Chapter 19

Millimeter-Wave (mmWave) Medium Access Control: A Survey

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Abstract
As millimeter-wave (mmWave) radio wave propagation is highly directional, new medium access control (MAC) mechanisms are required for directional mmWave wireless systems. Therefore, directional beam management is required in mmWave MAC. This chapter summarizes the beam management schemes in academic literatures and industry standards in mmWave systems. In addition, mmWave-specific scheduling and relaying features are discussed. Video streaming and cellular network-related MAC features are also introduced in this chapter.

19.1 Introduction
One of the fundamental roles of medium access control (MAC) in wireless and computing networking is “collision and interference management.” One of the most famous and successful random access schemes in wireless networking is carrier sensing multiple access with collision avoidance (CSMA/CA), and this also coordinates wireless medium access with the concept of collision avoidance.

However, collision and interference management is no longer a key role in millimeter-wave (mmWave) wireless networks because of the high directionality of mmWave wireless beams/links [1]. If the azimuth and elevation beamwidths are assumed to be \( \theta \) and \( \phi \), respectively, the probability of interference existence is theoretically analyzed as \( \left( \frac{\theta}{2\pi} \right) \left( \frac{\phi}{2\pi} \right) \) [2]. Therefore, the probability of interference existence is around \( 7.7 \times 10^{-2}\% \) when the azimuth and elevation beamwidths are 10°; that is, interference management is no longer an important element in mmWave wireless networks [1].

On the other hand, “directional beam management” has become one of the key research topics in high-directional mmWave wireless networks such as “beam training and tracking.” Based on this research direction, the Institute of Electrical and Electronics Engineers (IEEE) 802.11ad standard, which is one of the best-known 60 GHz mmWave wireless standards, contains a detailed description of “Beamforming and Training.” If cellular base stations (BSs) want to use mmWave technologies for next-generation fifth-generation (5G) cellular networks, the directional mmWave antennas in the BS should be able to rapidly track mobile cellular users. Otherwise, mobility support is no longer possible. Therefore, fast beam training and tracking are essential for using mmWave in mobile cellular systems.

The remainder of this chapter is organized as follows. Section 19.2 gives an overview of mmWave beam management schemes in IEEE standards and academic literatures. Section 19.3 presents an overview of scheduling and relay selection methodologies for mmWave wireless systems. Section 19.4 presents the video applications of mmWave wireless systems and corresponding MAC features. Section 19.5 presents the MAC design considerations of next-generation 5G mmWave wireless cellular networks. Finally, Section 19.6 concludes the chapter.
19.2 Directional Beam Management in mmWave MAC Design

As explained in Section 19.1, directional beam-management schemes are important in mmWave wireless systems. Therefore, this section presents various beam-training schemes in IEEE standards and academic publications.

19.2.1 Exhaustive/Brute-Force Search

The general beam-forming and training procedure using transmit beam forming (TXBF) is illustrated in Figure 19.1, as explained in [3]. In Figure 19.1, each beam-training initiator (BI) and beam-training responder (BR) has $N$ beam directions.

First of all, the brute-force search with transmit beam forming works as follows. To initiate the beam-training procedure, the BI sweeps through all beam directions, transmitting one training packet in each direction. During this time, the BR receives the packets with an omnidirectional antenna pattern. At the end of this period, the BR can figure out which beam direction of the BI resulted in the highest signal-to-noise ratio (SNR) at the BR. Subsequently, the BI and the BR exchange their roles and repeat the procedure, allowing the BI to determine the direction of the BR leading to the highest SNR. A last step of exchanging feedback packets allows both sides to learn their own optimal directions.

A variant of this approach uses receive beam forming (RXBF) instead of TXBF, as illustrated in Figure 19.1a. Each node, BI and BR, has $N$ beam directions. The BI transmits packets in the omnidirectional mode, while the BR scans through all directions; then the BI and the BR exchange roles. The two nodes then know their best beam directions without further exchange of feedback packets. In addition,
the brute-force search with receive beam forming is not impacted by constraints on equivalent isotropically radiated power (EIRP), but only on transmitted absolute power.

As presented in [4,5], the beamwidth of commercial mmWave high-gain horn and Cassegrain antennas is near 1°, and similar values can be achieved with adaptive antennas of realistic size. Thus, in the worst case, $N$ should be $360°/1° = 360$ for two-dimensional beam geometry and $360°/1° \times 1800°/1° \approx 6.5 \times 10^4$ for three-dimensional beam geometry. Consequently, the beam-training procedures can require a significant overhead.

### 19.2.2 Two-Stage Beam Training in IEEE Standards

This section presents an overview of currently existing standardized mmWave beam-training schemes. In IEEE, there are two standards for 60 GHz mmWave wireless networks, IEEE 802.15.3c WPAN and IEEE 802.11ad WLAN, as explained in [4,5].

In the IEEE 802.11ad WLAN and IEEE 802.15.3c WPAN beam forming and training, the standards use a two-stage beam-forming and training operation: coarse-grained beam training (called sector sweeping in IEEE 802.11ad and low-resolution (L-Re) beam training in IEEE 802.15.3c) and fine-grained beam training (called beam refinement in IEEE 802.11ad and high-resolution (H-Re) beam training in IEEE 802.15.3c [6–8]).

If the standards consider TXBF, BF and BI determine the optimum coarse-grained beam according to the exhaustive-search protocol described in Section 19.2.1. In the next stage, fine-grained beam training, the same type of operation is performed to identify the best beam in each coarse-grained beam. Similar principles hold when RXBF is considered. This procedure is illustrated in Figure 19.2.

![Two-stage beam training in IEEE standards.](image)

**Figure 19.2** Two-stage beam training in IEEE standards.
Even if both standards have their own specific beam-forming and training protocols, the protocols are fundamentally based on two-stage beam training. While this can accelerate the beam forming, it is still slow, as shown by simulation results in [5].

In addition, the numbers of coarse-grained and fine-grained beam-training search spaces also have an impact on the performance of beam-training speed. The proposed algorithm in [9] finds the numbers of coarse-grained and fine-grained beam-training search spaces that minimize the overall number of control signal transmissions. This reduces the beam-training time as well as the number of transmitted control signals. This is good for fast link configuration, and is additionally beneficial in terms of energy awareness, as discussed in [9].

19.2.3 Interactive Beam Training

The fundamental reason why brute-force search is inefficient lies in the fact that even when a BI or a BR finds a fairly good beam direction, it cannot stop in the middle of the brute-force search operation, because it has to search all possible beam directions. Of course, to find the globally optimum direction, a complete search is necessary. However, it is often sufficient to find a “good enough” direction that can maintain the mmWave wireless communications. Therefore, beam-training overhead can be reduced by letting the beam search stop when both the BI and the BR find acceptable beam directions. This is the main design philosophy of interactive beam training, and details are presented in [4,5].

As illustrated in Figure 19.3, the BI and the BR change their communication mode between transmitter (TX) and receiver (RX) after every training packet transmission. Thus, after sending a training packet in an omnidirectional TX (Omni-TX), the device, either the BI or the BR, updates its communication mode as a beam-formed Rx (BF-RX) to receive the training packet from

![Figure 19.3 Interactive beam training.](image-url)
the given direction of the opposite side via RXBF. Having identified a beam direction with “sufficient quality” (i.e., sufficient SNR), the RX will continue the search till it can be sure of having found a local optimum, that is, until it has determined that the SNR is worse on both sides of the “sufficiently good” direction. This is done to increase the robustness of the received scheme, and in light of the fact that finding the local optimum does not impose a significant increase in training overhead. This concept is illustrated in Figure 19.3 (termination condition).

If either the BI or the BR finds an acceptable beam direction in a BF-RX mode, it can piggyback this information on the next training packet. When both the BI and the BR have found their acceptable beam directions, this beam-training procedure immediately stops.

The performance of interactive beam training is well studied, and the plotting is shown in Figure 19.4 [5]. As presented in this figure, if the link configuration time is less than the session reinitiation thresholds of voice over IP (VoIP) and video services, the link can be reconnected and serve the corresponding VoIP or video services without any disconnection. The exhaustive search with RXBF shown in Figure 19.4 (i.e., brute-force search with RXBF) cannot serve VoIP and video services even if the beamwidth is near 10°. In the case of average performance, if the beamwidth is larger than 5.3°, VoIP service can be served (i.e., VoIP service sessions can be reconnected before the session threshold expires) even though the service user is moving. Similarly, if the beamwidth is larger than 9°, video streaming service can be served (i.e., reconnection of video service sessions before the

![Figure 19.4 Performance of interactive beam training.](image-url)
session threshold expires) even though the service user is moving. In the case of worst performance, if the beamwidth is larger than 7.5°, VoIP service can be served (i.e., VoIP service sessions can be reconnected before the session threshold expires) even though the service user is moving.

### 19.2.4 Prioritized Sector Search Ordering

To accelerate the average search speed, the order of RX beam directions to be searched can be prioritized. For this purpose, this proposed prioritized sector search ordering (PSSO) orders the segmented spaces in terms of network association request/response (NAR) statistics. Note that the term *segmented spaces* is equivalent to “sectors” in IEEE 802.11ad and “low-resolution (L-Re) beams” in IEEE 802.15.3c.

This PSSO is quite useful in mmWave wireless systems, because physical obstacles can constitute very strong attenuators, thus greatly restricting the angular range from which useful signals can come in a given room (this is especially true for walls, which can be easily penetrated by microwaves, but are impervious to mmWaves, and which might not be effective reflectors for certain geometric configurations either). The regions with the highest number of NAR statistics might thus constitute the angular regions from which radiation can physically occur, or they might be regions that are preferred by users. This operation is illustrated in Figure 19.5.

In Figure 19.5, the system has eight sectors, and each sector has its own different NAR value. The NAR of Sector 8 is the highest value, which means that the sector has the best population. Thus, the system starts beam searching from Sector 8. In the same way, the system searches the given sectors in terms of ordering by NAR statistics.

![Figure 19.5 Prioritized sector search ordering.](image-url)
19.3 Scheduling and Relay Selection for mmWave Systems

In conventional wireless networking systems, designing scheduling algorithms is one of the key issues in wireless MAC research. Due to the high directionality of mmWave wireless communications, network device densification is achievable by spatial reuse. However, there is discussion in the literature about scheduling schemes even in mmWave high-directional wireless communications with various optimization criteria. In addition, several relaying schemes are proposed and introduced in the 60 GHz mmWave IEEE 802.11ad standard to combat the short-distance data transmission limitation due to high attenuation in the air.

19.3.1 Scheduling

The fundamental directionality is considered on top of various currently existing channel access mechanisms. The scheme proposed in [10] considers directionality in CSMA/CA random access. Similarly, the algorithm proposed in [11] is for time division multiple access (TDMA) under consideration of spatial reuse due to the high directionality of mmWave beams.

In addition, directional CSMA/CA can cause a deafness problem, which is clearly defined in [12], and the issue was resolved with a multihop RTS/CTS mechanism in high-directional wireless mesh networks.

Lastly, due to the high attenuation characteristics in mmWave radio wave propagation, blockage-aware robust scheduling algorithms have also been designed in [1,13].

19.3.2 Relay Selection in IEEE 802.11ad

According to the limited coverage of IEEE 802.11ad, the standard draft defines two kinds of relaying, link cooperating (LC) and link switching (LS), as explained in [14].

In LS, if the source–destination direct physical mmWave wireless propagation link is disrupted, the source redirects the mmWave wireless transmission of frames addressed to the destination via the relay. The direct link between the source and the destination can resume after the direct link between them has been recovered.

In LC, a frame transmission from the source to the destination is repeated by the relay even when the source–destination link is being used at the same time. This may increase the signal quality received at the destination by taking advantage of cooperative diversity and improve the network capacity significantly [15]. For LC, both cooperative communications with amplify-and-forward and cooperative communications with decode-and-forward are possible. Since it offers better performance than LS, we henceforth consider only LC.
Furthermore, the possibility of source and destination communicating with each other without relaying noncooperative communications needs to be taken into account.

Interestingly, constructing relay networks are required for both indoor and outdoor applications, but the fundamental reasons are different. In indoor applications, the relay deployment is needed to combat non-line-of-sight (NLOS) situations, whereas in outdoor applications, the relay deployment is required for extending wireless communication coverage.

### 19.4 Video Streaming

#### 19.4.1 Uncompressed Video Streaming Indoors

Since the year 2000, mmWave wireless systems have attracted a lot of attention, because an mmWave system was used for uncompressed high-definition (HD) wireless video transmission, and thus the WirelessHD consortium was established to define 60 GHz mmWave wireless technologies for this point-to-point stationary video streaming. In addition, the major use case scenarios of 60 GHz IEEE 802.11ad are for indoor video streaming over 60 GHz mmWave wireless channels.

In the WirelessHD and IEEE 802.11ad standards, CSMA/CA is also defined; however, the standards consider reserved/scheduled time allocation (with TDMA) for this wireless HD video streaming.

In a 1080p HD video stream, one frame consists of $1080 \times 1920$ pixels, each of which is represented by $3 \times 8 = 24$ bits (8 bits red, green, and blue [RGB]). Thirty frames of image data are transmitted per second in a standard mode. Thus, the required data rate to transmit uncompressed 1080p HD video is approximately 1.5 Gbps ($1080 \times 1920 \times 24 \times 30$). In enhanced mode, the number of frames per second is doubled, and thus a data rate of 3 Gbps is required. For the format of YCbCr 4:2:0 (instead of RGB), the number of bits in a frame is half as many as for a frame of RGB; that is, 0.75 and 1.5 Gbps are required for uncompressed 1080p HD video streaming in standard and enhanced modes, respectively.

The 60 GHz mmWave IEEE 802.11ad standard includes four subchannels with a bandwidth of 2.16 GHz for each; thus, uncompressed 1080p HD video wireless transmission can be achieved in ideal channel conditions.

#### 19.4.2 Real-Time Video Streaming Outdoors

In outdoor video streaming, most applications are for longer-distance scenarios compared with indoor applications. As calculated in [16,17], the achievable distance when the target threshold is set to 1 Gbps is about 200–300 m even if high-gain Cassegrain and horn antennas are used. This means that mmWave wireless links are not suitable for long-distance outdoor video delivery. To overcome this
disadvantage, it is necessary to construct relay networks. A well-studied example is given in [16,17]. The authors construct two-hop relay networks and then design an algorithm for joint relay selection and video stream allocation.

As illustrated in Figure 19.6, each source (a wireless video camera) is located at the top of the target network. Each source records video signals, which are delivered to relays and eventually arrive at the destination $D$ (i.e., the broadcasting center). In this architecture, the authors [16,17] designed an optimization framework for joint source coding and video stream distribution.

As illustrated in Figure 19.7, HD video cameras record the scene using the embedded camera. Then, the recorded signals travel to a scalable video coding (SVC) encoder, and the bit streams are reorganized as layered information (one basement layer and multiple enhancement layers for video quality enhancement). If the mmWave channel condition is not good, the source needs to compress more (select a lower number of enhancement layers) for transmitting video signals in a real-time manner. On the other hand, if the channel condition is quite good, the source node can transmit more enhancement layers for better video quality.

![Figure 19.6 Two-hop outdoor mmWave streaming networks.](image)

![Figure 19.7 Source devices in outdoor mmWave streaming platforms.](image)
As illustrated in Figure 19.8, each relay receives streams from its connected sources. Then, each relay aggregates the streams and sends them to the final destination (the broadcasting center).

As illustrated in Figure 19.9, the broadcasting center is wirelessly connected with all deployed relays. Then, the broadcasting center aggregates all signals from end-hop wireless HD video cameras; it generates multimedia contents; and forwards the contents to customers.

19.5 Next-Generation Wireless Cellular Network MAC

As presented in Figures 19.10 and 19.11, two types of cellular networking architectures are considered for mmWave cellular networks.
In Figure 19.10, 5G BSs are directly talking with deployed mobile users via mmWave wireless access. For this purpose, fast beam-training and tracking algorithms are required for supporting mobile services.

However, deploying mmWave BSs in entire areas is not possible because of the cost. Because mmWave beams are directional, the mmWave BSs should be densely deployed, which is worse in terms of deployment cost. Therefore, deploying mmWave (APs) in required areas can be considered in terms of cost-effective design. Figure 19.11 illustrates the deployment of mmWave small cells. Service providers can deploy mmWave small cells only in the required hot-spot areas. In addition, the backhaul links between the APs and the BS can be designed with mmWave channels to achieve high capacity.

Lastly, direct communication between two mobile users (so-called device-to-device communications) can be performed with mmWave wireless technologies, because most device-to-device applications are for social network-based video delivery; that is, a large bandwidth is required for higher data rates. In [18], a device-to-device routing algorithm under the consideration of video-quality maximization is proposed.

For these three major mmWave cellular access technologies (broadband mmWave cellular access, small-cell mmWave cellular access, and device-to-device cellular access), the following considerations are required for cellular MAC protocol design.

For broadband and small-cell mmWave cellular access technologies (as in Figures 19.10 and 19.11), fast beam-training and tracking algorithms are required for mobile service support. In addition, reliable technologies to support mobile users who are suffering from blockage and NLOS situations are required.

For device-to-device cellular access technologies, fully distributed MAC should be additionally designed, because there is no centralized network component that...
can make adequate scheduling decisions. One good example of fully distributed MAC mechanisms for cellular networks is FlashLinQ, which was designed by Qualcomm. Because the key component of FlashLinQ is signal-to-interference ratio (SIR)-based scheduling, the implementation of FlashLinQ for mmWave wireless channels will be simpler, because interference in mmWave wireless systems is rare [19].

19.6 Concluding Remarks

This chapter discusses MAC issues in mmWave wireless systems. Because mmWave radio wave propagation is highly directional, interference is no longer a major consideration in MAC. Rather, managing high-directional beams has become a major consideration in mmWave MAC design. Therefore, fast mmWave beam-training and tracking algorithms have been discussed in mmWave research. This chapter summarizes beam-training and tracking algorithms in academic literatures and IEEE standards (including IEEE 802.11ad and IEEE 802.15.3c). Then, fundamental scheduling and relaying technologies are introduced. In addition, video streaming in indoor and outdoor scenarios in mmWave wireless systems is discussed. Lastly, various mmWave cellular architectures (broadband, small-cell, and device-to-device networks) are presented, and corresponding design issues are addressed.

References


