Chapter 2
Cognitive MAC Designs: Background

This chapter first presents an overview on the MAC mechanisms currently deployed in IEEE 802.11 WLANs. The basic coexistence capabilities and recent enhancements of 802.11 MAC are discussed as enablers for realizing full cognitive MAC designs. Then, the second part of this chapter reviews various state-of-the-art cognitive MAC designs in OSA networks, which serve as the background for the development of cognitive MAC designs in subsequent chapters. We discuss and categorize the MAC design approaches in OSA networks, considering the need for network-wide coordination, the network structure of SUs, and the transmission model of PUs.

2.1 IEEE 802.11 MAC Protocol as Enabler

The IEEE 802.11-based WLANs are becoming more popular and widely deployed around the world. One of the main reasons for such success is the robust and flexible MAC protocol with coexistence capabilities. In IEEE 802.11 standard, the basic MAC mechanism has two different operation modes: distributed coordination function (DCF) and *optional* point coordination function (PCF). PCF is a centralized MAC protocol in which a centralized scheduler at the AP coordinates access among different STAs by sending polling messages, aiming to support collision-free services. However, DCF is a contention-based access scheme, based on CSMA/CA using binary exponential backoff rules to manage retransmission of collided packets [1]. The uncoordinated yet reliable access mechanism of DCF made it the fundamental MAC mechanism of 802.11. In the following, the operation of listen-before-talk DCF is briefly reviewed, as an initial step toward more intelligent spectrum access schemes.

M. Derakhshani, T. Le-Ngoc, *Cognitive MAC Designs for OSA Networks*,
SpringerBriefs in Electrical and Computer Engineering, DOI 10.1007/978-3-319-12649-4_2

2.1.1 Distributed Coordination Function

DCF requires a STA, with a new packet for transmission, to sense the channel activity prior to transmission. If the channel is sensed idle for a time interval equal to a distributed inter-frame space (DIFS), the STA transmits. Otherwise, if the STA senses a transmission either immediately or during the DIFS, it continues monitoring the channel. When the channel is measured idle for a DIFS, the STA backoffs for a random period of time. The backoff mechanism enables collision avoidance by minimizing the probability of collision with other STAs. Furthermore, a STA must go through the backoff mechanism between two consecutive packet transmissions to avoid the channel capture [1].

DCF uses a discrete-time backoff mechanism, i.e., the time following a DIFS is slotted. The backoff time-slot length needs to be designed equal to the time a STA requires to detect the transmission of a packet from any other STA. At each packet transmission, the backoff time is selected according to a uniform distribution in the interval $(0, W-1)$ where W represents the contention window which is a function of the number of transmissions already failed for the packet. Each STA starts the packet transmission by setting W equal to the minimum contention window size (i.e., $CW_{\min}$). According to the binary exponential backoff rules, W is doubled after each unsuccessful transmission. Each STA increases W up to the maximum contention window size $CW_{\max} = 2^m CW_{\min}$ where m represents the maximum backoff stage [1].

The backoff time counter is decremented and a STA transmits when the backoff time counter reaches zero. Once the data packet is received successfully, the receiver waits for a period of time called short inter-frame space (SIFS), and then sends an acknowledgment (ACK). By sensing the ACK, the receiver informs the transmitter about the successful reception of the transmitted packet. If the ACK is not received by the transmitter, it retransmits that packet according to the exponential backoff rules [1].

To improve the throughput performance of CSMA/CA in IEEE 802.11, in addition to the basic access mechanism, an optional four-way handshaking technique, i.e., request-to-send/clear-to-send (RTS/CTS), has been proposed for a packet transmission. In the RTS/CTS access mechanism, a STA who is ready to transmit, after waiting for a DIFS and passing the backoff process, has to transmit a special short frame called request-to-send (RTS) before transmitting its packet. After detection of the RTS frame by the receiver, it responds by transmitting a clear-to-send (CTS) frame after a SIFS. If the CTS frame is correctly detected by the transmitter, it is allowed to transmit its packet afterwards. The RTS/CTS access mechanism effectively reduces the average collision time because collisions can be early detected by the transmitters when the CTS is not received [1].

Figure 2.1 illustrates an example of the channel-access procedure of two STAs using CSMA/CA with the RTS/CTS access mechanism. At the end of the packet transmission of STA 1, both STAs wait for a DIFS and pick their backoff times. Since the backoff time of STA 2 is shorter, it wins the competition and starts the packet transmission, while STA 1 is still in the middle of its backoff procedure.

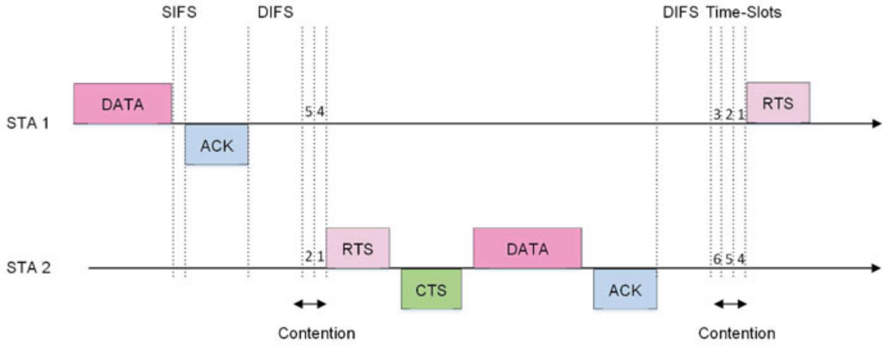

Fig. 2.1 Example of the channel-access procedure of two STAs using CSMA with the RTS/CTS access mechanism in time domain

When STA 1 senses the channel busy because of the transmitted RTS, it stops its backoff mechanism. When the channel is measured idle again for a DIFS, STA 1 joins the competition and sets its backoff time to 3 without resetting its backoff counter. However, STA 2 randomly picks a new backoff time (i.e., 6).

Although the binary exponential backoff mechanism is effective in controlling collision among STAs, the coexistence capabilities of DCF are limited. For instance, taking into account QoS support, DCF fails to adequately meet the performance requirements of voice and video applications, since it was initially developed only for best effort services. As a result, in high traffic scenarios, the delay increases significantly for different types of traffic using DCF as traffic load goes high. Thus, in the following section, we review MAC enhancements introduced by different 802.11 amendments and standards, to improve the overall throughput of the network and provide QoS guarantee for real-time multimedia applications.

2.1.2 MAC Enhancements

2.1.2.1 IEEE 802.11e for Quality-of-Service Support

IEEE 802.11e is an amendment to the IEEE 802.11 base standard which introduces significant QoS support features. To provide better QoS provisioning, it defines hybrid coordination function (HCF), which is an enhanced MAC protocol by introducing two different access mechanisms, i.e., HCF controlled channel access (HCCA) and enhanced distributed channel access (EDCA). HCF is called hybrid since two proposed access mechanisms, i.e., HCCA and EDCA, cover both centralized contention-free and distributed contention-based control, respectively [2, 3].

HCCA is an improved version of PCF to provide centralized medium access scheduling. Until now, no known device exists that uses HCCA. More popular MAC mechanism is EDCA. EDCA provides traffic differentiation between four different

AC	Voice	Video	Best Effort	Background	Legacy DCF
AIFSN	2	2	3	7	2
CW_{min}	3	7	15	15	15
CW_{max}	7	15	1023	1023	1023
TXOP(ms)	1.504	3.008	0	0	0

Table 2.1 EDCA default parameters for different ACs

access categories (ACs) or traffic classes, which are voice, video, background and best effort. These four types of traffic can have service differentiation based on the following parameters [2, 3].

- **Arbitration inter-frame space number (AIFSN):** By assigning variable waiting times (before transmission) to different ACs, EDCA can prioritize one AC over the other. More specifically, AIFSN represents the required number of backoff time-slots that a STA should wait before either starting a transmission or going through the backoff process [4]. In fact, AIFSN is a variable alternative for fixed DIFS in DCF.
- **Contention window:** Another method for service differentiation is to allow different maximum and minimum contention window sizes to different ACs. Higher priority ACs are assigned smaller $CW_{\min}$ and $CW_{\max}$, to ensure smaller backoff times, more frequent transmissions, and hence less delay.
- **Transmit opportunity (TXOP):** To decrease the collision avoidance overhead, frame bursting is offered in 802.11e in which the STA that obtains transmission opportunity (after winning in the backoff competition) can send a burst of back-to-back packets based on its channel quality for a fixed period of time. A STA cannot transmit longer than a TXOP. Consequently, in 802.11e, TXOP length can be varied for different ACs to achieve different levels of priority [5, 6].

Table 2.1 shows the default values of AIFSN, $CW_{\min}$, $CW_{\max}$, and TXOP for four different ACs recommended in the 802.11e draft standard [4].

In addition to the basic QoS functionalities provided by EDCA in 802.11e, there have been several algorithms proposed in the literature to further improve QoS in this standard. In [7], various such techniques have been presented including bandwidth allocation, data control, and distributed admission control to protect on-going high-priority traffic.

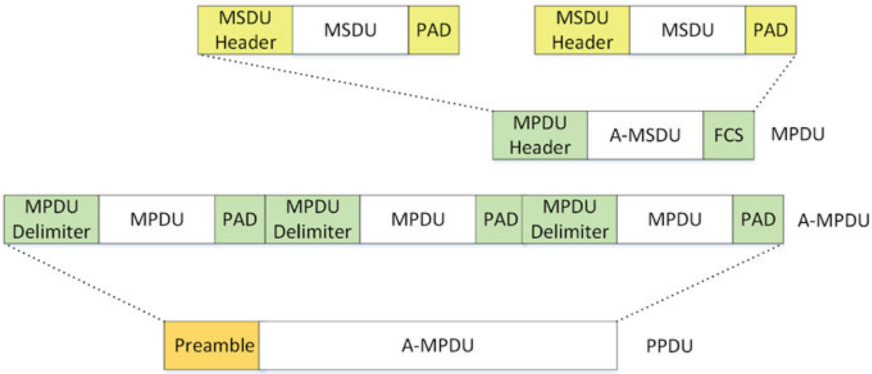

Fig. 2.2 Two-level frame aggregation with A-MSDU and A-MPDU [3]

2.1.2.2 IEEE 802.11n for High Throughput

IEEE 802.11n was released in 2009 in order to improve throughput over earlier standards (i.e., 802.11a and 802.11g). There are major PHY enhancements introduced in 802.11n such as the use of 5 GHz band in addition to the 2.4 GHz, orthogonal frequency division multiplexing (OFDM), and multiple input multiple output (MIMO). Adding 5 GHz, it creates an opportunity to have more channels with 20 MHz as well as 40 MHz bandwidth.

With a large number of packets to be transmitted, signaling load on the channel from PHY and MAC headers can be significant. Furthermore, multiple single packets will require multiple random backoff periods which will decrease the throughput as well. One way to reduce such overhead and also minimize the wasted time in waiting is frame aggregating. In the frame aggregation, by concatenating or packing multiple packets together, overheads can be added over a group of packets rather than over separate ones. Furthermore, there is no need to pass the backoff procedure for every single packet. More specifically, the three major MAC enhancements developed in 802.11n to reduce overheads are aggregated MAC service data unit (A-MSDU), aggregated MAC protocol data unit (A-MPDU), and block acknowledgments (BA), which are explained in the following [3, 8–10].

- **MSDU Aggregation:** The principle of A-MSDU is to concatenate multiple MSDUs destined for the same receiver into a single MPDU. This will require only one MPDU header for all aggregated MSDUs within an A-MSDU. In order to achieve this aggregation, the incoming packets from the link layer are first buffered to collect a number of them before aggregation. Although MSDU aggregation reduces overheads, it will increase delay for these packets which is a drawback for aggregation. As shown in Fig. 2.2, each MSDU has its own headers of source and destination addresses, data packet length, and some padding bits in the end. A-MSDU aggregates only those packets which have the same source and destination addresses [3, 8–10].

- **MPDU Aggregation:** The principle of A-MPDU is to allow multiple MPDUs to be concatenated and sent with a single PHY header. This achieves reduction in overhead by decreasing the number of required PHY headers. Each MPDU consists of an A-MSDU along with a MPDU header and frame check sequence (FCS) for data validation. While forming an A-MPDU, padding bytes are added along with a MPDU delimiter which is added for each MPDU. MPDU delimiter contains the MPDU length field and the signature field [3, 8–10].
- **Block Acknowledgment:** During a TXOP, a STA sends a burst of frames separated by SIFS. Instead of sending back an ACK for each frame, a BA is sent in 802.11n. The transmitter sends a BA request, then the receiver responds with a BA after a SIFS period. The length of a SIFS is 10 μs for 2.4 GHz and 16 μs for 5 GHz band in 802.11n. To further improve efficiency, the reduced inter-frame space (RIFS) has been introduced which is only 2 μs of length, and thus much shorter than SIFS. This results in reduced overheads of frequent ACKs and waiting times [3, 8–10].

2.1.2.3 IEEE 802.11ac for very High Throughput

Although the recent WLAN standard 802.11n can support up to 600 Mbps for a single STA in a BSS, the network-wide throughput is still restricted by the maximum link data rate. To improve the network throughput, IEEE 802.11ac has been developing since 2011 and was approved in January 2014. The major PHY enhancements in this standard are supporting wider channel bandwidths, higher modulation schemes, larger number of MIMO spatial streams, and, last but not least, downlink multi-user MIMO. Enabling channel bonding techniques, in 802.11ac, separate 40 MHz bands can be combined to form one 80 MHz or even 160 MHz channel, which leads to increase the overall throughput to more than 1Gbps. Modulation up to 256 QAM is possible in this standard adding two bits per symbol as compared to 64 QAM in the earlier standard to increase the throughput. Additionally, 8×8 MIMO and downlink multi-user MIMO are supported in order to enable sending multiple packets to multiple STAs simultaneously [3, 11].

The MAC enhancements in this standard mainly deal with multi-user MIMO, wider channel bandwidths, and co-existence with legacy WLANs. One of the most important MAC enhancements is TXOP sharing. TXOP sharing allows multiple downlink traffic streams to be sent to multiple receivers in the same TXOP. There are serious limitations with the legacy EDCA TXOP where frames belonging to a single AC can be sent to a STA in one TXOP. Thus, neither packets belonging to different STAs nor packets belonging to different ACs could not be put in one TXOP. With downlink multi-user MIMO capability, in 802.11ac, TXOP sharing makes it possible to send packets to different ACs of the same STA as well as to different STAs within the same TXOP [3, 12].

Enabling TXOP sharing, in a downlink scenario with different AC queues at AP, each AC uses its own EDCA parameters to compete for a TXOP. Once an AC gets the TXOP, this AC is called the primary AC. After this phase, the primary

AC decides whether secondary ACs are permitted on the same TXOP or not. The primary AC can have multiple STAs as well but only one AC can be the primary AC. The length of this TXOP is also determined and limited by the transmission of the primary AC even though secondary ACs have more packets to send. After the TXOP period is over, each STA sends a BA separately in separate times to ensure packet delivery [3, 12].

In 802.11n, frame aggregation is first introduced by presenting A-MSDU and A-MPDU. To further increase MAC efficiency and improve PHY data rates, in 802.11ac, an enhanced aggregation scheme is proposed, in which maximum size of A-MSDU and A-MPDU are increased [3, 13]. Furthermore, in order to improve coexistence capabilities which is harder with wider channels because of increased overlaps, enhanced secondary channel *clear channel assessment* has been introduced along with a new operating mode notification frame as more explained in [14]. The idea behind this mechanism is that if two STAs are partially interfering with each other while their respective different APs are not aware of it, the interfered STA can notify its respective AP to use only the interference free part of the channel instead of the complete channel. Thus, based on the interference from other systems, a STA might request an AP to reduce the used channels to a subset of the original channel bandwidth where interference is minimal.

2.1.2.4 IEEE 802.11ad for Multi-Gigabit Throughput

802.11ad is an amendment to 802.11 operating in 60 GHz, aiming to support multi-Gigabit wireless communication. This standard has been developing to serve throughput intensive and short-range applications such as multimedia wireless display and local data/file transfer. The motivations to use the 60 GHz band are providing the opportunity to have larger available unlicensed band compared to 2.4/5 GHz, and hence, the chance to use wider channels, reaching up to 7 Gbps transmission data rate [3, 14–16].

Operating at 60 GHz suffers from higher propagation and atmosphere loss compared to 2.4/5 GHz. To compensate the signal attenuation, beamforming can provide a solution allowing the transmitted power to be focused. The small wavelength of 60 GHz facilitates a feasible and efficient implementation of beamforming deploying phased-array antennas. This is because large antenna arrays can be integrated in mobile devices due to their small sizes. In addition to the wider channel, beamforming also helps in increasing throughput while reducing the interference between STAs [14, 15].

The major PHY enhancement provided by 802.11ad is to present a single carrier (SC) modulation and coding scheme in addition to OFDM PHY. This SC PHY is designed to reduce processing power and enable lower complexity transceivers, using shorter symbol structure and simpler coding. Introducing both SC and OFDM modulations provides the flexibility such that OFDM PHY enables high data-rate transmissions up to 7 Gbps in frequency-selective environment, while SC PHY supports over 4.6 Gbps data-rates with low-complexity transceiver [3, 14].

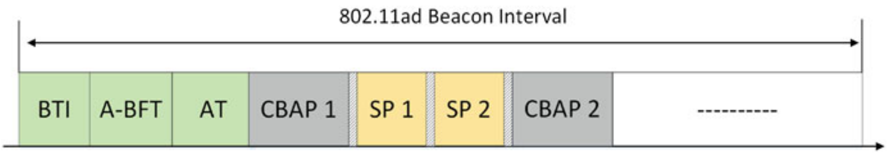

Fig. 2.3 The structure of a beacon interval in 802.11ad [3, 14]

In 802.11ad, MAC layer has been divided into two versions: basic MAC and enhanced MAC. Basic MAC is the same as the legacy 802.11e and 802.11n networks to support STAs from these networks. Enhanced MAC on the other hand is to support beamforming and high throughput through directional communication, including a *hybrid* random and scheduling-based access scheme. To provide a network more adaptable to directional transmission, 802.11ad defines a new structural building block, called personal BSS, which is also more appropriate for its target applications. In the PBSS, one STA takes the role of PBSS control point (PCP) which is responsible to transmit the beacon frames. If no beacons are received by a STA, it may become a PCP and start sending beacons. Similarly at another location, any other STA can act as the PCP. This makes this structure very flexible and adaptable [3, 14].

In a beacon interval (BI), the first phase is beacon transmission interval (BTI), in which a PCP would potentially discover new STAs by sending out beacons in different directions. In the second phase of BI, association beamforming training (A-BFT) is performed between the STA and the PCP to further tune the beamforming between PCP and STA. In the third phase, announcement time (AT), PCP transfers control and management information to all STAs. The last phase is the data transfer time (DTT), including the contention-based access periods (CBAPs) and service periods (SPs) [3, 14]. A structure of a beacon interval is illustrated in Fig. 2.3.

During a CBAP, any STA can access the channel based on the modified 802.11e EDCA with directional medium access rules, where CSMA/CA is used for channel access and aggregation for data as well as acknowledgments. A new aggregation scheme, called video aggregation MSDU (VA-MSDU), has been introduced able to support video traffic. [3, 14].

The SPs are dedicated and scheduled for particular STAs using TDMA. Since certain applications such as wireless display or VoIP have very strict requirements on jitter and delay, in order to fulfill such requirements TDMA has been introduced for SP periods of the beacon frame. Therefore SP uses TDMA for streaming and real time applications sensitive to jitter and delay while CBAP based on CSMA/CA is used for bursty traffic such as internet browsing. TDMA allocates some time-slots in the SP fields to some STAs where they wake up on these fixed time intervals to transmit and receive information. This is also beneficial since TDMA can be used for directional communication using beamforming while CSMA/CA can only operate in omni-directional transmission and reception mode [3, 14].

Standard		802.11e	802.11n	802.11ac	802.11ad
Release		2005	2009	2014	Under Development
Data Rate			600Mbps	1Gbps	7Gbps
PHY Enhancements	**Frequency**		2.4 GHz **5 GHz**	**5 GHz**	2.4/5 GHz **60 GHz**
	Channel BW		20 MHz **40 MHz**	20/40 MHz **80 MHz** **160 MHz**	**2160 MHz**
	Modulation		B/QPSK 16 QAM **64 QAM**	B/QPSK 16/64 QAM **256 QAM**	**OFDM** & **SC**
	MIMO Streams		4×4	8×8, Downlink MU-MIMO	-
MAC Enhancements	**Service Differentiation**	4 Access Categories	-	TXOP Sharing	Beamforming
	Frame Aggregation	Packet Bursting (TXOP)	A-MSDU A-MPDU Block ACK	Larger A-MSDU A-MPDU	VA-MSDU
	Access Mechanism	EDCA	EDCA	EDCA	Directional CSMA+TDMA

Table 2.2 Evolution of PHY and MAC enhancements in recent IEEE 802.11 generations

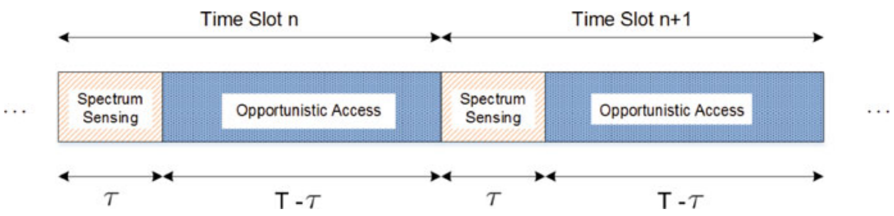

Fig. 2.4 Example of a general 2-phase time-slot structure for SUs

2.1.3 Summary of MAC Enhancements

Table 2.2 summarizes and compares MAC and PHY specifications, and also enhancements in all recent and upcoming 802.11 WLAN standards. The MAC enhancements are categorized into three categories considering proposed service differentiation, frame aggregation, and medium access techniques.

2.2 MAC Protocols for Opportunistic Spectrum Access

Although the MAC mechanisms of 802.11 standards can be already considered as cognitive MAC protocols, OSA requires more intelligent and flexible MAC protocol designs, specifically in the face of QoS support. MAC design in OSA networks includes two key functions, i.e., *spectrum sensing* to identify instantaneous spectrum opportunities, and *spectrum access* to coordinate SUs and protect PUs.

Spectrum sensing is one of the key elements in the establishment of cognitive radio, since its accuracy and response time directly affect the efficiency of opportunistic spectrum access. SUs need to periodically sense the channels to detect spectrum holes and avoid collisions. More specifically, each SU needs to follow a slotted transmission scheme. Each time-slot with an equal duration T consists of two periods: *sensing* of duration τ and *transmission* of duration $(T - \tau)$. Figure 2.4 depicts an example of the general time-slot structure employed by SUs.

Different approaches have been proposed for spectrum sensing in OSA networks, such as matched filtering, energy detection (e.g., in [17]), and feature cyclostationary detection (e.g., in [18]). We refer the interested reader to [19, 20] and references therein for reviewing recent advances in spectrum sensing techniques. Though MAC layer is not responsible for adopting a sensing approach, MAC protocols mainly support scheduling of spectrum sensing, e.g., optimizing sensing and transmission time tradeoff.

In the cognitive MAC design in OSA networks, *spectrum access* is responsible to maximize the spectrum utilization of SUs by properly designing their spectrum access strategies, while limiting the conflicts between SUs and PUs. More specifically, spectrum access specifies that which channels are assigned to who, when, and for how long. Different cognitive MAC protocols, including coordinated

http://www.springer.com/978-3-319-12648-7

Cognitive MAC Designs for OSA Networks
Derakhshani, M.; Le-Ngoc, T.
2014, XI, 96 p. 35 illus. in color., Softcover
ISBN: 978-3-319-12648-7