Chapter

MAC Aspects of Millimeter-Wave Cellular Networks

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Abstract

The current demands for extremely high data rate wireless services and the spectrum scarcity at the sub-6 GHz bands are forcefully motivating the use of the millimeter-wave (mmWave) frequencies. MmWave communications are characterized by severe attenuation, sparse-scattering environment, large bandwidth, high penetration loss, beamforming with massive antenna arrays, and possible noise-limited operation. These characteristics imply a major difference with respect to legacy communication technologies, primarily designed for the sub-6 GHz bands, and are posing major design challenges on medium access control (MAC) layer. This book chapter discusses key MAC layer issues at the initial access and mobility management (e.g., synchronization, random access, and handover) as well as resource allocation (interference management, scheduling, and association). The chapter provides an integrated view on MAC layer issues for cellular networks and reviews the main challenges and trade-offs and the state-of-the-art proposals to address them.

Keywords: millimeter-wave systems, initial access, resource allocation, mobility management, MAC layer design, 5G

1. Introduction

Increased demands for higher data rates in wireless communication systems, along with new applications such as massive wireless access have motivated enhancing spectral efficiency by using advanced technologies such as full-duplex communications, cognitive and cooperative networking, interference cancelation, and massive multiple-input multiple-output (MIMO). As these enhancements are reaching the fundamental capacity limits, determined by the available spectrum at the sub-6-GHz bands, the millimeter-wave (mmWave) band is becoming an alternative and promising option to support extremely high data rate wireless access [1–3]. The main reason is simple: the aggregated bandwidth of most current (main) commercial wireless systems is <2% of the bandwidth available at the mmWave. Such bandwidth can easily support a Gbps data rate in most use cases.

At the moment, the main use cases of the mmWave spectrum are satellite communications, military applications, point-to-point systems, local multipoint distribution service, and short-range networks [4]. Severe attenuation of the signal at the mmWave band, especially at certain frequency bands such as 60 and 180 GHz (see Figure 1.1 in [5]), had led to a common belief that mmWave communications are suitable either for special applications with special hardware (as mentioned above) or for “whisper radios” for wireless personal area networks (WPANs) with coverage distances of a few meters [2]. However, recent studies on mmWave mobile networks have convinced academia, industry, and regulatory bodies to repurpose the mmWave band for future wireless (and even mobile) networks.

MmWave communications are particularly attractive for ultra-short range/high rate communications and gigabit wireless applications such as wireless gigabit Ethernet and uncompressed high-quality video transmission, see **Table 1**.

Usage models	Latency (s)	Availability	Range (m)	Rate (Gbps)	Application scenarios
Ultra short-range communications	<1	NS	<10	10	Wireless tollgate and kiosks to transfer e-magazine, picture library, 4K movie trailers, 4K movies
Video streaming in smart homes	<0.005	NS	<5	28	8K video stream between a source device (e.g., set-up box, tablet) and a sink device (e.g., smart TV, split TV), replacement of wired interface
Augmented reality	<0.005	NS	<10	20	Interface between a constantly moving high-end wearable devices and its managing device to deliver 3D video
Data center	<0.1	99.99%	<5	40	Inter-rack connectivity, wireless backup connection
Vehicular networks	<0.1	NS	<1000	NS	Intra- and inter-car connectivity, intersection collision avoidance, public safety
Video on-demand	<0.01	NS	<100	NS	Broadcast in crowd public places (e.g., classroom, in flight, train, ship, bus, exhibitions)
Mobile offloading	<0.1	99.99%	<100	20	Offload video traffic from cellular interface to the mmWave interface
Mobile fronthauling	<0.035	99.99%	<200	20	Wireless connections between remote radio heads and base band unit
Mobile backhauling	<0.035	99.99%	<1000	20	Small cell backhauling, mutihop backhauling, inter-building communications

Table 1.
Application scenarios for mmWave networks. This table is deduced from ongoing discussions inside IEEE 802.11ay study group. "NS" means not specified yet.

The commercial potential of mmWave networks initiated several standardization activities within WPANs and wireless local area networks (WLANs), such as IEEE 802.15.3c [6], IEEE 802.11ad [7], WirelessHD consortium, Wireless Gigabit Alliance (WiGig), and recently IEEE 802.11ay study group on next-generation 60 GHz [8].

The unique hardware requirements and propagation characteristics of mmWave networks lead to many challenges at the physical, medium access control (MAC), and routing layers [9]. These challenges are exacerbated by the potential spectrum heterogeneity, i.e., coexistence with the legacy sub-6-GHz systems. Compared to the sub-6-GHz communications, mmWave systems exhibit orders of magnitude higher path loss and atmospheric absorption, higher penetration loss, very sparse-scattering environments, smaller wavelength, a much higher number of antenna elements, which may result in high antenna gains and possible noise-limited operation. These unique features demand a significant reconsideration in the design principles of the communication architecture and protocols, especially at the MAC layer.

2. Fundamentals

2.1 The directed mmWave wireless channel

MmWave communications use frequencies in the range 10–300 GHz. The mmWave systems exhibit high path-loss, high penetration loss, high frequency/short wavelength, and very large bandwidth. The small wavelength allows for the implementation of massive numbers of antennas in both transmitter and receiver, which boosts the achievable antenna gain with some extra signal processing, without affecting the size of their radio chips.

The additional antenna gain can almost completely compensate for the higher path-loss of mmWave communications. A byproduct of the directional communication is the new concept of directional spatial channel, i.e., a channel can be established in a specific direction with a range that varies according to the directionality level [9]. Directional communications and vulnerability to obstacles in mmWave networks have two main consequences: (1) deafness and (2) blockage [9].

Deafness refers to the situation in which a directional communication link cannot be established due to misalignment between the beams of the transmitter and the receiver. To address this problem, we may need a time-consuming procedure of beam training. That is, an operation in which the transmitter and receiver find a beam pair, pointing to each other, which maximizes the link budget. In one hand, the alignment procedure complicates the link establishment phase. On the other hand, it substantially reduces multiuser interference [10], as the receiver listens only to a specific directed mmWave channel. In the extreme case, mmWave networks may operate in a noise-limited regime where multiuser interference is almost completely suppressed and no longer limits the throughput. This is a noticeable change with respect to the conventional interference-limited sub-6 GHz networks. This unique feature makes mmWave suitable for ultra-dense networks (also called massive wireless access) with dense deployments of infrastructure nodes and terminals.

Blockage refers to a high penetration loss due to obstacles that may not be solved by increasing the transmission power. Addressing blockage requires utilizing alternative directed mmWave channels that are not blocked. These channels may be provided by reflectors or intermediate relay nodes. In both solutions, overcoming blockage entails the execution of a new time-consuming beam training procedure.

2.2 Beam training

The use of low-complexity and low-power mmWave devices, along with the massive number of antennas, makes traditional digital beamforming based on instantaneous channel state information very expensive. Instead, the existing standards assume the use of analog beamforming and establish an mmWave link using the so-called beam-searching approach. This approach searches among a set of pre-defined beam steering vectors for the transmitter and the receiver (beam training codebook) and selects the best beam pairs [1, 8, 9]. More specifically, current standards suggest a three-stage beam-searching technique to reduce alignment overhead. After a quasi-omnidirectional sweep with very wide beams, a coarse-grained sector-level sweep is performed, followed by a beam-level refinement phase (the highest resolution pattern specified in the codebook). Each level involves an exhaustive search over all possible transmission and reception directions through a sequence of pilot transmissions. The combination of vectors that maximizes the signal-to-noise ratio (SNR) is then selected for the beamforming.

This beam searching process introduces a new *alignment-throughput* trade-off [11]. That is, on the one hand, a narrower beamwidth enhances the beam resolutions, so increases the alignment overhead and leaves less time for data transmission. On the other hand, it provides a higher antenna gain, leading to a higher transmission rate.

One of the main drawbacks of analog beamforming is the lack of multiplexing gain, which is addressed by the hybrid digital/analog beamforming architecture [12]. Efficient beam training for hybrid beamforming is an active field of research.

2.3 Control channel

Many operations such as establishing a communication channel, discovering neighbors, exchanging routing information, and coordinating channel access rely on the exchange of signaling messages on a control channel. The characteristics of mmWave communications introduce fallback and directionality trade-offs, which also appear in mmWave cellular networks [13].

The *fallback* trade-off is the trade-off between sending control messages through an mmWave or a microwave channel. The mmWave channel is subject to blockage, reducing the reliability of the control channel. A dedicated microwave control channel facilitates network synchronization and broadcasting at the expense of [14]. The cost of this approach is higher hardware complexity and energy consumption since an extra transceiver should be tuned on the microwave control channel. Moreover, a microwave control channel cannot be used to estimate the mmWave channel and adopt proper beamforming. Note that realizing a control channel in the mmWave band with omnidirectional transmission/reception may substantially reduce the system performance. The main reason is a mismatch between the ranges at which a high-quality data link can be established (using directional communications) and the range at which control messages can be exchanged [13].

The *directionality* trade-off arises due to the potential of establishing a control channel with multiple antennas. An omnidirectional control channel is subject to a very short range due to the lack of antenna gains, but it diminishes the deafness problem. A directional control channel benefits longer coverage at the expense of extra alignment overhead.

Altogether, we may have two justifiable realizations for physical control channels: (1) omnidirectional-microwave, employed in ECMA 387 [15], and (2) directional-mmWave, employed in IEEE 802.15.3c [6] and IEEE 802.11ad [7].

3. Initial access and mobility management

Initial access and mobility management are fundamental MAC layer functions that specify how user equipment (UE) should connect to the network and preserve its connectivity. In this section, we highlight important design aspects of initial access that should be considered in mmWave cellular networks.

3.1 Synchronization and cell search

In the long-term evolution (LTE) systems, the so-called primary and secondary synchronization signals enable acquiring time-frequency domain synchronization during the cell search phase. Current cellular networks use beamforming only *after* omnidirectional synchronization and cell search procedure. However, as pointed out in [16], performing cell search on an omnidirectional physical control channel while having antenna gain in data transmission causes a mismatch between the ranges at which a link with reasonable data rate can be established and the range at which a broadcast synchronization signal along with cell identity can be detected. At a normal free-space propagation environment at 28 GHz, the data range can be at least four times larger than the synchronization range with only 30 dBi combined antenna gains. Such a huge mismatch in the ranges of the control and data plane can severely limit the performance of mmWave cellular networks.

3.2 System information

System information includes cell configurations such as frequency band, downlink and uplink bandwidth, cell identity, random access procedure, and the number of transmit and receive antennas. In LTE, the so-called master and system information blocks embed system information. They are transmitted in the physical broadcast dedicated channel and the physical downlink shared channel, respectively. While dedicated control channels can be established with omnidirectional communications, a UE still needs to decode a directional shared channel to extract system information in an mmWave cellular network. Consequently, it will become subject to the fallback and directionality trade-offs. This is a fundamental MAC layer challenge, which is not present in the legacy microwave cellular networks, as all their rendezvous signaling are done in the single antenna mode (omnidirectional physical control channels).

3.3 Random access

At the very beginning, a UE has no reserved channel to communicate with the BS(s). In this case, it sends a channel reservation request using either contention-free or contention-based channel access schemes. In the contention-free approach, the network broadcasts multiple access signals that uniquely poll individual UEs to avoid potential collisions. Upon decoding a signal, each UE knows its uplink parameters including analog or digital beamformer, random access preamble, and allocated resource for transmission of the preamble. Embedding all this information a priori is a challenging task due to the lack of spatial synchronization at the very beginning. The contention-based approach is another strategy to send channel access requests wherein requests may be dropped due to potential collision (in the case of simultaneous transmissions in the same cell) or not be received (in the case of blockage or deafness). The comprehensive analysis of the next chapter shows that small to modest size mmWave networks operating with a simple contention-based protocol (slotted ALOHA) experience a very small collision probability. Moreover, narrower transmission and reception beams reduce the contention level, making contention-based procedures more justifiable than complex and wasteful contention-free ones [17].

In LTE, a UE triggers a timer after sending a contention-based channel access preamble, and upon receiving no response from the base station (BS), it retransmits the preamble after a random waiting (backoff) time or/and with increased transmission power. As we have discussed, the deafness problem of mmWave communications cannot be efficiently addressed by an increased transmission power or a backoff time. In fact, a UE may undergo multiple subsequent backoff executions in the deafness condition, resulting in an unnecessarily prolonged backoff time [18]. To alleviate this problem, [18] introduces a novel collision-notification (CN) signal at the MAC layer to distinguish packet drops due to a collision to those due to deafness and blockage. It builds on the following observation: if the received signal has enough energy but it is not decodable, the receiver declares a collision event. Whereas, if the received signal is not decodable due to lack of energy, the receiver declares a deafness-or-blockage event. During the beam-searching phase, if a BS receives energy from a direction that is not decodable due to collisions, it sends back a CN message in that direction. After transmitting a preamble and depending on the received control signal, a UE will take one of the following actions:

1. A reservation grant is received before the timeout: the UE starts its transmission;

2. A CN message is received before the timeout: the UE assumes a contention in that spatial direction, starts the backoff procedure, and retransmit after a random delay;

3. No signal is received before the timeout: the UE assumes that there is a deafness-or-blockage event in that directed spatial channel, investigates another direction or adjusts the transmission beamwidth.

Action three avoids unnecessary backoff procedures in the case of deafness-or-blockage events, substantially improving the performance of contention-based random access.

3.4 Mobility management and handover

Pencil-beam operations of mmWave systems suppress the interference at the price of more challenging mobility management and handover tasks. Vulnerability to random obstacles, UE mobility, and loss of precise beamforming information may trigger frequent handovers if only the received signal strength indicator (RSSI) is used as a reassociation metric [13]. Every handover may entail a beam-training overhead. In the presence of frequent handovers, the transmitter and receiver may remain most of the time in the beam-training phase rather than the data transmission phase.

To alleviate extra handovers due to random blockage, we can adopt the following association options in mmWave networks:

- Multiple parallel connectivity, and

- Single sequential connectivity.

In the first approach, a client adopts multi-beam transmissions toward several BSs (relays) at the same time to establish multiple paths, either at the same band [13] or different frequency bands [19]. This approach provides seamless handover, continuous connectivity, and blockage robustness. However, we may observe an SNR loss for each beam (when a transmitter uses a fixed total power budget), higher signaling and computational complexities for beamforming, and more complicated resource management and relay selection. Cell-free access is a very similar approach wherein a processor unit coordinates the communication among multiple BSs and UEs, without associating a UE to a particular BS [20]. To enable this mode, we may need to have digital or hybrid beamforming [21]. To reduce the computational and signaling overhead of the beamforming with many antenna elements, current mmWave standards adopt analog beamforming, avoiding the realization of multiple parallel connectivity. Instead, a client may be associated with several BSs (relays) with several paths and establishes a data channel using only one of these paths, while using the others as backups. This single sequential connectivity scenario, as reported in [22], is standard-compliant and mitigates disadvantages of the multiple parallel connectivity scenario. Moreover, recent works exploited sparse scattering properties of mmWave channels to model the spatial and temporal correlation of the mmWave channels between a stationary BS and a mobile UE [23, 24]. Using this model, they have proposed efficient beam-tracking approaches to predict and facilitate handover events.

4. Resource allocation

4.1 Interference characteristics

To design a proper hybrid MAC for mmWave networks, the main steps are analyzing the multiuser interference, evaluating performance gain (in terms of throughput/delay) due to various resource allocation protocols, and investigating the signaling and computational complexities of those protocols. Roughly speaking, as the system goes to the noise-limited regime, the required complexity for proper resource allocation and interference avoidance functions at the MAC layer substantially reduces [11, 25, 26]. For instance, in a noise-limited regime, a very simple resource allocation such as activating all links at the same time without any coordination among different links may outperform a complicated independent-set based resource allocation [11]. Instead, pencil-beam operation complicates negotiation among different devices in a network, as control message exchange may require time-consuming antenna alignment (beam-training) procedure to avoid deafness.

The seminal work in [10] shows the existence of a noise-limited regime (also called pseudowired abstraction) in outdoor mmWave mesh networks. However, indoor mmWave WPANs may not be noise-limited, as shown in [11, 25–27]. In particular, the optimal resource allocation policy may need to deactivate some links to handle the non-negligible multiuser interference [11]; the noise power is not always the limiting factor. To have a concrete example, we have simulated an ad hoc network with a random number of mmWave links deployed on a 10×10 m^2 area, all operating with the same beamwidth at 60 GHz. Each transmitter/receiver is aligned to its own communication link, and they are active with some probability p independent of the activity of the other links. We assume 2.5 mW transmission power, 16 dB/Km atmospheric absorption, (on average) one obstacle on every a 4 m^2 area, and sector blockage model [28]. We computed and depicted in **Figure 1** the area spectral efficiency (ASE), defined as the network sum-rate divided by the area size,

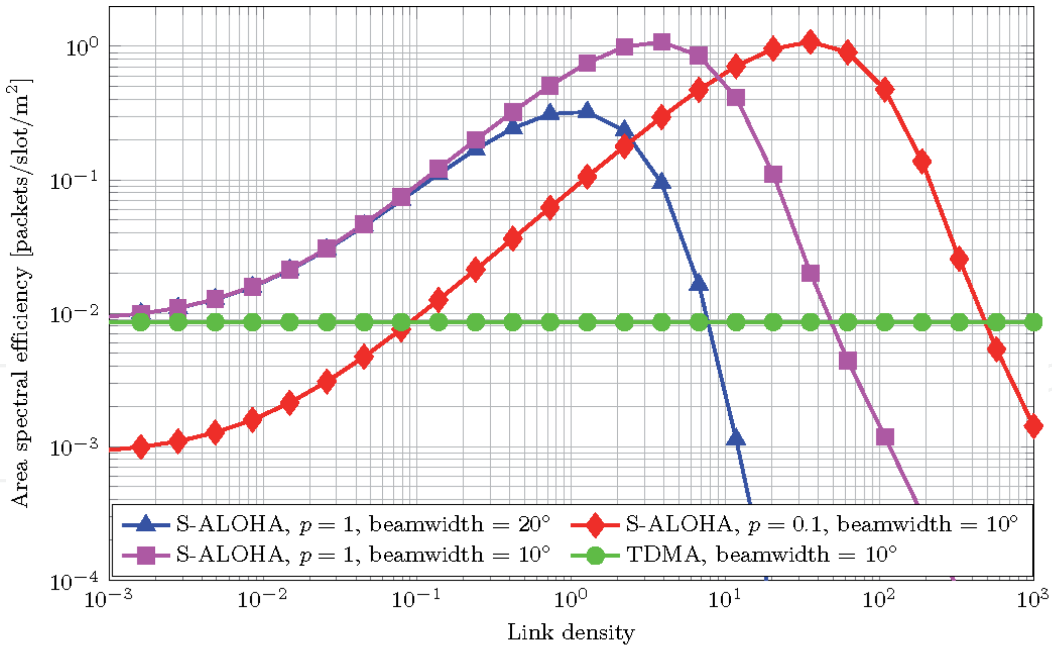

Figure 1.
Area spectral efficiency against link (one transmitter-receiver pair) density (m^2). Area size is 10 × 10 m^2. The obstacle density is one every 4 m^2. Slotted ALOHA provides substantially higher area spectral efficiency, compared to TDMA. These performance gains may improve with the number of links.

as the performance measure. From this figure, increasing the number of links in the network does not affect ASE of TDMA, which is slightly lower than one packet per slot. The reason is packet loss due to blockage on some links, and this loss almost vanishes when the obstacle density goes to zero. Slotted ALOHA with transmission probability $p = 1$ provides the highest ASE, which is firstly increasing with the link density and then shows a strictly decreasing behavior due to excessive collision. Using narrower a beamwidth or lower transmission probability alleviates the collision level and improves the ASE at the expense of the alignment-throughput trade-off [11].

The numbers of the figure indicate that, from the perspective of ASE, mmWave networks benefit from dense deployment, yet every link may observe some level of performance degradation when we increase the number of devices in the network [11]. Reference [29] reported similar observations in mmWave cellular networks. Such performance drops imply that the accuracy of the noise-limited assumption to model the actual network behavior reduces with the number of links. The increased directionality level in a mmWave network reduces multiuser interference; however, this reduction may not be enough to take an action (e.g., resource allocation) based on the assumption of being in a noise-limited regime. Consequently, a pseudowired assumption may be detrimental for proper MAC layer design. However, the interference footprint may not be so large that we need to adopt very conservative resource allocation protocols such as time division multiple access (TDMA), which activates only one link at a time, as already adopted by the current mmWave standards [6, 7]. Reference [30] proposed an index to quantify the impact of various components of the interference models and to propose a tractable and accurate interference model for mmWave networks.

4.2 Beam-searching and concurrent transmission

Despite the small interference footprint of mmWave networks, the option of concurrent transmissions scheduling was not included in the existing standards and proposed only recently. The authors of [27] consider the problem of maximizing the number of scheduled flows such that their quality of service requirement is not violated. A greedy scheduling scheme is proposed, where an additional link is activated in each time slot if it improves the total throughput, i.e., throughput gain from this extra link overweighs the performance drop due to additional interference. Reference [31] proposed a similar greedy heuristic by designing a priority ordering of the links. As long as the signal to interference plus noise ratio at all receivers exceeds a threshold, additional links are activated according to this list. The main issue of those approaches is that they are reactive protocols, i.e., a link has to be activated to deduce if it is compatible with other transmissions.

In proactive protocols, one may need to address the alignment-throughput trade-off while designing concurrent scheduling problem. Because, a narrow beamwidth, besides boosting the link budget, reduces multiuser interference, so increases SINR and thereby achievable transmission rate. However, the price of this rate enhancement is higher alignment overhead per-link and possibly complicated scheduling procedures. Reference [11] addressed this problem by an optimization problem that brings together beam-searching and transmission scheduling using estimates of the interference terms.

4.3 Association

Association governs the long-term allocation of communication resources among various BSs. Due to high penetration loss, blockage in mmWave networks may be only addressed by re-association or relaying procedures not by increasing the transmit power [9].[1] The association and relaying are particularly important in mmWave networks due to the dense deployment of the BSs and limited size of the cells [32]. Relaying techniques can provide a more uniform quality of service by offering robust mmWave connection, load balancing, coverage extension, indoor-outdoor coverage, efficient mobility management, and smooth handover operation [1, 9, 13, 32–34]. As shown in, an alternative path through relay nodes can increase the connectivity of a mmWave system by about 100%. Furthermore, the relaying technique can enable high-quality live video streaming over 300 m [34]. Therefore, proper association of clients to BSs and relaying techniques are very important routines in mmWave networks.

Developing proper association techniques has been the focus of intense research in the last years [35–40], as it may govern the long-term resource allocation policies of conventional wireless networks [35]. The current mmWave standards use the minimum-distance association, which leads to a simple association metric based on the RSSI [14]. This metric is proved to be suitable for an interference-limited homogenous network, but it may lead to poor use of the available resources in the presence of a non-uniform spatial distribution of clients, non-interference-limited environments, and heterogeneous BSs/relays with a different number of antenna elements and different transmission powers [35]. It may lead to an unbalanced number of clients per BS, drastically reducing the available resources per client in highly populated areas [13] while wasting resources in sparse areas. This poor load balancing indeed decreases network-wide fairness, since overloaded BSs cannot provide their associated clients as much resource as less-loaded BSs. Thus, it is possible for the clients to associate with farther BSs for better load sharing.

Besides the existing association techniques of the current mmWave standards, there are many more solutions for the association and relaying from the literature of microwave networks. In [37], a client association policy is investigated to ensure

[1] As an alternative approach, link establishment via reflectors may address a blockage, given the existence of such reflectors with sufficiently large reflection indices.

network-wide max-min fair bandwidth allocation to the clients in WLANs. In the seminal work of [36], a joint association and resource allocation problem is formulated for a heterogeneous cellular network to ensure network-wide fairness, by a distributed solution algorithm. These association procedures are highly sub-optimal for mmWave networks due to frequent handovers of mmWave networks and small interference footprint. Reducing the overhead of frequent reassociation, together with the natural need of load balancing among the BSs, justifies that a client in mmWave networks may be advantageously served by a farther but less-loaded and easy-to-find BS [13]. Robustness of the association to random blockage should be improved to reduce the number, and thereby the overhead/delay, of reassociation and to provide a seamless handover [9, 13]. Reference [41] addressed the association problem in 60 GHz mmWave communications. However, it did not consider relays, a vital part of mmWave networks, which substantially increases the difficulty of the association and relaying problem. This problem has been addressed in [42] where the authors showed that the optimal relay selection improves the load-balancing throughout the network and affects heavily the ability of a terminal to reach a farther BS. Moreover, [22] proposed an adaptive reassociation mechanism for time-varying mmWave networks, wherein the previous association solution is used as a proper initial guess to solve a new network-wide association optimization problem.

4.4 Spectrum sharing

Spectrum sharing between multiple operators was recently proposed as a way to allow more efficient use of the spectrum in mmWave networks. Preliminary studies have shown that the specific features of mmWave frequencies, including the propagation characteristics and narrow beam operations, facilitate spectrum sharing in the mmWave bands. Reference [43] proposed a mechanism to let two different IEEE 802.11ad access points transmit over the same time/frequency resources. To realize this mechanism, the authors introduced a new signaling report, which is broadcast by each access point to establish an interference database that facilitates scheduling decisions. A similar approach was proposed in [44] for mmWave cellular systems, with both centralized and distributed coordination among operators. In the centralized case, a new architectural entity determines the links that cannot be concurrently activated, based on the reports of the interference powers. In the decentralized case, the victim network sends a message to the interfering network. The two networks can further refine the coordination pattern via multiple iterations.

Reference [45] investigated the feasibility of sharing the mmWave spectrum between the device-to-device/cellular and access/backhaul networks and proposed a new MAC layer in order to regulate concurrent transmissions in a centralized manner. Given the sporadic presence of strong interference in mmWave networks, reference [13] showed the need for only on-demand inter-cell interference coordination as opposed to often heavy coordination requirements of spectrum sharing at the sub-6-GHz bands. Reference [46] investigated the feasibility of spectrum sharing in mmWave cellular networks and showed that, under certain conditions such as idealized antenna pattern, spectrum sharing may be beneficial even without any coordination in the entire network. Reference [47] showed that infrastructure sharing in mmWave cellular networks is also beneficial and its gain is almost identical to that of spectrum sharing. Reference [48] discussed the architectures and protocols required to make spectrum sharing work in practical mmWave cellular networks and provided preliminary results regarding the importance of coordination. Reference [49] studied the performance of a hybrid spectrum scheme in which exclusive access is used at frequencies in the 20–30 GHz range while spectrum sharing (or even unlicensed spectrum) is used at frequencies around 70 GHz.

5. Conclusions

This chapter summarized main characteristics of mmWave systems, including severe attenuation, sparse-scattering environment, huge bandwidth, blockage and deafness, and possible noise-limited operation. We discussed initial access and mobility management (e.g., synchronization, random access, and handover), characterized interference footprint and reviewed existing solutions for resource allocation in mmWave networks.

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