kind of PHY scheme. Consequently, a PNC can obtain the information about the existence of a nearby piconet. Then it has the chance to join it instead of establishing a new, independent one. Hence the sync frame mechanism is an effective way to create, maintain, and manage the coexistence of piconets and to avoid co-channel interference between nearby piconets.
- *Frame Aggregation:* In WLAN and WPAN systems, the transmission rate of the frame header is usually fixed at the lowest mandatory rate in the PHY for reliable reception. Thus, with the increase of the transmission rate of the data payload, the network efficiency will decrease because the ratio between the overhead time and the payload time increases, especially in high-speed networks. To improve transmission efficiency and effective throughput, frame aggregation

is used. The principle is to concatenate the payload data from multiple MAC service data units (MSDUs) and remove the extra overhead (such as the preamble and PHY/MAC header). In the 802.15.3c standard, the standard aggregation and low-latency aggregation methods are specified.

- *Beamforming:* The high-speed WPAN is expected to achieve MAC throughput of a few gigabits per second over a short to moderate range. To accomplish this, a high received SNR is critical. In order to compensate the high propagation loss (especially for the 60 GHz band) and mitigate the attenuation caused by shadowing, directional transmission is preferable. By concentrating the signal power in the target direction, the received SNR can be increased significantly compared with the omni-directional emission. Using multiple antennas (antenna array) and beamforming is an effective way to realize directional transmission. Integrating multiple antennas into a portable device has also become feasible, because the dimension and the necessary spacing between the antennas operating at 60 GHz are in the order of millimeters [51].

In summary, as the first IEEE wireless standard for data rate higher that 1 Gbps at the MAC service access point (SAP), IEEE 802.15.3c is designed to not only develop three new PHY schemes, but also enhance the existing 802.15.3 MAC by specifying piconet management mechanism, frame aggregation, and beamforming capability. Benefitting from the spectrum regulation and standardization effort, the rapid deployment of WPANs throughout the world has become possible. The commercial products following the 802.15.3c standard have already appeared, and consumers can have the WPANs device coexistence without worrying about the interference.

There are a lot of research opportunities for WPANs. For example, because of the high propagation loss of 60 GHz signals in indoor environments, the signal coverage may be too limited to form an expected home network. Thus, repeaters and multihop solutions for a typical WLAN deployment will be necessary. The range enhancement by employing new technologies such as advanced coding and steerable antennas is also an option. It can be predicted that the new efficient MAC protocol for high-speed WPANs will consistently play an important role in improving the network throughput, delay performance, data delivery reliability, network maintenance, and QoS provisioning.

2.3 Wireless Body Area Networks

(1) Overview of WBANs

With the rapid growing demands of ubiquitous communications and great advances in very-low-power wireless technologies, there have been considerable interests in the development and application of wireless networks around humans. A body area network (BAN), also referred to as a wireless body area network (WBAN) or a body sensor network (BSN), is an RF-based wireless network that

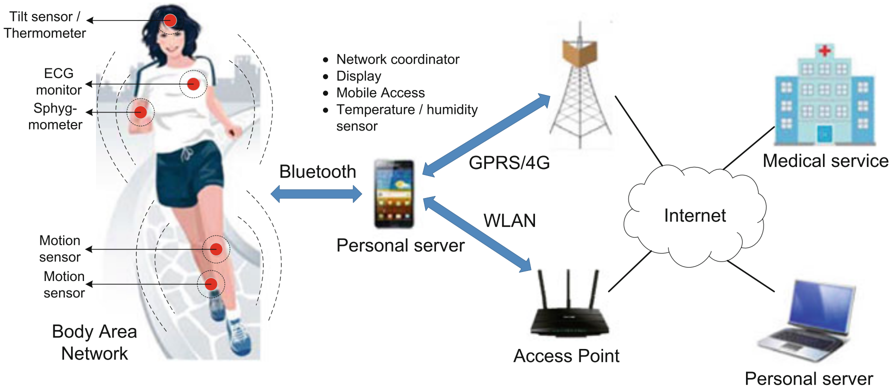

Fig. 2.6 Interconnection of WBAN, WPAN, (W)LAN, and wide area networks

interconnects tiny nodes of wearable sensor or computing devices to implement sensing and communications within the proximity of a body. With the trend towards the miniaturization of devices and wearable technology, humans can carry the BAN devices in different locations, for example, embedded inside or surface-mounted on the body in fixed positions, in pockets, by hand or in bags. BANs target diverse applications including healthcare, athletic training, workplace safety, consumer electronics, secure authentication, and safeguarding of uniformed personnel.

Based on the miniaturized devices, a BAN network usually consists of several body sensor units (BSUs) together with a single body central unit (BCU). Larger-sized communication devices (smart phones or pads) also play an important role in terms of acting as a data hub, data gateway to the Internet and/or providing a user interface to view and manage BAN functions. Typically, the transmissions of the BSUs and BCUs cover a short range of about 2 m. Through gateway devices, a BAN can be connected to local and wide area networks, as illustrated in Fig. 2.6.

WBANs will play an important role in enabling ubiquitous communications and creating a huge potential market. In the area of healthcare, according to the World Health Organization's statistics, millions of people suffer from obesity or chronic diseases every day, while the aging population is becoming a significant problem. Using the WBAN technologies, medical professionals can collect various first-hand physiological changes for health monitoring and care using the Internet regardless of the patients' locations. If an emergency is detected, the physicians can immediately inform the patient and medical service through the networks by sending appropriate messages or alarms. From the consumer electronics perspective, short-range wireless networks for human-computer interaction (HCI) and entertainment are also promising.

From the technical point of view, to design and implement such WBANs faces a series of challenges.

- The importance of reliability is obvious especially when WBANs are used for monitoring the health status of patients. Particularly any emergency signal cannot be missed.
- Energy utilization and efficiency are critical for WBAN sensors, because their battery capacities are very limited due to their tiny sizes. It is difficult to replace batteries of the implanted BSUs.
- Another important issue is inter-operability. WBAN systems need to be scalable and support seamless data delivery over various networks such as Bluetooth and ZigBee. The smooth migration through networks is required to ensure ubiquitous connectivity and coverage.
- The BAN sensors must have low complexity, small size and weight, and high power efficiency.
- Interference should be regulated. Wireless links in a WBAN should reduce the interference level to other physically close networks, and allow the coexistence especially when WBANs are densely deployed.

The application requirements such as extreme energy efficiency and the unique characteristics of the wireless channels, require novel solutions in resource management and MAC protocols of WBANs. In the following, we present some networking techniques and the studies of WBAN channels that could be used to address these challenges.

(2) The BAN Standards

Multiple standards have been proposed for WPANs, such as Bluetooth [15, 16, 117] and IEEE 802.15.4 [89, 90, 97], which are candidate approaches to address the challenges raised in WBANs. Comparisons of the traditional and new standards for the WPANS and WBANS are listed in [19]. In addition to the WPAN standards such as Bluetooth Low Energy, Bluetooth 3.0, UWB, and ZigBee, other proprietary and open technologies such as Insteon, Z-Wave, ANT, RuBee, and RFID are introduced. Insteon and Z-Wave are both proprietary specifications which define the mesh networking and can be used for home automation. Z-Wave operates in the 2.4 GHz ISM band, while Insteon utilizes both power lines and the 900 MHz ISM band. ANT is another proprietary sensor networking technology, and it features the simple protocol stack and low power consumption. ANT has been embedded in some Nike shoes to collect workout data and talk to iPod by wireless connection. RuBee and RFID are technologies to support asset management and tracking. They are complimentary specifications by utilizing different frequency bands and battery life, and used for different application scenarios.

These standards have all been implemented by application specific integrated circuit (ASIC) and are being sold in comparable volumes each year. With the advances in very large-scale integrated (VLSI) circuit, dual and even multi-standard radios are integrated on a single chip, greatly reducing the cost and hardware system complexity, which will boost the applications and deployment of WBANs.

(3) IEEE 802.15.6 MAC

The IEEE 802.15.6 working group was created in November 2007 and concentrated on developing a standard for low-power and short-range wireless networks [99]. The objective is to address the challenges in covering the wide application spectrum and tough reliability and energy efficiency requirements in WBANs. In December 2011, the 802.15.6 standard was approved for WBANs operating in the vicinity of or inside a human body (the standard is not limited to humans). The standard can support different kinds of applications as discussed earlier. The physical and MAC layer schemes are specified. Each application has specific QoS requirements, in particularly, the data rate, reliability, and energy efficiency, and these parameters may not be simultaneously optimized. One of the key features of 802.15.6 is the flexibility and manufacturers can select the proper PHY and MAC schemes for the target application scenario.

The PHY is responsible for (1) the operations of the radio transceiver, (2) channel status estimation and selection, and (3) signal processing and detection. IEEE 802.15.6 specifies three operational PHYs. The UWB and human body communication (HBC) schemes are mandatory while the narrowband one is optional. Furthermore, according to the scenario and network setting, a set of carrier frequency bands can be selected [17]. The frequency spectra which can be used by WBANs are managed by the spectrum authorities in various countries, as summarized in [129]. The technology to adopt can be selected depending on the applications and radio regulations. For example, the radio signals in lower frequency bands experience less path loss and attenuation by a human body, but UWB frequency band offers higher transmission speed. Furthermore, some particular applications are regulated to be allowed only at certain frequencies (e.g., implants may operate only at 402–405 MHz worldwide).

In the MAC layer, nodes are organized into one or two-hop star-topology wireless networks. Similar to other low-power standards, 802.15.6 utilizes a network coordinator (or hub) to control the behavior of each device. In a WBAN with two-hop topology, a node which is capable of relaying data can serve as the relay to forward frames from a node to a coordinator and vice versa.

The IEEE 802.15.6 specifies multiple channel access modes. The representative one is the beacon mode which utilizes a superframe structure for timing boundaries. The coordinator sends out *beacons* periodically to setup a timing reference. The intervals between beacons are *superframes* and each superframe is divided into small intervals called *slots* which are used by the sensor nodes in a multiple access manner. In this mode, the coordinator is responsible for allocating the slots by beacon frames. The coordinator transmits beacons in active superframes where there are transmissions inside. If there are no scheduled data to transmit, one or more inactive superframes can be inserted. As illustrated in Fig. 2.7, the superframe is divided into exclusive access phases (EAPs), random access phases (RAPs), a managed access phase (MAP), and a contention access phase (CAP). The EAPs are utilized by nodes to transfer high-priority or emergency traffic, while the RAPs and CAP are designed to accommodate bursty traffic. In the EAP, RAP, and CAP

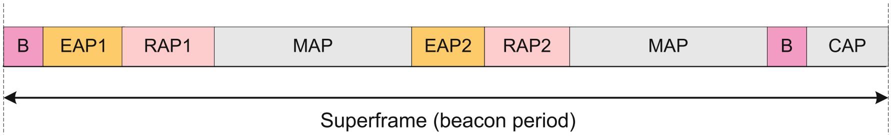

Fig. 2.7 Beacon mode with superframe boundaries in IEEE 802.15.6

periods, the coordinator may employ slotted ALOHA and CSMA/CA for UWB and narrowband PHYs, respectively. The MAP period is used for the allocation of uplink, downlink or both. Type I polled and posted allocations which are used to obtain scheduled allocations based on the access scheduling mechanism are also transferred in MAP. A detailed description of these schemes can be found in [99].

In addition, IEEE 802.15.6 introduces a polling and posting mechanism which is also referred to as "improvised and unscheduled access". In this mechanism, the coordinator informs the devices that they have been given time slots to transmit or receive data exclusively. It can select the improvised access to transmit poll or post commands. In this mode, a station may not perform pre-reservation or provide notice in advance in the beacon mode or the non-beacon mode with superframe boundaries. The commands can be employed to initiate the transactions of one or multiple data frames transmitted by the nodes or coordinator outside the scheduled allocation interval. Each device does not need to implement all of the access control mechanisms, and it can just select only those suitable for its operation.

Reliability is another key consideration in many BAN applications, especially when used for medical care. Considering that radio spectrum has been more and more crowded, the mutual interference among a variety of wireless networks is also increasing. The IEEE 802.15.6 task group has attempted to improve the robustness against interference of WBANs from various aspects. First, FCC has approved the allocation of 40 MHz of spectrum bandwidth for low-power medical BAN (MBAN) in the band of 2360–2400 MHz.[1] Thus the traffic from medical BAN can be off-loaded from the already saturated ISM band of 2400–2500 MHz. Second, by shifting or rotating the offsets of the beacon periods, the coordinator can switch the scheduled slot allocation. Consequently, the impact of interference can be further reduced. Third, the standard provides a dynamic channel hopping method which allows the network to escape from the narrowband interference from other systems. Finally, the standard has also specified a two-hop relaying by using a single relay node. This mechanism can be used when the basic star network topology with single-hop transmissions only cannot provide the necessary levels of reliability. For example, when a person is blocking the LOS path between a pair of transceivers,

[1]The 2360–2400 MHz frequency range is available on a secondary basis. As this spectrum is primarily used for aeronautical telemetry, usage of the this frequency band is restricted to indoor operation at health-care facilities and are subject to registration and site approval.

the link may be attenuated too much due to the propagation obstruction to keep the received signal power above the receiver sensitivity [120, 151].

In IEEE 802.15.6, energy utilization is increased via the mechanism of low-power sleep mode. Sensor nodes can stay in the sleep mode for a long time (e.g., for a number of beacon periods) before transmission/reception. Boulis et al. [17] presented four MAC techniques that can be used to increase both the 802.15.6 system reliability and the energy utilization.

In summary, the 802.15.6 standard offers three PHY options and the hybrid mode including different channel access scheduling methods by controlling their lengths and places in a superframe. Therefore, it gives device manufacturers much flexibility in a way to select the working mode which can satisfy the requirements on cost, reliability, energy, etc., and make the tradeoff among these features according to the target application scenario.

(4) The BAN Wireless Channels

Accurately modeling the WBAN channels is vital for researchers to evaluate the network performance in realistic environments. For example, while the WBAN signals are sent from one sensor to a coordinator, the signals propagating through a body will experience attenuation, diffraction, and reflection around the body. The power fading and temporal spread of the signals will degrade the reliability and rate of data transmissions, in particular when sensors are located on various positions on a body. As shown in [147], it is preferable that the packet error rate (PER) is smaller than 1 %.

In the last decade, extensive efforts have been made to characterize the BAN channels based on both measurements and simulations, in order to predict link level performance and develop more effective antennas. These works have been conducted in both the ISM bands around 400 MHz and 2.45 GHz and the UWB spectrum between 3.1 and 10.6 GHz. In all of the bands, intra, on, and off-body propagation environments are investigated [47]. Significant progress has been made, such as the statistical models for the fading of BAN links. The channel models for different body movements and poses with sparse or rich scatterers around have been proposed. The multipath effects on signal transmissions have also been investigated [122]. For example, the measurement results in [19] have demonstrated the path loss for different body positions and frequency bands.

It has been shown that, compared with the UWB signals through the human body conduction systems, narrowband wireless communication is debatably suitable for the medical care applications. Within the spectrum of typical narrowband BANs, the radio channel is essentially flat and slow fading, and the intersymbol interference caused by multipath may be insignificant [6, 17]. The narrowband propagation channel inside a body may be modeled by, for instance, the Rician fading with an appropriate K-factor. The K-factor is the ratio between the average power of the direct propagation path and that of the scattered/reflected paths, and it denotes the channel fading level [113].

In the last decade the UWB channel modeling has drawn great interest and the standardization bodies have put a lot of effort due to the much wider available bandwidth. The standardized channel impulse response (CIR) models for UWB channels have been developed, and typical modulation schemes have been evaluated based on the channel models. For example, the authors in [154] conducted the field measurements on a human body over 3.1–10.6 GHz in an indoor environment and also in an anechoic chamber, and the path loss exponents under different conditions were obtained.

By considering the attenuation, multipath effect, interference, and mobility in wireless body channels, more applicable network structure, MAC protocols, and routing mechanisms in BANs can be developed.

2.4 Summary

The advancements in low-power, large-scale integrated circuits, and wireless communications have promoted the popularity of local, personal, and body area networks, which allow inexpensive and continuous connectivity. This chapter overviews the most important features of the network architecture, PHY, MAC, and resource management defined in the relevant standards.

The 802.11 specifications and a series of amendments have standardized a set of technologies for WLANs. The signal transmissions with the bandwidths of 5, 10, 20, and 40 MHz over multiple channels in the unlicensed 2.4, 5, 45, and 60 GHz and the sub 1 GHz frequency bands have been defined. Based on the PHY schemes, the MAC protocols for channel access and resource scheduling are specified, including the DCF, PCF, EDCA, and HCCA. The LANs based on 802.11 have successfully supported a wide range of applications from data service such as E-mail to multimedia streaming such as IPTV. Driven by customers' manifold demands and advancement of radio technologies, the expansion of the 802.11 products will continue, for example, for very high throughput and dense networks. The very high throughput (VHT) Study Group of IEEE 802.11 is working on the next-generation WLAN standards.

IEEE 802.15, Bluetooth, ZigBee, etc. have been designed for WPANs to cover a range of 10 m. IEEE 802.15.3c operates at the mmWave band and is supposed to provide the data rate over 1 Gbps at the MAC layer. The range of 60 GHz signals is very limited due to high propagation attenuation at this high frequency band. Therefore, repeaters are necessary, and the link-layer mechanisms for multihop relay need to be developed for the deployment of mmWave networks. Furthermore, other technologies such as advanced channel coding and steerable antennas with high directional gain can be employed to improve the coverage. Considering the current advancement of the 60 GHz systems, we can predict that new efficient MAC protocols for resource management are needed to fully exploit the new characteristics of the PHY and will consistently play an important role in the development of next-generation WPANs.

As the last-meter access to the Internet, WBAN is a critical part in providing ubiquitous coverage to users. Located in the close proximity of human bodies, WBANs have enabled a variety of applications, such as medical care, personal entertainment, automatic workspace, cable replacement, etc. In the last decade, the research on WBANs has been an active topic, including the application scenarios, sensor/actuator devices, radio transceivers, wireless channel models, and interconnection/coexistence of WBANs. While the WBAN technologies have realized the ubiquitous coverage, there are still many open issues to be addressed, particularly for the network interconnection and resource management.

The development of the WLANs, WPANs, and WBANs is driven by the interdisciplinary research interest and great efforts from the academia, industry, and standardization bodies such as the IEEE 802 working group. New challenges need to be met in the development of the wireless networks, including

- Extreme energy efficiency,
- Unique characteristics of the wireless channels,
- Inter-operability and seamless connectivity,
- Managing interference,
- Application requirements, and
- System and device-level security.

While these technologies are currently in the primitive stage, they are undergoing rapid development. A preliminary introduction of the network standards is presented in this chapter, which provides a source for quick understanding of the key ideas, methodologies, and technologies of these networks and their potential applications. The interested readers are referred to the mentioned references for a more comprehensive treatment.

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