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A Survey of Millimeter-Wave Communication: Physical-Layer Technology Specifications and Enabling Transmission Technologies

This survey discusses the state of the art and the development trends of mmWave communication.

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ABSTRACT | Millimeter-wave (mmWave) frequency bands, which offer abundant underutilized spectral resources, have been explored and exploited in the past several years to meet the requirements of emerging wireless services highlighted by high data rates, ultrareliability, and ultralow delivery latency. Yet, the unique characteristics of mmWave, e.g., continuous wide bandwidth, large path, and penetration losses, along with hardware constraints, call for innovative technologies for mmWave communication. Recently, an extensive amount of work on mmWave communication has been carried out by researchers and practitioners from both academia and industry, and various technologies have been developed for mmWave communication systems to fulfill the full potential of mmWave frequency bands. In this article, we present a comprehensive survey of the standardization of mmWave communication, the latest progress and outcomes of the research on mmWave communication technologies, and the emerging applications of mmWave communication. In particular, we provide a timely and in-depth summary of the state-of-the-art technology specifications of mmWave communication with an emphasis on the physical (PHY) layer. Then, we elaborate on a number of well-established or promising antenna architectures in mmWave communication systems and investigate the enabling PHY layer transmission technologies. Finally, we show some existing and emerging applications of mmWave communication and discuss the potential open research issues.

KEYWORDS | Antenna architecture; hardware impairment; millimeter-wave (mmWave) communication; technology specification; transceiver design.

NOMENCLATURE

3GPP	Third-generation partnership project.
5GCM	5G channel model.

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AS	Angular spread.
AoA	Angle of arrival.
BS	Base station.
CA	Cellular access.
DAC	Digital-to-analog converter.
D2D	Device-to-device.
GHz	Gigahertz.
GC	Green communication.
HDTV	High-definition television.
IoT	Internet of Things.
IF	Interfrequency
ITU-R	ITU radio regulation.
LO	Local oscillator.
mmWave	Millimeter wave.
MIMO	Multiple-input multiple-output.
MBPAAs	Multibeam phased array antennas.
MRP	Medium-rate PHY.
O2I	Outdoor to indoor.
OFDM	Orthogonal frequency-division multiplex.
PAR	Project authorization request.
PHY	Physical.
PN	Phase noise.
PSmC	PHY security mmWave communication.
PEP	Power elevation profile.
RF	Radio chain.
rms AS	rms angular spread.
SaC	Satellite communication.
SG	Study group.
SSW	Sector level sweep.
TG	Task group.
ULA	Uniform linear array.
UMa	Urban macro.
A/VR	Augmented/virtual reality.
WB	Wireless backhaul.
WLAN	Wireless local area network.
WPAN	Wireless personal area network.
WRC	World Radio Conference.
5G	Fifth generation.
ADC	Analog-to-digital converter.
APDP	Average power delay profile.
AoD	Angle of departure.
BRP	Beam refinement phase.
CSI	Channel state information.
DS	Delay spread.
FCMBPAAs	Fully connected MBPAAS.
Gb/s	Gigabits per second.
HDMI	High-definition multimedia interface.
HRRP	High-rate PHY.
IEEE	Institute of Electrical and Electronics Engineers.
ITU	International Telecommunication Union.
LoS	Line-of-sight.
LRP	Low-rate PHY.
Mb/s	Megabits per second.
MBA	Multibeam antenna.
MCS	Modulation and coding scheme.
QAM	Quadrature amplitude modulation.
O2O	Outdoor to outdoor.
PA	Power amplifier.
PAP	Power azimuth profile.
PCMBPAAs	Partially connected MBPAAs.
PS	Phase shifter.
PPDU	PHY-layer convergence procedure protocol data unit.
Ref.	Reference.
rms	Root mean square.
RMa	Rural macro.
SC	Single carrier.
SM	Small cell.
SWIPT	Simultaneous wireless information and power transfer.
UAV	Unmanned aerial vehicle.
UMi	Urban micro.
UPA	Uniform panel array.
VN	Vehicular network.
WD	Wearable device.
WirelessHD	Wireless high definition.
Wi-Fi	Wireless fidelity.
YoP	Year of publication.

I. INTRODUCTION

According to Ericsson's mobility report, worldwide mobile subscriptions will increase to 8.9 billion, cellular IoT connections will reach 3.5 billion, and worldwide total monthly mobile data traffic will reach 107 exabytes by 2023 [1]. The proliferation of various smart devices and the popularity of mobile Internet services, as illustrated in Fig. 1, have significantly stimulated the demands for wireless communication with multi-Gb/s peak throughputs, tens of Mb/s cell edge rates, ultrareliable delivery, and end-to-end latency at the order of 1 ms. These emerging demands not only bring challenges to the design of wireless network architecture but also drive the existing communication systems to evolve toward higher frequency bands [2]. Developing wireless communication technologies that have the ability to support high data rates in ultradense networks has drawn considerable attention from both academia and industry. mmWave communication, with abundant underutilized spectral resources, provides a promising solution to satisfy the aforementioned demands in the beyond 5G and 6G wireless communication systems. However, a great deal of research is still required to enable mmWaves for mobile users, including hardware and algorithms to overcome the large path loss and penetration loss. This survey focuses on discussing the state of the art and the development trends of mmWave communication.

A. Brief Introduction of mmWave

The very limited spectral resources in microwave frequency bands are insufficient to satisfy the demands of explosive data traffic and high data rate (up to 10 Gb/s). Consequently, exploiting the vast amount of unused spectrum in high-frequency bands in 5G/6G mobile

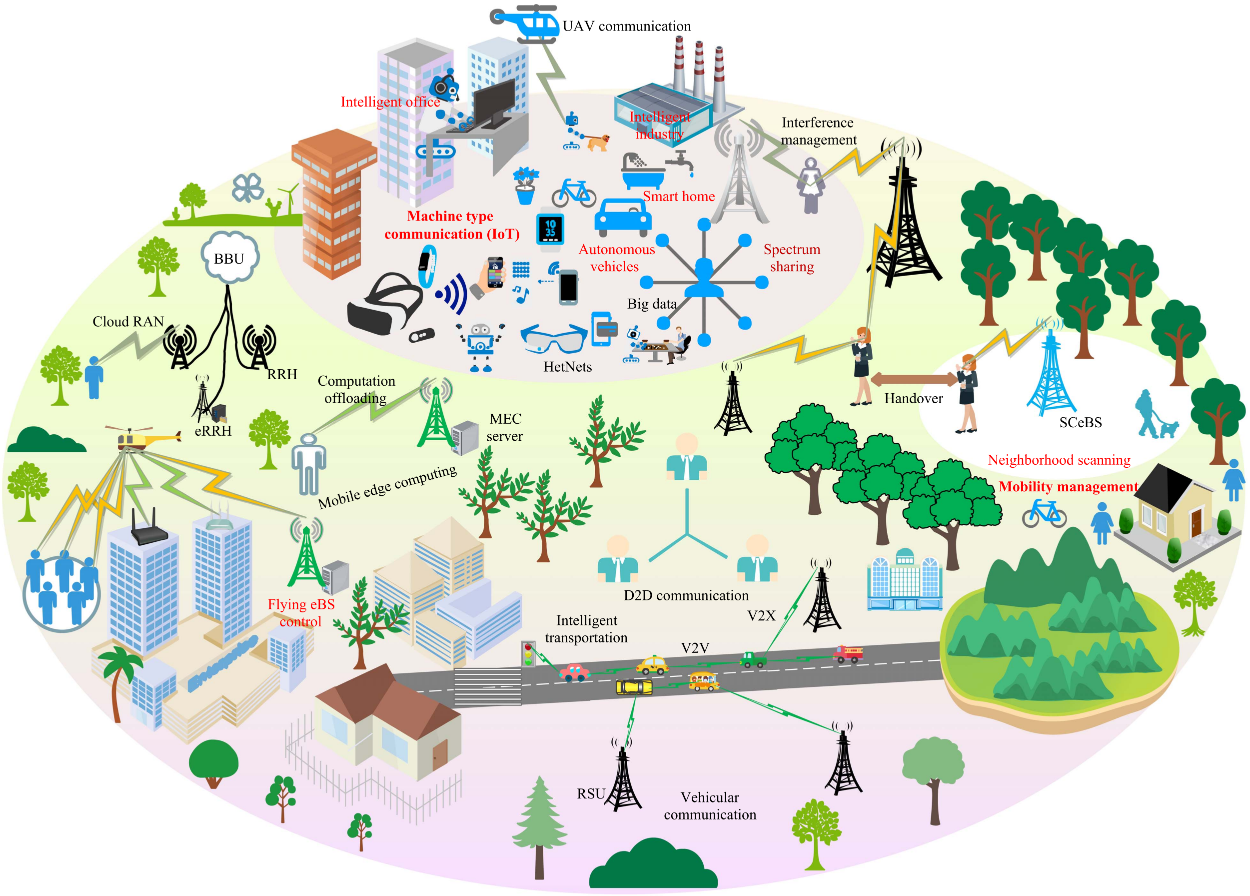

Fig. 1. ***Illustration of future communication networks.***

communication systems has recently gained significant interest from both academia and industry. In particular, mmWave communication operating at the frequency range of 30–300 GHz has emerged as a new frontier to realize extremely high rate transmission. Fortunately, the recent advancements of mmWave integrated chips pave the foundation for Gb/s wireless transmission operating beyond sub-6-GHz frequency bands. The research and development (R&D) on mmWave devices and technologies have facilitated understanding the propagation characteristics of mmWave, establishing technology specifications for mmWave communication, and designing efficient transceivers with acceptable cost and implementation complexity [3]. Until recently, researchers begin to pay a lot of attention to mmWave cellular communication networks. In practice, a large number of mmWave frequency bands have not been used in practical wireless communication systems. For example, some underutilized mmWave frequency bands include [4] the following.

1) *28-/38-GHz licensed but underutilized:* 3.4-GHz bandwidth available in total.
2) *57–64-GHz unlicensed:* 7-GHz bandwidth available in total.
3) *71-/81-/92-GHz light-licensed band:* 12.9-GHz bandwidth available in total.

In contrast with the increasingly crowded microwave frequency bands, there are abundant spectrum resources in mmWave frequency bands possibly available for wireless communication, for example, 5-GHz continuous bandwidth at above 57 GHz. It means that an extremely high data rate (10+ Gb/s) can be achieved using simple modulation schemes, such as quadrature phase shift keying (QPSK). Yet, to harvest the full benefits of mmWave communications in practice, there are many technical challenges that require novel design principles and breakthrough technologies [5].

B. Brief Introduction of Hybrid Architecture

It is widely known that, at mmWave frequency bands, electromagnetic waves suffer from severe path and blockage losses, which significantly degrade communication performance. An effective approach is to adopt large-scale antenna arrays to compensate for the performance loss. Fortunately, packing a large number of antenna elements at the transceiver and adopting directional transmission can be easily implemented in mmWave communication systems. Large arrays comprised of many antenna elements are a preferable choice for obtaining beamforming gain to overcome path loss and establish links with a reasonable signal-to-noise ratio. Furthermore, spatial

Table 1 Comparison and Summary of Related Surveys on mmWave Communication

Discussion on Technical Specifications of mmWave							Discussion on enabling PHY-layer transmission technologies									
WirelessHD	802.15.3		802.11			Cellular	Antenna Architecture	Channel model	Channel estimation	Beam-forming	Hardware impairments	Wave-form	Network layer	Use case	Ref.	YoP
	c	d	ad	aj	ay											
								✓							[6]	2017
							✓	✓		✓					[7]	2018
								✓							[8]	2018
								✓							[9]	2020
	✓		✓										✓	WB, SM, CA	[10]	2015
			✓				✓			✓				GC	[11]	2016
			✓		✓		✓			✓					[12]	2018
	✓					✓	✓	✓		✓	PA, PN	✓	✓	WD, VR, VN, SaC, 5G	[13]	2018
						✓	✓	✓	✓	✓	ADCs		✓		[14]	2017
							✓			✓					[15]	2017
			✓				✓	✓	✓	✓	ADCs				[16]	2016
						✓	✓		✓	✓		✓		Health and safety issue	[17]	2018
						✓	✓			✓			✓		[18]	2018
							✓		✓						[19]	2020
							✓	✓	✓	✓					[20]	2021
							✓	✓		✓			✓	UAVs	[21]	2018
						✓		✓		✓			✓		[22]	2018
							✓								[23]	2017
							✓								[24]	2019
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	PA,ADCs, DACs,I/Q, PSs, PN			Ultra-dense, UAV, GC, Physical security, Content-centric, Sensing and Imaging, intelligent communication, . . .	This survey	

multiplexing may be used to improve spectral efficiency via using large arrays. However, signal processing in mmWave systems is subject to a set of nontrivial practical constraints [16]. For example, in the conventional MIMO communication systems, each antenna requires a dedicated baseband and radio frequency (RF) chain, which facilitates digitally controlling the phase and amplitude of the baseband signal. However, both the hardware cost and the power consumption increase with the numbers of the antennas and RF chains, as well as carrier frequencies. Hence, it is difficult to provide an RF chain for each antenna and perform all signal processing in the baseband digitally in mmWave communication systems. This motivates us to develop new transceiver architectures and analyze their impact on MIMO signal processing, including precoding/combining and channel estimation. How to balance the system performance, hardware cost, and power consumption becomes a key point for mmWave communication systems.

An alternative approach, aiming to reduce the number of RF chains and alleviate the hardware implementation cost and computational complexity, is the digital–analog hybrid antenna array architecture for mmWave communication systems. In this architecture, transceivers have the ability to apply high-dimensional (tall) RF precoders/combiner, implemented via analog PS networks, followed by low-dimensional (small) digital precoder/combiner implemented at baseband. In the existing research, fully connected and partially connected structures are the two most commonly used digital–analog hybrid antenna array architectures. In the former, each RF chain is connected to all antennas, while, in the latter, only a subset of antennas connects with each RF chain. From the design perspective, fully connected architecture has the ability to obtain higher spectral efficiency, while partially connected architecture is expected to achieve higher energy efficiency. In addition, a variant of these two architectures, i.e., dynamically connected architecture, has also attracted the attention of some researchers [25]. There are three main difficulties for digital–analog hybrid antenna array architectures. First, each element of an analog transceiver is constrained to constant modulus. Second, the cascade of the analog precoder/combiner and digital precoder/combiner complicates the transceiver design. Third, the number of antennas is larger than that of RF chains, which makes it very difficult to obtain sufficient information to directly estimate the channel coefficients. Meanwhile, the directional transmission requires a large number of training overheads. To overcome these difficulties, in recent years, researchers from both academia and industry have done various studies on mmWave communication. In addition, many novel mmWave antenna designs, such as the Lens antenna and fully digital antenna architecture, have been investigated extensively for mmWave communication systems.

C. Related Surveys of mmWave Communication

In this section, we review some existing surveys on the progress of mmWave communication, as listed in Table 1. Rappaport *et al.* [6] provide an overview of mmWave communication for 5G wireless networks from the perspective of propagation models. They begin by describing an architecture of the 5G wireless network, aiming to provide great flexibility to support a myriad of Internet protocol devices, SM architecture, and dense coverage areas. After a brief introduction of propagation challenges of mmWave, they comparatively summarize channel models, including the LoS model, large-scale path-loss models, O2I penetration loss, and spatial consistency developed by the various parties, such as the 3GPP TR 38.901, 5GCM, mobile and wireless communication enablers for the Twenty-Twenty Information Society (METIS), mmWave-based mobile radio access network for 5G integrated communications (mmMAGIC) model, mmWave evolution for backhaul and access (MiWEBA) channel model, and quasi-deterministic radio channel generator (QuaDRiGa) model. Hemadeh *et al.* [7] give a more comprehensive summary of the propagation characteristics of mmWave and further discuss the efforts and challenges of mmWave channel modeling. To effectively exploit mmWave frequency bands for future wireless communication, they provide some constructive guidelines for the system architecture and antenna design and further discuss the link budget analysis of mmWave networks. Wang *et al.* [8] first summarize the requirements of the 5G channel modeling and then extensively review the progress of channel measurements and models in recent years. Finally, they provide future research directions for channel measurements and modeling. Abadal *et al.* [9] review the state of the art in wave propagation and channel modeling by characterizing the wave propagation at chip scales with different methods and discuss, in detail, the works on mmWave, terahertz, and optical frequency bands. At the same time, they discuss the major challenges with the characterization of the wireless network-on-chip channel and potential solutions to address them. Their analysis shows that, compared to microwave, mmWave possesses a high path loss, penetration loss, and precipitation attenuation. To overcome these shortcomings of mmWave and achieve performance enhancement, directional transmission and (massive) MIMO are two enabling techniques to simultaneously achieve the diversity, multiplexing, and beamforming gains for mmWave communication systems.

Niu *et al.* [10] first review the propagation characteristics of mmWave and the concept of basis service set of IEEE 802.11ad and 802.15.3c.[1] They further discuss interference management and spatial reuse mechanisms, including time division multiple access, multihop concurrent transmission mechanism, carrier sensing multiple access/collision avoidance, and frame-based directive medium access control (MAC), taking into consideration the propagation characteristics of mmWave. The use case of mmWave, e.g., SM, D2D in cellular, and WB, is discussed. Finally, some open research issues, including MIMO, full duplex, soft defined, control mechanism, heterogeneous network, and network state measurement, are pointed out for the research of future mmWave communication. Kutty and Sen [11] focus on discussing the beamforming of three potential antenna architectures, i.e., analog antenna array, fully connected architecture, and partially connected architecture. Furthermore, they describe in detail the beam training procedure of 802.11ad and the codebook design for mmWave communication systems. Some emerging research trends, including mmWave MIMO beamforming, multiuser concurrent beamforming, joint transmit–receive beamforming, hybrid beamforming, and beamforming for GC and security communication, are suggested for mmWave communication systems. By recalling the directional multiple Gb/s channel access and directional multiple Gb/s beamforming mechanisms in 802.11ad, Zhou *et al.* [12] discuss the beam training procedure in detail, which may be used in the next generation of 802.11ad, i.e., 802.11ay, taking into account the channel bonding mechanism and multiuser mmWave communication. Note that the surveys [11] and [12] mainly focus on the beam training procedure based on codebook for mmWave communication.

Wang *et al.* [13] provide a comprehensive survey from the perspective of taxonomy, research on PHY-layer, MAC-layer, network layer, cross-layer optimization, use case, and available resources of mmWave communication. In particular, about the research of PHY-layer, they first discuss the impact of nonlinear distortion of PA and PN on mmWave communication systems, as well as the development of reflector antennas, lens antennas, horn antennas, mmWave microstrip antennas, on-chip antenna, and phased antennas. Then, the beamforming selection, precoding, channel model, new waveforms, and security of mmWave communication are discussed. Following that, the related protocols of mmWave in *ad hoc* network, mesh network, WPAN, and cellular network are briefly discussed from the perspective of MAC-layer. They further summarize the related works on the network layer, cross-layer optimization, use case, and the available resource of mmWave communication. For the application of mmWave in future mobile networks, Xiao *et al.* [14] first discuss the key challenges and potentials, such as large path loss, abundant spectrum resource, and narrow beam, of mmWave communication systems. Then, they summarize the related channel measurement actives and briefly introduce various channel models. They review the concept of three potential MIMO antenna architectures, i.e., fully connected architecture, partially connected architecture, and lens antenna, and discuss the channel estimation based on codebook and channel tracking, low-resolution ADC architecture, and the related progress in [14]. Furthermore, they discuss the multiple access technologies, e.g., spatial division multiple access and nonorthogonal multiple access (NOMA), backhaul, coverage, and connectivity topics for mmWave communication. Finally, the authors briefly discuss the standardization of mmWave frequency bands in 3GPP from the viewpoint of use cases, mmWave and massive MIMO, and hybrid beamforming architecture.

Three hybrid beamforming structures are categorized for the downlink transmission at BS according to the connection relation between RF chains and antennas [15]. Molisch *et al.* [15] further point out the challenges encountered in the design process of the transceiver, such as the couple between the analog domain and digital domain, the constant modulus on the analog domain, and finite precision hardware implementation. To overcome these challenges, they discuss the design of hybrid precoding according to the instantaneous or average CSI and then suggest adopting a dynamic hybrid structure to adapt

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[1] "IEEE" is omitted when referring to its WLAN and WPAN standards.

to the change of CSI to achieve the best performance of hybrid beamforming. Heath, Jr., *et al.* [16] provide an overview of signal processing challenges in mmWave wireless systems. They first summarize the propagation characteristics of mmWave and then discuss the antenna architectures, including antenna array, (adaptive) hybrid antenna structure, and lens antenna structure. Afterward, they focus on the design of precoding/combining and channel estimation based on dictionary codebook by using the spatial sparsity of mmWave and the orthogonal matching pursuit methods. In addition, they discuss the design of hybrid receivers with lower resolution ADCs, beam training, and sparse channel estimation in lens-based continuous aperture phased MIMO transceivers. Busari *et al.* summarize the progress of mmWave communication starting with discussing the evolution of cellular network technologies, such as from MIMO to massive MIMO, multitier cellular heterogeneous networks, and the propagation characteristics of mmWave [17]. They further discuss the progress of mmWave massive MIMO models, including the antenna architecture, precoding, channel estimation, channel measurement and modeling, and receiver processing techniques. In addition, the authors summarize the cross-layer design considerations, such as waveform, access scheme, and fronthaul design. Ahmed *et al.* [18] summarize the research progress of hybrid beamforming technologies from the perspective of the configuration of transceiver antenna and RF chains for mmWave communication. They further discuss the mmWave heterogeneous network and the resource management, including resource block allocation, beam management, MAC, and initial search and tracking for mmWave cellular communication. The work [19] summarizes the research progress on channel estimation for mmWave communication with several architectures, including the analogy antenna array, hybrid architecture, lens array architecture, and few-bit ADCs architecture. Uwaechia and Mahyuddin [20] investigate the channel modeling, beamforming, and SWIPT for mmWave communication. They further simply discuss some potential topics for 5G research activities.

Zhang *et al.* [21] first discuss the integration of mmWave and UAVs from the viewpoint of key technical advantages and challenges of mmWave. Then, they present in detail the progress of antenna design, beam tracking and optimization, and channel model for mmWave UAV communication. The mobility of UAVs makes the mmWave UAV communication mechanism different from that of cellular and Wi-Fi communication. Consequently, some specific research issues, such as the UAV BS placement and trajectory tracking, are carried out for mmWave UAV communication. Mezzavilla *et al.* [22] summarize the end-to-end simulation of mmWave network from the perspective of the evaluation of network performance via using ns-3 network simulator. The construction modules of the simulation platform are given out in detail for evaluating the performance of mmWave cellular networks. In addition, Hong *et al.* [23] and Ghosh and Sen [24] provide a summary of the progress of the design of antenna array for mmWave communication from the viewpoint of hardware implementation.

D. Scope and Organization

Though there exist surveys on an overview of the research progress of mmWave communication, the lack of radio resources and the requirements of emerging data traffic on wireless communication have been driving the rapid development of emerging mmWave communication technologies in recent years. Different from the aforementioned studies, this survey starts with a comprehensive investigation of standardization of mmWave communication, especially for WLAN and WPAN mmWave technology specifications, as well as mmWave cellular communication. We identify and discuss in detail the differences among established and proceeding technology specifications of mmWave communication from the perspective of PHY-layer technologies. Then, we investigate in-depth the antenna structures and designs that may be used in the technology specifications or in the practical communication systems. Moreover, we study the state of the art of PHY-layer transmission technologies that make mmWave communication available in practice. Finally, the recent progress of emerging use cases of mmWave communication is introduced. The specific structure of this survey is shown in Fig. 2, and the outline of the contributions are presented as follows.

1) To cater for the rapid growth and high data rate requirement of various emerging data services, new technology specifications of mmWave communication, such as 802.15.3c/d, 802.11ad/aj/ay, and mmWave cellular communications, have been established or are to be established by the standardization organizations, such as IEEE and 3GPP. To compare their difference, this survey investigates the PHY-layer transmission technologies of these technology specifications.
2) This survey further analyzes several popular or potential mmWave antenna architectures that are used or may be used in the technology specifications or practical mmWave communication systems or extensively applied in the literature from the perspective of antenna design.
3) This survey summarizes the latest study progress of enabling PHY-layer transmission technologies, including channel estimation and tracking, analog beamforming, hybrid precoding, and fully digital transmission for mmWave communication with hybrid architecture and fully digital architecture.
4) We also provide a summary of related researches in several emerging applications of mmWave communication, including ultradense mmWave communication, UAV mmWave communication, green mmWave communication, PHY-layer security mmWave communication (PSmC), content-centric

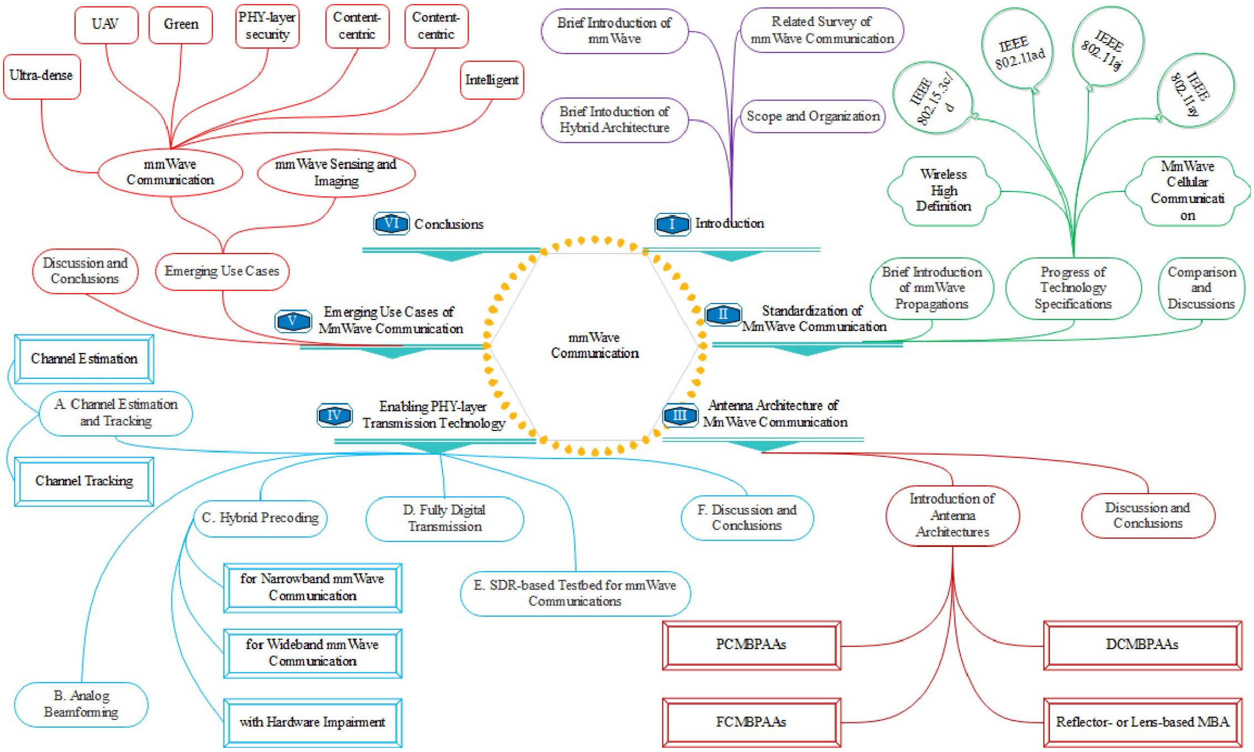


Fig. 2. *Structure of this survey.*

mmWave communication, and intelligent mmWave communication.

The remainder of this survey is organized as follows. The progress of technology specifications is described in Section II. Few potential antenna array architectures are summarized in Section III. The research progress of enabling PHY-layer transmission technologies is investigated in Section IV. Section V discusses the research progress of several emerging applications of mmWave communication. Conclusions are drawn in Section VI. A complete list of acronyms is given in Nomenclature.

II. STANDARDIZATION OF mmWave COMMUNICATION

In the future wireless communication networks, enhanced mobile broadband, massive machine type communication, and ultrareliable low-latency communication are three major application scenarios. In these scenarios, high data rate (10+ Gb/s), ultrareliable, and ultralow latency are three key performance indices. For example, A/VR applications require Gb/s data rate, and typical emerging IoT applications require a latency from 0.25 to 10 ms and an outage probability (or packet loss rate) in the order of 10^{-3}–10^{-9} [26]. It is challenging for current communication systems operating at sub-6-GHz frequency bands to satisfy these targets due to the lack of radio resources. For example, the 802.11ac can only achieve the maximum theoretical data rate of 7 Gb/s [27], and the 802.11ax under development has the ability to support the transmission rate with up to 10 Gb/s [28]. However, in practice, it is difficult to realize these theoretical peak data rates due to various communication constraints. To achieve higher data rates, Wi-Fi alliance and IEEE standard organization have established a series of technology specifications for mmWave frequency bands, including WirelessHD [29], 802.15.3c [30], 802.15.3d [31], 802.11ad [32], and 802.11aj [33]. In addition, IEEE standard organization is establishing a new technology specification, i.e., 802.11ay, operating at 60-GHz frequency band, to support higher data rates [34]. The main usage cases of WirelessHD and 802.11ad/aj/ay are listed in Table 2 [35]. Meanwhile,

Table 2 New WLAN Usage Models

Category	Usage Model
Wireless display	• Desktop storage and display • Projection to television (TV) • Projector in conference room or auditorium • In-room gaming • Streaming from camcorder to display • Professional HDTV outside broadcast pickup
Distribution of HDTV	• Video streaming around the home • Intra-large-vehicle applications • Wireless networking for office • Remote medical assistance
Rapid upload&download	• Rapid file transfer/sync • Picture-by-picture viewing • Airplane docking (manifests, fuel, catering,···) • Downloading movie content to mobile device • Police surveillance data transfer
Backhaul	• Multi-media mesh backhaul • Point-to-point backhaul
Outdoor campus/auditorium	• Video demotele-presence in auditorium • Public safety mesh (incident presence)
Manufacturing floor	• Automation

Table 3 Summary of mmWave Channel Measurement Activities

Group	Measurement domain	Frequency (GHz)	Scenario	Ref.	YoP
NCEPU	Time domain	32	Outdoor	[38]	2017
NIST	Time domain	60, 83.5	Indoor	[39]	2018
NYU	Time domain	38, 60, 73	Outdoor, Indoor	[40]	2015
QUALCOMM	Time domain	60, 61	Outdoor, Indoor	[41]	2017
Shandong University	Frequency domain	38, 60	Indoor	[42]	2017
Southeast University	Time domain	25.5, 28, 37.5, 39.5, 45	Indoor	[43]	2018
Tongji University	Frequency domain	39, 72	Outdoor, Indoor	[44]	2015

Table 4 Summary of mmWave Channel Measurement Parameters

Frequency (GHz)	Scenario	Parameters	Ref.	YoP
32	Outdoor (Campus)	PADP, Path-loss, RMS DS, RMS AS, K-factor, numbers of cluster	[38]	2017
38	Indoor (Office)	APDP, PAP, PEP, RMS DS, correlation properties, and massive MIMO properties	[42]	2017
39	Outdoor (Campus)	Vegetation attenuation, RMS DS, AS	[45]	2018
60	Indoor (Office)	RMS DS, RMS AS, inter-cluster and intra-cluster parameters	[46]	2017
73	Outdoor (Rural)	Path-loss	[47]	2017
83.5	Indoor (Laboratory)	Power-azimuth-delay profile, path-loss, doppler frequency spread, coherence time	[48]	2016
37.5, 39.5	Indoor (Conference room)	RMS DS, cross-polarization ratio and cross-correlation coefficients	[43]	2018
30, 140, 300	Indoor	Path-loss	[49]	2017

3GPP is carrying out the standardization of new radio technologies for mmWave frequency bands over 52.6-GHz frequency bands [36].

A. Brief Introduction of mmWave Propagations

In developing a new technology specification, the first task is to establish the propagation channel model, which is the foundation of evaluating the link- and system-level performances of various communication technologies [37]. In order to understand, in-depth, the mmWave propagation characteristics more comprehensively and accurately, in recent years, a large number of measurement activities have been carried out via various measurement methods. In particular, there are a lot of channel measurement activities for the 15-, 28-, 38-, 45-, 60-, 73-, and 80-GHz frequency bands, respectively. For example, the researchers in New York University (NYU) conduct extensive measurements for the 28-, 38-, 60-, and 73-GHz frequency bands. National Institute of Standards and Technology (NIST) and QUALCOMM have done various measurements for other frequency bands. Some research groups in China, including Shandong University, Southeast University, North China Electric Power University (NCEPU), and Tongji University, also explored the propagation characteristics of mmWave via propagation measurements. A summary of mmWave channel measurement activities is given in Table 3, and the latest measurement parameters are listed in Table 4. The results obtained by these measurement activities show that mmWave has very different channel propagation characteristics compared with microwaves, such as high path loss, high penetration loss, high directivity, high delay resolution, and large human blockage loss. To effectively characterize the propagation features of mmWave, many new channel models are established by many organizations from both industry and academia. An overview focusing on the propagation models of mmWave is provided for 5G wireless network [6], and some important mmWave channel models are listed in Table 5.

B. Progress of Technology Specifications

1) Wireless High Definition: In most home consumer electronic systems, the high-definition video is transferred using HDMI cables that are expensive and have length restrictions. To reduce the implementation cost and increase the flexibility in installation, wireless transmission is a promising alternative to HDMI cable transfer or wired transmission. Driven by this, the WirelessHD specification established by the first industrial consortium and not Wi-Fi compatible aims to provide a high-definition digital interface operating at the 60-GHz frequency band. WirelessHD specification defines a novel wireless protocol that enables directional connection with the ability to adapt to the change of environments [29].

Table 5 Summary of mmWave Channel Models

Channel Model	Frequency (GHz)	Scenarios	Ref.	YoP
QuaDRiGa	0.45 to 100	UMa, UMi, RMa, indoor.	[50]	2014
MiWEBA	60	Access scenarios (open area, street canyon and hotel lobby), backhaul/fronthaul scenarios (above roof top, street canyon) and D2D scenarios (open area, street canyon and hotel lobby).	[51]	2014
METIS	up to 100	UMi, UMa, RMa, Indoor office, cafeteria, square, shopping mall, stadium, highway, open air festival.	[52]	2015
5GCM	6 to 100	UMi (street canyon, open square) with O2O and O2I, UMa with O2O and O2I, indoor (open and closed office and shopping malls).	[53]	2016
mmMAGIC	6 to 100	UMi (street canyon, open square), UMa, indoor (office, shopping mall, airport), O2I, stadium, and metro station.	[54]	2017
3GPP	0.5 to 100	UMi street canyon, UMa, indoor office including open office and mixed office, and RMa scenarios.	[55]	2017

Table 6 HMRP Frequency Plan

Channel index	Start frequency (GHz)	Center frequency (GHz)	Stop frequency (GHz)
1	57.240	58.320	59.400
2	59.400	60.480	61.560
3	61.560	62.640	63.720
4	63.720	64.800	65.880

A massive antenna array that supports dynamic beamforming and beam steering is adopted to compensate for the large path loss and weak penetration of mmWave in WirelessHD specification. The dynamic beamforming and beam steering not only optimize the LoS link but also utilize the reflections and other indirect paths when the LoS connection is lost. Furthermore, two kinds of antenna architectures are suggested in WirelessHD specification, i.e., partially connected and fully connected antenna architectures, which are discussed in detail in Section III-A. Meanwhile, two different methods for beamforming are defined in the WirelessHD specification, i.e., explicit feedback beamforming and implicit feedback beamforming.

WirelessHD specification supports three kinds of PHY-layer mechanisms, i.e., HRP, MRP, and LRP with OFDM modulation. A total of four channels in the frequency range of 57–66 GHz is listed in Table 6 for both HRP and MRP (HMRP). Not all of these channels are available in all geographic regions due to regulatory restrictions. However, for LRP, five LRP channels are defined within each of the four HMRP channels, and only one LRP channel is used for each transmission at a time. Both HMRPs support multiple Gb/s throughputs at a distance of 10 m through adaptive antenna technology. However, LRP is multiple Mb/s bidirectional links over a range of 10 m. When transmitting a single stream, HRP can achieve at least a 7-Gb/s data rate. When spatial multiplexing and high-order modulation with a high coding rate are adopted, HRP can provide 28+ Gb/s data rate [29].

2) IEEE 802.15.3c/d: The 802.15.3 Task Group 3c (TG3c) has developed an mmWave-based alternative PHY-layer in 802.15.3c, which was published in October 2009 [30]. The operating frequency of 802.15.3c-2009 is within the 57.0–66.0-GHz range allocated by the regulatory agencies in Europe, Japan, Canada, and the United States. Note that these frequency bands can also be available in other areas, depending on the regulatory bodies. The channelization defined in 802.15.3c-2009 is the same as WirelessHD specification given in Table 6 [30].

802.15.3c-2009 defines three PHY modes, i.e., SC mode, high-speed interface mode, and audio/visual mode. Three classes of MCSs are provided by SC mode for different wireless connectivity applications. Through using SC PHY, 802.15.3c-2009 supports very high data rate (up to 5 Gb/s) transmission for short-range (10 m) applications, including high-speed Internet access, streaming content download (video on demand, HDTV, home theater, and so on), real-time streaming, and wireless data bus. The high-speed interface mode using OFDM modulation is designed for devices with low-latency and bidirectional high-speed transmission. The audio/visual mode is further divided into two PHY modes, HRP and LRP, both of which use OFDM modulation. To further increase the data rate, a high rate close proximity PHY is defined in 802.15.3e-2017 to achieve the largest data rate 52.5652 Gb/s with 256 QAM and code rate 14/15 by bonding four 2.16-GHz bandwidth channels [56].

To effectively improve the signal quality, 802.15.3c-2009 recommends to use full analog antenna architecture and also provides the beamforming codebooks for antenna array with uniform spacing of 0.5λ, where λ denotes the carrier wavelength. Each beamforming codebook is identified by the number M of antenna elements and the desired number K of beam patterns. For the case where $K \geq M$, the codebook beam vectors are given by for $m = 0, \ldots, M-1$, and $k = 0, \ldots, K-1$

$$\mathbf{W}(m,k) = j^{\mathrm{fix}\left\{\frac{m \times \mathrm{mod}[k+K/2,K]}{K/4}\right\}} \tag{1}$$

where $j = \sqrt{-1}$, function $\mathrm{fix}(\cdot)$ returns the biggest integer smaller than or equal to its argument, and $\mathrm{mod}(a,b)$ is the modulo operation. The generation of codebooks given by (1) is simple because they are generated with a 90° phase resolution without adjusting amplitude for reducing power consumption. The shortcomings of codebooks generated by (1) are detailed in [11, Sec. III. C]. Fig. 3 illustrates the polar plots of array factor $M = 4$ for the 2-bit resolution codebook defined in 802.15.3c-2009, the 3-bit resolution codebook, and discrete Fourier transformation codebook. The codebooks defined in 802.15.3c-2009 result in the beam gain and loss in some beam directions. The 3-bit resolution beam codebook and discrete Fourier transformation codebook provide a symmetrical uniform maximum gain pattern with reduced side lobes and a better resolution [11]. Terahertz interest group established in 2008 aims to develop a wireless communication standard, i.e., 802.15.3d-2017, operating at terahertz frequency bands [31]. It is an amendment to 802.15.3-2016 that defines an alternative PHY at the lower

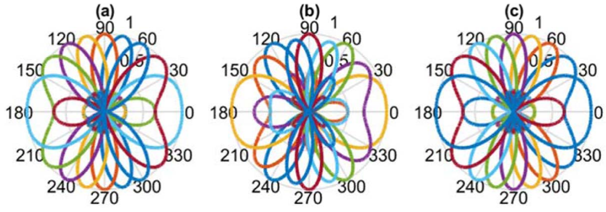


Fig. 3. *Polar plots for array factor of 2- and 3-bit resolution codebooks with eight patterns, M = 4 and K = 8. (a) Three-bit resolution codebook. (b) IEEE 802.15.3c codebook. (c) Discrete Fourier transformation codebook.*

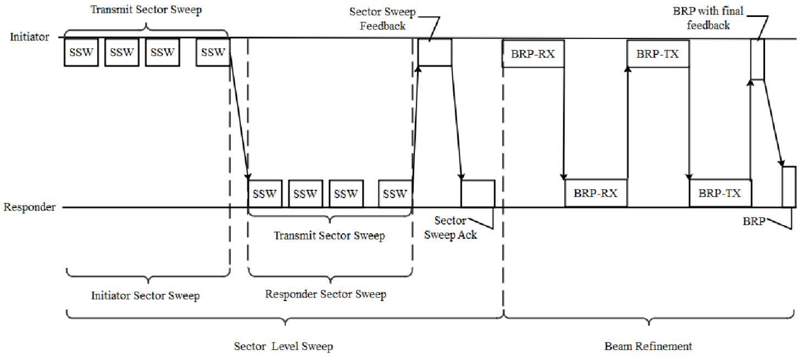


Fig. 4. ***Example of beam training.***

terahertz frequency range, between 252 and 325 GHz for switched point-to-point links [57]. 802.15.3d-2017 defines eight different channel bandwidths between 2.16 and 69.12 GHz and two kinds of selectable PHY modes (SC and ON–OFF keying) for achieving either ultrahigh-speed operation or system simplicity. The highest data rate defined in 802.15.3d-2017 is 315.39 Gb/s with 64 QAM and code rate 14/15 [31].

3) IEEE 802.11ad: Before 802.11ad belonging to the 802.11 family was officially published, 802.11n operating at 2.4- and 5-GHz frequency bands provides a theoretical peak rate of 600 Mb/s via transmitting four spatial streams with the highest order modulation 64 QAM, code rate 3/4, and short guard interval of 400 ns [27]. Due to an increasing number of high-definition videos on smartphone usage and home entertainment, the demand for higher speeds drives a new SG established in May 2007 to investigate very high throughput technologies [58].

Due to a large amount of unlicensed spectrum available in 57–66-GHz frequency bands (60-GHz frequency band in short) around the world, there exists a potential to achieve multiple Gb/s wireless transmission in these frequency bands. Meanwhile, the appearance of building inexpensive 60-GHz transceiver components using silicon germanium and complementary metal–oxide–semiconductor drives the industry to standardize 60-GHz radio technology. In November 2008, a PAR was completed to include the purpose and scope statements for establishing new technology specification operating at 60-GHz frequency band, called IEEE 802.11ad [59]. The PAR outlines the scope of PHY and MAC modifications to the existing 802.11 standards. The primary requirement is that this technology specification needs to support a mode of operation that enables a throughput of at least 1 Gb/s on top of the MAC. The PAR includes two specific requirements, i.e., enabling fast session transfer between the 802.11 PHYs, and maintaining the 802.11 user experience. Fast session transfer provides seamless switch among frequency bands 2.4, 5, and 60 GHz. A functional requirement document [60], evaluation methodology document [61], and channel model document [62] are initially developed by the task group ad (TGad). There are three additional requirements, except for the requirements defined in [59], which are detailed in the function requirements document [60]. First, all devices are required to support a maximum PHY rate of at least 1 Gb/s. Second, a way must be provided in the amendment to achieve 1-Gb/s throughput at a range of at least 10 m in some NLoS scenarios. The third additional requirement is actually a set of requirements to support uncompressed videos. The ability to support uncompressed videos is a major differentiating feature from the 802.11 systems operating at the 2.4- or 5-GHz frequency band. A rate of 3-Gb/s throughput with a packet loss rate of 10^{-8} and a maximum of delay of 10 ms must be supported. In January 2009, TGad began the process of developing an amendment to the existing 802.11 standards aiming to establish 802.11ad that was formally published in December 2012 [32].

Different from the existing 802.11b/a/g/n, the main challenges faced by mmWave communication are the large path loss and weak penetration. For example, the brick wall and a composite wall with studs in the path can result in 20- and 35-dB attenuations, respectively. The path loss due to concrete is found to be as high as 70 dB. The person obstructing makes a path loss within 10–15 dB. In addition, according to Friis' law, there is an additional 21-dB free space path loss compared to the transmission at a 5-GHz frequency band. To compensate for the large path loss and enhance the robustness of communication systems, 802.11ad adopts beamforming technology that implements via an analog PS network forming a beam with increased signal strength toward a certain direction. The peak beamforming gain increases as the number of antenna (N_a) increases (i.e., $\mathrm{Gb[dB]} = 10\log_{10} N_a$). As a result, device discovery becomes more complicated due to the directional transmissions for management and control frames that are transmitted via omnidirectional styles in the other existing 802.11 standards operating at 2.4- and 5-GHz frequency bands. Furthermore, the best direction for communication needs to be found before formally transmitting data via a beam training protocol [63]. As illustrated in Fig. 4, the beam training protocol is

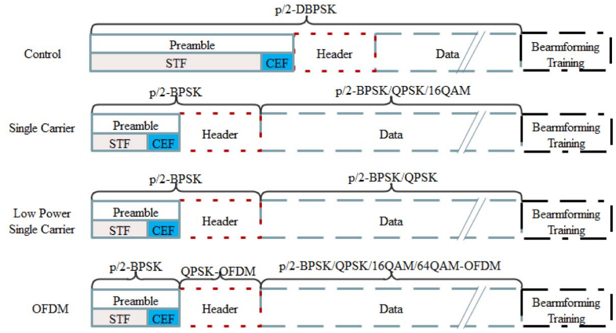


Fig. 5. *Frame format of control, SC, and OFDM PHY defined in 802.11ad.*

divided into three subphases. First, the SSW is performed to select the best transmit and optionally receive antenna sector. Then, the transmitting and receiving beams are obtained during the BRP. Finally, during data transmission, beam tracking is also executed to adapt to channel changes. In addition, beam steering has the additional ability to circumnavigate minor obstacles, such as people moving in a room or a piece of furniture blocking LoS transmission.

Besides improving the quality of signal via beam steering, the implementation of the PHY transmission mechanism needs to account for the hardware characteristics of mmWave systems. In other words, compared to the other existing 802.11 standards, the implementation of 802.11ad devices faces many challenges in tackling 100 times wider bandwidths (2.16 GHz) and ten times higher frequencies. To this end, 802.11ad defines three distinct modulation methods with corresponding PHY: 1) spread-spectrum SC modulation, i.e., control PHY; 2) SC modulation, i.e., SC PHY and low-power SC PHY; and 3) OFDM modulation, i.e., OFDM PHY, as illustrated in Fig. 5. The first two PHY modes must be supported by all devices. The goal of control PHY is to guarantee the basic coverage of mmWave communication with low SNR operation prior to beamforming. SC PHY is used to reduce power and transceiver complexity and achieve the maximum rate (8.805 Gb/s) with $\pi/2$-64 QAM and coding rate 7/8. Low-power SC PHY is designed to further reduce the implementation processing power with simpler coding and a shorter symbol structure. OFDM PHY is designed for high-performance applications over frequency-selective channels and to achieve a maximum data rate of 6756.75 Mb/s by using 64 QAM and coding rate 13/16. However, 802.11-2016 has especially emphasized that, for 802.11ad, the transmission and reception of OFDM PPDUs are optional, and using directional multiple gigabit OFDM mode is obsolete. This implies that this option may be removed in a later revision version [27]. To efficiently and quickly distinguish different PHY layer PPDU transmission, TGad has carefully designed a preamble sequence that consists of a series of Golay complementary sequences having good autocorrelation property and a simple correlator structure. Furthermore, the three types of PHYs can be quickly and efficiently distinguished via using the sign flip at the end of the short training sequence and channel estimation sequence fields [64].

4) IEEE 802.11aj: In general, from the perspective of sectorized communication networks, one needs at least three independent channels to effectively avoid intercell interference. However, there are only two independent 2.16-GHz channels at the 60-GHz frequency band in China, as illustrated in Fig. 6 [27]. Motivated by this observation, as early as 2010, SG5 (also known as Q-LinkPAN SG) began investigating the possibilities of the 45-GHz frequency band for application in WPAN [65]. To further standardize the usage of this frequency band, in January 2012, a new SG for Chinese Millimeter Wave (CMMW) was formed in the 802.11 working group, aiming to study the possibilities of defining enhancements to support operation in CMMW frequency bands, including 45 and 59–64 GHz. With the efforts of CMMW SG, 802.11aj PAR and five criteria were finished in July 2012 [66].

802.11aj belonging to the 802.11 family is developed by IEEE Standard Associations for two frequency bands, i.e., 45 and 60 GHz, to provide high-throughput WLAN communications. As a result, 802.11aj defines two technology specifications operating at different frequency bands. One is China directional multiple gigabit (CDMG) operating at the 60-GHz frequency band. The other is China mmWave multigigabit (CMMG) that operates at the 45-GHz frequency band. Different from 802.11ad, two kinds of channel bandwidths, i.e., 1.08 and 2.16 GHz, are defined in the CDMG. Major technical specifications in CDMG are similar to those defined in 802.11ad, except for defining some specific technologies to adapt to the change of channel bandwidth, such that the backward compatibility can be maintained. However, CDMG only supports SC mode transmission.

To further reduce the hardware cost/complexity and power consumption, CMMG defines two smaller channel bandwidths, i.e., 540 and 1080 MHz. Similarly, CMMG

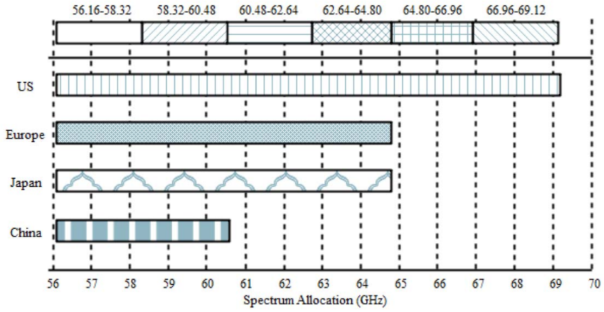
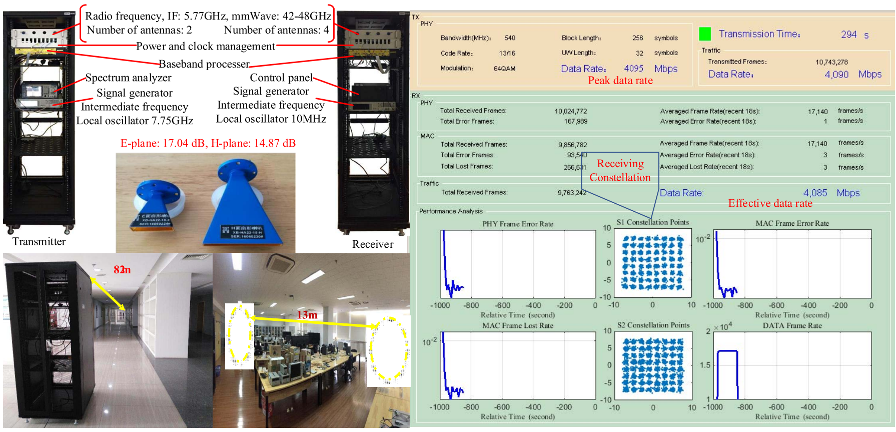


Fig. 6. *Spectral allocations of 60 GHz for WLAN in different countries.*



TX
PHY
Bandwidth(MHz): 540
Code Rate: 13/16
Modulation: 64QAM
Block Length: 256 symbols
UW Length: 32 symbols
Data Rate: 4095 Mbps
Transmission Time: 294 s
Traffic
Transmitted Frames: 10,743,278
Data Rate: 4,090 Mbps

RX
PHY
Total Received Frames: 10,024,772
Total Error Frames: 167,989
Averaged Frame Rate(recent 18s): 17,140 frames/s
Averaged Error Rate(recent 18s): 1 frames/s
MAC
Total Received Frames: 9,856,782
Total Error Frames: 93,540
Total Lost Frames: 266,631
Averaged Frame Rate(recent 18s): 17,140 frames/s
Averaged Error Rate(recent 18s): 3 frames/s
Averaged Lost Rate(recent 18s): 3 frames/s
Traffic
Total Received Frames: 9,763,242
Data Rate: 4,085 Mbps

Fig. 7. ***Test platform, environment, and performance of 802.11aj CMMG.***

PHY supports a beam-steering mechanism and includes the control PHY, SC PHY, and OFDM PHY. All devices need to support the first two PHY modes. A sign flip-based channel estimation field pattern is designed to efficiently distinguish the combination of the PHY mechanisms and channel bandwidth by using a zero-correlation zone sequence. To efficiently exploit the NLoS path and spatial multiplexing gain, MIMO technology is adopted to support multiple data streams (up to four) transmission. The highest theoretical rate supported by CMMG PHY is 15.015 Gb/s with 64 QAM and a coding rate of 13/16 [33]. Except for exploiting the antenna array gain to compensate for the large path loss and weak penetration, a novel low-density parity checking code-based robust packet encoding is designed to improve the code gain with up to 0.2–0.5 dB [67]. To effectively evaluate the performance of mmWave communication operating at 45-GHz frequency bands, according to the CMMG technology specification defined 802.11aj, an mmWave MIMO prototype communication system based on the BEEcube's BEE7 platform is built by the research group from the National Key Laboratory of mmWave of Southeast University. The mmWave MIMO prototype communication system consists of two transmitting antennas and four receiving antennas, in which each antenna has a dedicated baseband and RF chain, as illustrated in Fig. 7. The two transmitting antennas consist of one E-plane horn antenna and one H-plane horn antenna. The four receiving antennas consist of two E-plane horn antennas and two H-plane horn antennas. The test results show that the effective data rate of 4.085 Gb/s is achieved via transmitting two data streams on the 540-MHz bandwidth. This also validates that the mmWave MIMO communication system with RF chain per antenna is a feasible scheme in certain indoor environments.

5) IEEE 802.11ay: Though 802.11aj operating at the 45-GHz frequency band has been published to support high data rate (up to 15 Gb/s) transmission, it can be used only in China as other countries have not opened this frequency band for WLAN applications at present. In addition, 802.11ad operating at the 60-GHz frequency band supports globally the maximum data rate of 8.805 Gb/s but cannot satisfy the demand of emerging applications or services. More recently, the second generation of 802.11ad (called IEEE 802.11ay) under development aims to define at least one mode of operations to support a maximum throughput of more than 20 Gb/s while maintaining or improving the power efficiency per station.

Similar to 802.11ad, 802.11ay includes three PHY modes, i.e., control PHY, SC PHY, and OFDM PHY. The first two PHY modes are mandatory for supporting the following functions [34]:

1) enhanced DMG (EDMG) format (transmit and receive);
2) 2.16-GHz PPDU using EDMG control mode with MCS 0 and SC mode with MCSs 1–5 and 7–10 (transmit and receive);
3) 4.32-GHz PPDU using EDMG control mode with MCS 0 and SC mode with MCSs 1–5 and 7–10 (transmit and receive);
4) single spatial stream (transmit and receive) in all channel bandwidths;
5) normal guard interval type;
6) 2.16-GHz PPDU using non-EDMG control mode with MCS 0 and SC mode with MCSs 1–4 (transmit and receive);
7) 4.32-GHz PPDU using non-EDMG duplicate control mode with MCS 0 and SC mode with MCSs 1–4 (transmit and receive).

In comparison with 802.11ad that has six channels with 2.16-GHz bandwidth [27, Table E-1], 802.11ay defines eight channels with 2.16 GHz bandwidth, as illustrated in Table 7. Furthermore, in addition to retaining the advantages of 802.11ad and 802.11aj, many novel technologies, such as channel bonding, multibeam transmission, single-user MIMO, and multiuser MIMO transmission, are introduced to achieve a 20-Gb/s data rate. Specifically, the 802.11ay PHY supports the transmission of multiple space–time streams, downlink multiuser transmission, and multiple channel bandwidths, including 4.32-, 6.48-, 8.64-, 2.16 + 2.16-, and 4.32 + 4.32-GHz PPDU transmissions. The channel making up a 2.16 + 2.16- or 4.32 + 4.32-GHz PPDU transmission can be contiguous or noncontiguous. The maximum number of spatial streams per station is eight. The multiuser PPDU transmission supports up to eight STAs. For 2.16 + 2.16- or 4.32 + 4.32-GHz transmission, the maximum number of spatial streams in each channel is four [34].

6) mmWave Cellular Communication: To satisfy the requirement of high data rate transmission that is one of the three key performance indices of future communication systems, new radios exploiting a new spectrum, i.e., mmWave frequency bands, are defined to support new techniques, such as massive MIMO and flexibility in terms of the frame structure, and target different use cases and multiple deployment options [68]. The ITU and 3GPP divide the research of 5G mmWave communication standards into two phases. The first phase, i.e., the research for frequencies less than 40 GHz, has completed in September 2018 with aiming to address the more urgent subset of commercial needs. The second phase over 2018 and 2019 focuses on frequencies up to 100 GHz, to address the key performance indices outlined by International Mobile Telecommunications (IMT)-2020 [69].

To efficiently develop new radio mmWave technology specifications, 11-candidate mmWave frequency bands within the range of 24–86 GHz were proposed by ITU in 2015 for 5G broadband systems. Table 8 lists the candidate frequency bands identified in WRC-19 between 24 and 86 GHz [70]. The allocation within the frequency range of 52.6–116 GHz in ITU-R is listed in Table 9 [71]. Protection of some incumbent services may apply and incur in-band and/or out-of-band limitations to IMT-2020 systems. Such incumbent services are documented in the comments column of Table 9, but there is no definition of the incurred limitations in Radio Regulation.

The main advantage of above 52.6-GHz frequency bands is the abundant spectrum resources, which makes these frequency bands suitable for ultrahigh-speed transmission. However, the large path loss and expensive hardware cost restrict the use cases and deployment scenarios. Considering both the advantages and challenges, the following deployment scenarios should be considered [71].

Table 7 Channelization of EDMG With 2.16-GHz Bandwidth

Channel index	Start frequency (GHz)	Center frequency (GHz)	Stop frequency (GHz)
1	56.160	57.240	58.320
2	58.320	59.400	60.480
3	60.480	61.560	62.640
4	62.640	63.720	64.800
5	64.800	65.880	66.960
6	66.960	68.040	69.120
7	69.120	70.200	71.280
8	71.280	73.360	74.440

Table 8 IMT-2020 Candidate Bands in WRC-19 AI 1.13

Candidate frequency bands (GHz)	Candidate frequency bands of requirement additional conditions (GHz)
24.25 − 27.5	31.8 − 33.4
37 − 40.5	40.5 − 42.5
42.5 − 43.5	47 − 47.2
45.5 − 47	–
47.2 − 50.2	–
50.4 − 52.6	–
66 − 76	–
81 − 86	–

1) *Ultradense services area:* The main characteristics of ultradense services scenario, such as indoor hot spots and dense urban, are the high requirement of capacity and consistent user experience, high user density, and less requirement on coverage distance.
2) *UMa/RMa (mainly for fixed wireless access and backhaul transmission):* Although the bands above 52.6 GHz have high propagation loss, relatively large coverage can still be achieved with LoS transmission and high gain antennas. Therefore, UMa/RMa can be a deployment scenario for the fixed wireless access and backhaul applications, which have LoS transmission conditions.
3) *Multi-Gb/s (ultrahigh) data rate services:* The scarcity of spectrum resources at sub-6-GHz frequency bands makes them difficult to support multiple Gb/s (ultrahigh) data rate (up to 20 Gb/s) services, such as augmented reality, virtual reality, 4k/8k UHD video streaming transmission, D2D connections, and high-speed WB transmission. The large bandwidth in the abundant spectrum resources above 52.6 GHz facilitates the realization of multi-Gb/s (ultrahigh) data rate transmission with simple modulation and low-power consumption.
4) *V2X services:* Some of the bands above 52.6 GHz are already recommended or identified for information technology system applications by ITU-R, e.g., 57 to 66 GHz.

C. Comparison and Discussion

The aforementioned technology specifications have their own advantages and differences. The comparisons of their key technologies are listed in Table 10, where $n_1 = 1, 2, 3$, 4, 6, 8, 12, and 32, and $n_2 = 1, 2, 3$, and 4. In Table 10, 802.11ac is an enhancement for high-throughput operation at the 5-GHz frequency band by supporting high-order modulation, a large number of spatial streams, and downlink multiuser transmission [27]. 802.11ax that is an ongoing technology specification will replace both 802.11n and 802.11ac as the next-generation high-throughput WLAN amendment. The key feature of 802.11ax is the adoption of OFDM access (OFDMA), which is widely used in cellular networks, but brand new in Wi-Fi networks. The interested reader can see the detailed discussion for 802.11ax [28]. Since this survey focuses on the technology progress of mmWave communication, the detailed discussion on the technology progress of below 6 GHz is omitted.

All aforementioned technology specifications adopt antenna array technology, i.e., beamforming, to compensate for the severe path loss and blockage of mmWave. In addition, in 802.11aj and 802.11ay, multiantenna technology, i.e., transmitting simultaneously multiple data streams, is further adopted to enhance the transmit rate by exploiting the spatial multiplexing mechanism. For traditional MIMO communication systems, each antenna has a dedicated RF chain. It also means that, for massive MIMO communication systems, a large number of RF chains have to be deployed. However, the cost of hardware implementations increases with an increasing carrier frequency. Furthermore, a large number of RF chains not only consume a large amount of energy but also increase the cost of wireless communication systems [72]. This implies that it is challenging for mmWave communication systems to equip a dedicated baseband and RF chain per antenna. It is necessary to develop a novel multifunctional antenna architecture, which has the ability to obtain simultaneously the array gain, multiplexing gain, and diversity gain to overcome the shortcoming of mmWave.

On the other hand, in order to obtain the desired signal-to-noise ratio, aligning the beam direction of the transceiver is the first task for mmWave communication systems equipped with an antenna array [63]. This implies that channel estimation becomes difficult due to the low signal-to-noise ratio before aligning the transceiver beam directions. One of the main tasks of mmWave communication systems is to design an efficient beam alignment scheme. In addition, to reduce the cost of mmWave communication systems, novel multifunctional antenna structures that are different from the conventional microwave MIMO architectures require corresponding transceiver technologies, such as beam training, the design of precoder/combiner, and channel estimation. Furthermore, compared to the microwave communication systems, the practical implementation of mmWave communication systems faces more severe challenges and more hardware costs with an increasing carrier frequency. The hardware constraints seriously undermine the system performance and deployment progress of mmWave communication systems. Therefore, disruptive solutions are needed by taking into account the cross design of analog and digital modules for mmWave communication systems.

In recent years, to address the unique characteristics possessed by mmWave communication, a large number of researchers in both industry and academia have invested a lot of manpower and material resources to study new antenna array architecture with multiple RF chains and novel transceiver technologies. In what follows, we summarize the research progress of mmWave communication systems from two aspects, i.e., antenna architecture and transceiver technologies.

III. ANTENNA ARRAY ARCHITECTURE OF mmWave COMMUNICATION

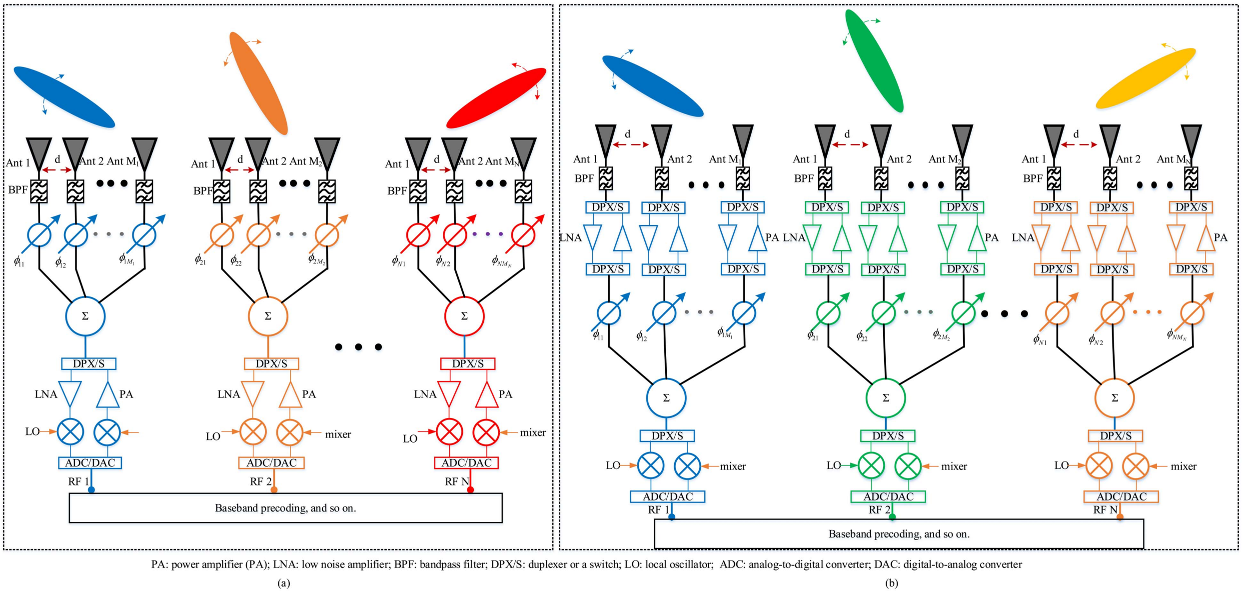
The propagation of electromagnetic waves in mmWave frequency bands suffers from more severe path loss and blockage when comparing to the electromagnetic waves operating at microwave frequency bands, which drastically degrades the quality of wireless communications or even causes a communication interruption. To this end, the design principles of mmWave antennas are significantly

Table 9 Frequency Bands in the Range of 52.6–116 GHz in Radio Regulation

Frequency band (GHz)	Allocated to Mobile Service on a primary basis	Allocated to Fixed Service on a primary basis	Comments
52.6 − 54.25	No	No	EESS (passive) and SRS (passive), all emissions are prohibited in this band.
54.25 − 55.78	No	No	EESS (passive) and SRS (passive)
55.78 − 59	Yes	Yes	EESS (passive) and SRS (passive) This band available for high-density applications in the fixed service.
59 − 59.3	Yes	Yes	EESS (passive) and SRS (passive) Radiolocation.
59.3 − 64	Yes	Yes	Radiolocation.
64 − 65	Yes	Yes	This band available for high-density applications in the fixed service.
65 − 66	Yes	Yes	This band available for high-density applications in the fixed service.
66 − 71	Yes	Yes	WRC-19 AI 1.13 frequency band, sharing and compatibility studies and potential limitations information.
71 − 76	Yes	Yes	WRC-19 AI 1.13 frequency band, sharing and compatibility studies and potential limitations information.
76 − 81	No	No	Radiolocation.
81 − 86	Yes	Yes	WRC-19 AI 1.13 frequency band, sharing and compatibility studies and potential limitations information.
86 − 92	No	No	EESS (passive) and SRS (passive), all emissions are prohibited in this band.
92 − 94	Yes	Yes	Radiolocation.
94 − 94.1	No	No	Radiolocation.
94.1 − 95	Yes	Yes	Radiolocation.
95 − 100	Yes	Yes	Radiolocation.
100 − 102	No	No	EESS (passive) and SRS (passive), all emissions are prohibited in this band.
102 − 105	Yes	Yes	N/A.
105 − 109.5	Yes	Yes	SRS (passive).
109.5 − 111.8	No	No	EESS (passive) and SRS (passive), all emissions are prohibited in this band.
111.8 − 114.25	Yes	Yes	SRS (passive).
114.25 − 116	No	No	EESS (passive) and SRS (passive), all emissions are prohibited in this band.
Earth Exploration-Satellite Service: EESS; Space Research Service: SRS; Agenda Item: AI;			

Table 10 Comparison of Key Technologies and Parameters Between Various Technology Specifications

	802.11n	802.11ac	802.11ax	WirelessHD	802.15.3c	802.15.3d	802.11ad	802.11aj		802.11ay
								CDMG	CMMW	
Frequency Band (GHz)	2.4, 5	5	2.4, 5, 6	60		$252-325$	60		45	60
Bandwidth (MHz)	20, 40	20, 40, 80, 160		2160		$2160n_1$	2160	1080 2160	540 1080	$2160n_2$
Peak Data Rate (Mbps)	600	6933.3	9607.8	28	5775	315390	8085		15015	379170
Key features	MIMO			Beamforming MIMO	Beamforming				Beamforming MIMO	
Carrier modulations	OFDM		OFDMA	SC	SC OFDM	SC, OOK	SC OFDM	SC	SC OFDM	
Highest order modulation	64QAM	256QAM	1024QAM	64QAM						
Multi-user transmission	–	Downlink Downlink	Uplink	–						Downlink
Maximum number of spatial streams	4	8	8	1					4	8
Maximum number of simultaneously serving users	4	4	8	4	1				1	8
Channel coding	BCC, LDPC			LDPC, RSC, Block code		LDPC	LDPC, RSC, Block code		LDPC	
Highest coding rate	5/6				7/8	14/15	13/16			7/8
BCC: binary convolutional code; LDPC: low-density parity check; RSC: reed solomon codewords; OOK: on-off key										



PA: power amplifier (PA); LNA: low noise amplifier; BPF: bandpass filter; DPX/S: duplexer or a switch; LO: local oscillator; ADC: analog-to-digital converter; DAC: digital-to-analog converter

(a) (b)

Fig. 8. ***Partially connected architecture: (a) passive multibeam phased array antennas and (b) active multibeam phased array antennas.***

different from those of microwave antennas, which should take into account the demand of both high gain and wide-angle coverage ability simultaneously [23].

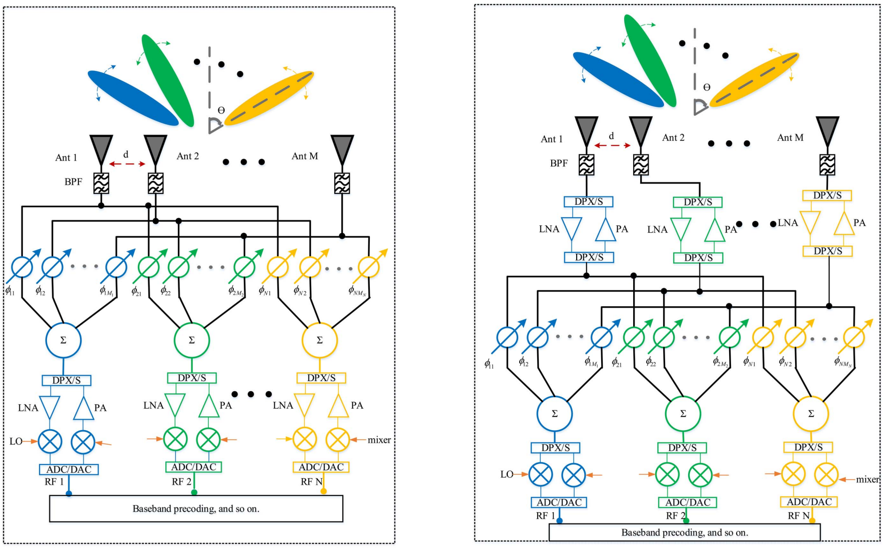
A. Introduction of Antenna Architectures

MBA is an extensively focused technique that has found applications in mmWave communication systems, which is the basic building block for massive MIMO or large-scale MIMO systems [73]. In an mmWave massive MIMO system, the BSs are installed with a large number of antennas to support simultaneous links at the same time–frequency domain through a space domain or a beam domain division. MBAs can simultaneously provide a wide scanning coverage and support remote links to overcome or alleviate the aforementioned path loss and blockage problems. MBAs are generally categorized into three types, i.e., passive, active, and hybrid MBAs. The advantages and disadvantages of these types of MBAs have been interpreted in terms of schematics, radiation performance, system complexity, cost, and digital processing complexity in [74]. From the aforementioned technology specifications and studies on mmWave communications, the MBAs, which can efficiently support the digital–analog hybrid antenna array architecture, have been adopted in some technology specifications, such as 802.11ad/aj/ay, or regarded as the system model for studying the PHY-layer transmission technologies for mmWave communications.

The multibeam phased antenna arrays (MBPAAs) are usually known as the active MBAs with analog PSs at either RF, intermediate frequency (IF), or baseband.

In terms of system architecture, they can be further categorized into PCMBPAAs, FCMBPAAs and dynamically connected MBPAAs (DCMBPAAs), by checking the connection relationship between antenna elements and RF chains, as illustrated in Figs. 8–10, respectively. Note that ULA is illustrated as an example in each figure, and the following discussions can be either applied to a 2-D panel antenna array, which is also an implementation style of MBA architecture. The architectures of PCMBPAAs, FCMBPAAs, and DCMBPAAs have abilities to fulfill the high-density integration requirements raised in mmWave frequency bands. For this reason, the three types of MBPAAs are discussed and compared in the following. Furthermore, another type of passive MBAs, based on the quasi-optical method, is very popular in mmWave communications due to the low loss and easy implementation of multibeam performance, i.e., reflector- or lens-based MBAs, which are also reviewed and compared with the active MBAs.

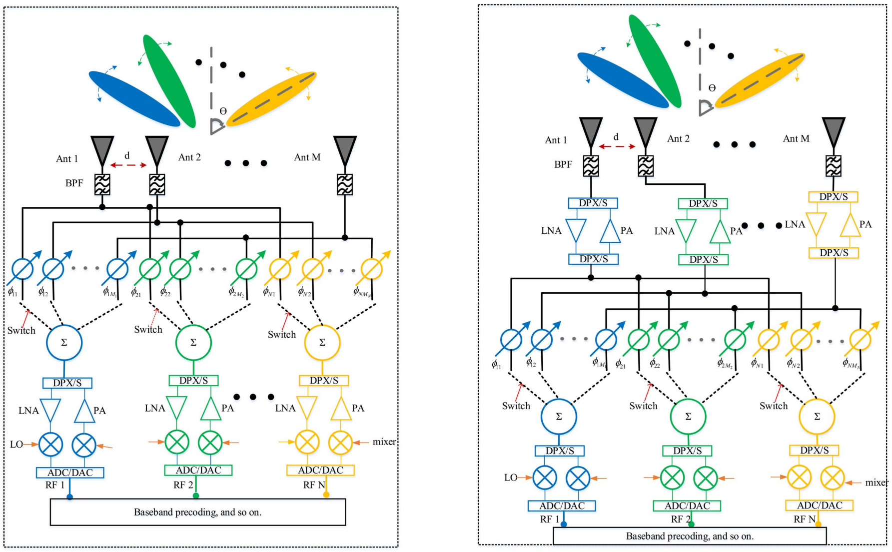
1) PCMBPAAs: Two typical PCMBPAA architectures with RF PSs are illustrated in Fig. 8, which are popular and highly attractive for mmWave communications. For example, 802.15.3c and 802.11ad adopt this structure with a single RF chain (i.e., $N = 1$), while 802.11aj adopts it with a single RF chain or multiple RF chains. As shown in Fig. 8(a), the passive PCMBPAA with RF PSs is comprised of N RF chains. Each RF chain is connected with a M_i-element ULA through a group of M_i RF PSs, so a total number of $M = \sum_{i=1}^{N} M_i$ antenna elements are employed. Each chain has an identical transceiver connecting the ULA through either a diplexer or a switch depending on whether a frequency-domain division or a time-domain division is adopted, and all these chains are connected to a common baseband. Thus, this type of passive PCMBPAA can generate multibeams in a two-peripheral way, controlled either by the M_i RF PSs contained in the subarray of each chain or by the baseband precoding of the entire antenna system. Fig. 8(b) illustrates the architecture of an active PCMBPAA, which has an apparent difference from the passive one in that the PSs and the RF transceivers are reconfigured. Each antenna element, followed by a bandpass filter (BPF), connects to its own low-noise amplifier (LNA) and PA through either a diplexer or a switch. The RF PSs are inserted in-between the LNAs/PAs and the mixers contained in each RF chain and with a total number of M. The mixers in either Fig. 8(a) or (b) are connected to baseband through a pair of ADC and DAC. There are all together N pairs of ADCs/DACs. Thus, the scale of the active PCMBPAA is the same as that of the passive one in terms of the antenna array. Twofold enhanced performance is achieved by using such a different architecture. First, the system noise figure and the receiving sensitivity can be improved as the LNAs are placed close to the antenna element since the PS is relocated at the place after the LNA in the receive chain. Second, there are totally $N \times M$ PAs, which can jointly generate a high level of RF power and provide good linearity by adopting a power combination in free space. Meanwhile, the insertion loss of PSs can be compensated since the power is amplified by the PA behind the PS in the transmitting chain. A similar two-peripheral phase-shifting scheme, as mentioned in the passive PCMBPAA, is also supported in the active PCMBPAA. It controls the phases of the antenna elements via the RF PSs and the baseband precoding simultaneously. A common drawback of PCMBPAAs, including both the passive and active architectures, is that each subarray can generate only one beam at one time, leading to a low aperture utilization efficiency.



PA: power amplifier (PA); LNA: low noise amplifier; BPF: bandpass filter; DPX/S: duplexer or a switch; LO: local oscillator; ADC: analog-to-digital converter; DAC: digital-to-analog converter

(a) (b)

Fig. 9. ***Fully connected architecture: (a) passive multibeam phased array antennas and (b) active multibeam phased array antennas.***



PA: power amplifier (PA); LNA: low noise amplifier; BPF: bandpass filter; DPX/S: duplexer or a switch; LO: local oscillator; ADC: analog-to-digital converter; DAC: digital-to-analog converter

(a) (b)

Fig. 10. ***Dynamically connected architecture: (a) passive multibeam phased array antennas and (b) active multibeam phased array antennas.***

The full-angle coverage is realized by using the multiple beams generated by the N subarrays. By increasing M_i, i.e., the number of the antenna elements in each subarray, much narrower beamwidth can be achieved. However, the distance between any two adjacent subarrays should be increased accordingly, which results in a reduced scanning range and even the presence of grating lobes. Therefore, PCMBPAAs are apt to be adopted at BSs or access points to provide a full area coverage with multibeams. In such scenarios, the size of the antenna array is not stringent, and large-scale antenna arrays can be used to generate a great number of narrow beams so that the coverage depth and width are enhanced simultaneously. Specifically, if the scale of PCMBPAA reduces to $N = 1$, then it can also be applied in mobile terminals because, in this case, it is transferred into a conventional phased array. This simplest PCMBPAA is widely used in 5G commercial terminals.

2) FCMBPAAs: To improve the aperture utilization efficiency or to generate concurrent beams for wide-angle coverage and suppressing grating lobes, FCMBPAA architecture is proposed, as shown in Fig. 9, including both passive and active FCMBPAAs. Passive FCMBPAA, as illustrated in Fig. 9(a), has M antenna elements, N RF chains, and $N \times M$ RF PSs. Different from passive PCMBPAA, each antenna element in passive FCMBPAA connects to all N RF chains simultaneously through a group of M RF PSs, respectively. All antenna elements are simultaneously contributing to generate N concurrent beams, which can further reduce the number of antenna elements compared with passive PCMBPAA or reach a higher antenna gain when having the same number of antenna elements as the passive PCMBPAA. A similar conclusion can be made between active FCMBPAA and active PCMBPAA. The two types of active MBPAAs are different in that each antenna element in active FCMBPAA is connected to one channel through a group of RF PSs, which results in N concurrent beams as each antenna element is excited by N RF chains simultaneously. In comparison, FCMBPAAs have advantages of the reduced number of antenna elements or high utilization on antenna elements and the PHY aperture of the antenna array. Furthermore, without any subarray, the theoretical scanning angle is much wider than that of PCMBPAAs, while there should be no grating lobe when the distance between any two adjacent elements equals a half operating wavelength. Due to the higher aperture utilization efficiency and wider scanning angle range, FCMBPAAs are potentially used in the scenarios where the antenna size is the priority consideration. Thus, in compact BSs or accessing points, FCMBPAAs are a promising architecture to support high-density coverage and high data rate transmission through the simultaneously radiated multibeams in a limited aperture [75]. In certain applications, small-scale FCMBPAAs can also be implemented on mobile terminals so that the design complexity, hardware cost, and power consumption can be greatly reduced with a compact size.

3) DCMBPAAs: DCMBPAA is achieved by extending an FCMBPAA by inserting the switching array in-between the PSs and RF chains. A DCMBPAA can fulfill either an FCMBPAA or a PCMBPAA by controlling the switching states. Specifically, when all the switches are with the ON-state, each RF chain is connected to all of the antenna elements through PSs, resulting in an FCMBPAAs. To realize PCMBPAAs, all the antenna elements are divided into N

Table 11 Comparison among the three types of MBPAAs

	Number of RF Chains	Number of Antenna elements	Antenna Array Gain	Beam Sweeping Range	Cost
PCMBPAAs	N	$\sum_{i=1}^{N} M_i$	Moderate	Narrow	Moderate
FCMBPAAs	N	M	Moderate	Wide	High
DCMBPAAs	N	M	Highest	Flexible	Highest

clusters, and the antennas in each cluster are connected to one specific RF chain by adjusting the switches. The inserted switching array does not apparently increase the complexity and the cost of the system comparing with FCMBPAAs, but it offers flexibility for DCMBPAAs in different application scenarios with a minimal expense of insertion loss. Since DCMBPAAs can transfer to PCMBPAAs or FCMBPAAs by controlling the used switch arrays. DCMBPAAs can be applied in BSs, accessing points, or mobile terminals, and the scale of a DCMBPAA can be flexibly configured according to the specific application scenarios. For instance, for BS applications, the scale of DCMBPAAs can be sufficiently large to support large area coverage and high-density connections. Favorably, a DCMBPAA can also be reconfigured according to the real-time requirements so that it can be operated as an FCMBPAA in business hours and simplified to a PCMBPAA in the later night. Such reconfigurability of DCMBPAAs is also attractive in mobile terminals.

A comparison among the three types of MBPAAs is shown in Table 11 under the assumption of the same RF chains used in each type of MBPAAs. Note that, in PCMBPAAs, only a subarray of antenna elements can be utilized for each beam; thus, its gain is usually lower than the other two types of MBPAAs, of which the full antenna array contributes to each beam. Meanwhile, the subarray topology used in PCMBPAAs cannot support wide-angle beam sweeping (coverage), but the RF architecture of PCMBPAAs is the simplest. DCMBPAA is a flexible candidate in terms of both performance and complexity.

4) Reflector- or Lens-Based MBA: In mmWave frequency bands, both the aforementioned passive/active PCMBPAAs, FCMBPAAs, and DCMBPAAs are rarely deployed at a large scale due to the system complexity and huge cost of mmWave chains, especially the PSs. Passive MBAs, active MBAs, or hybrid MBAs without or containing fewer RF PSs are preferred alternates. In the following, MBA architectures are reviewed for either macro BSs, micro BSs, customer premise equipment (CPE), and user equipment (UE), respectively, in various application scenarios, as shown in Fig. 1, to ensure sufficient coverage and robust connections at both low system cost and complexity.

For both macro and micro BSs, the passive MBAs dominate because they can radiate multiple concurrent beams without the requirement of a complex BS system compared with active or hybrid MBAs [74]. As omnidirectional beam coverage is essential for macro BSs, MBAs with wide scanning angles and high gains should be adopted to achieve an effective isotropic radiation power for large coverage. As shown in Fig. 11, as a promising candidate, the focal-plane array with broadband optical beamforming property is recently proposed and experimentally prototyped at 28 GHz [76]. For the same purpose of providing multiple beams with wide scanning angles, flat lens-based or Luneburg lens-based MBAs are recently implemented for Ka-, V-, and E-bands, respectively. They exhibit desired performance such as wide scanning angle, a large number of concurrent beams, flat gain envelope, and easy of installations [77], [78]. A metamaterial-based planar lens is presented with seven feeders to achieve seven beams [79], which shows that the lens antenna has the advantage to realize multibeams with a simple structure. Furthermore, a folded reflectarray is implemented to provide multibeams for wide-angle coverage with the presence of multiple feeders [80]. The metasurface-based multibeam array has been further implemented in a 2-D form for practical applications [81]. The reflector- or lens-based MBAs have a simple structure, low insertion loss, and high efficiency, resulting in better performance at mmWave frequency bands than other types of passive MBAs configured with beamforming networks, i.e., the Butler matrix [82], the Rotman lens [83], and intelligent metasurfaces [84].

The lens antenna has multiple feeders located on the circle of its focus, and each feeder is connected to an RF chain through the beam selector, which is a switch array to determine the connection between the RF chain and the feeder by switches. All the RF chains are connected to the baseband, as shown in Fig. 12. The multibeam pattern is generated by the lens and feeders only, which is regarded as an air-feed scheme or optical focus. Thus, it has a simple structure when comparing to the MBPAAs since no PSs are required. Moreover, the RF chains are connected to feeders one by one to form isolated RF-feed chains, which means that the numbers of RF chains and feeders are equal. Since no intersection or crossover is needed in-between different RF-feed chains, the RF infrastructure is much simpler. All the beams can be radiated simultaneously or only several or only one beam is radiated by switching the beam selector, without any loss on the signal [85]. In short, the type of reflector- or lens-based MBAs is better than the PCMBPAAs, FCMBPAAs, and DCMBPAAs, in terms of architecture, cost, and simultaneously multibeam performance. However, the cost of a larger bulk size due to the focal length and large aperture of reflector and lens should be kept. This type of MBA is apt to be equipped in BSs. Meanwhile, it is a low-power-consumption solution for energy-efficient or energy-limited systems because

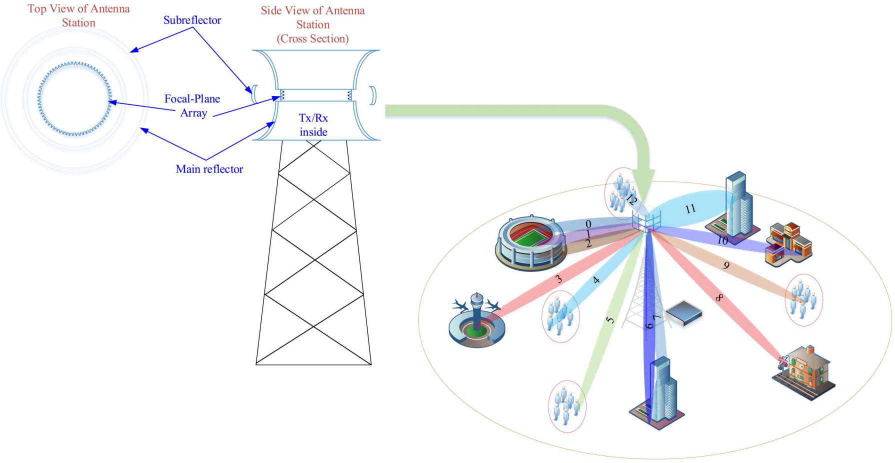


Fig. 11. ***Focal-plane array for 5G-mmWave communication.***

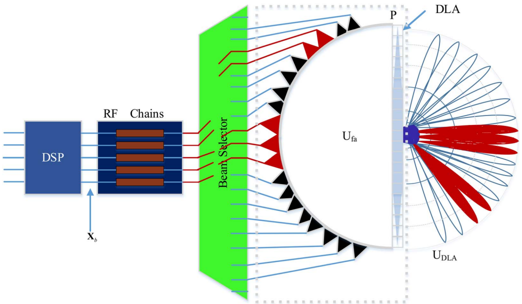


Fig. 12. ***Lens antenna arrays.***

the used reflector or lens can generate a relatively high gain to relieve the output of PAs. As mentioned in [74] and [75], there are also circuit-based reflectors or lens designs that have been explored for multibeams or massive MIMO applications. The loss introduced by the circuits or transmission lines is server than that of air-fed reflectors and lens. Moreover, due to the conventionally planar form of the circuit-based components, a 2-D beam scanning is always a design issue.

B. Discussion and Conclusion

Active MBAs, especially MBPAAs, are another choice for BSs because their RF circuits can provide much flexible functions of amplitude and phase control. However, high cost and complex RF circuit infrastructure are required. Therefore, active MBAs are usually developed for micro BSs and CPEs, which has much lower requirements of the number of beams and scanning ability than macro BSs and achieves a tradeoff between cost and performance. Especially, for application scenarios with low mobility and the requirement of high data rate, e.g., indoor access or point-to-point links, active MBAs will have certain advantages due to their flexible beam switching. Active MBAs can be further divided into RF-domain, IF-domain, LO-domain, and baseband-domain active MBAs. The circuit domain (including RF-, IF-, and LO-domains) MBAs are extensively investigated and experimented with in mmWave high density integrated circuits [86]. The scale of integrated antenna elements is significantly increased from a few to a large number, e.g., 64, 128, 256, or even more, because of the increasing integration density of putting multiple channels into a single chip [87]. Different from the widespread circuit domain MBAs, the design of a pure baseband-domain MBA, known as fully digital MBA, is carried on the digital processing circuits. A 64-channel fully digital MBA has been successfully developed at 28 GHz with a bandwidth of 500 MHz, which can achieve a peak data rate of 50.73 Gb/s with a spectrum efficiency of 101.5 Bps [88]. However, the hardware complexity and limited data processing rate pose a great challenge for its extensive applications. To achieve a balance between the performance and hardware cost, hybrid MBAs are competitive candidates for mmWave communication [89]. The concept of hybrid MBAs is simple, which is an agile combination of the aforementioned active MBAs, passive MBAs, and digital MBAs. In contrast, the promising topologies and infrastructures for hybrid MBAs are very versatile because the potential combinations seem to be uncountable, and different types of hybrid MBAs can provide different yet competing performances. To this end, the design and implementation of hybrid MBAs not only are the focus of antenna design but also should be evaluated from a perspective view of the system architecture.

In the aforementioned MBPAAs, the control of phase for antenna arrays is implemented with PSs, as illustrated in Figs. 8–10. Conventionally, the PSs are widely used in RF circuits design due to their mature fabrication, stable performance, and low cost, but they are suffering limited bandwidth problems. Because the phase delay provided by conventional PSs cannot fulfill the required frequency-dependent phase shifting for array elements,

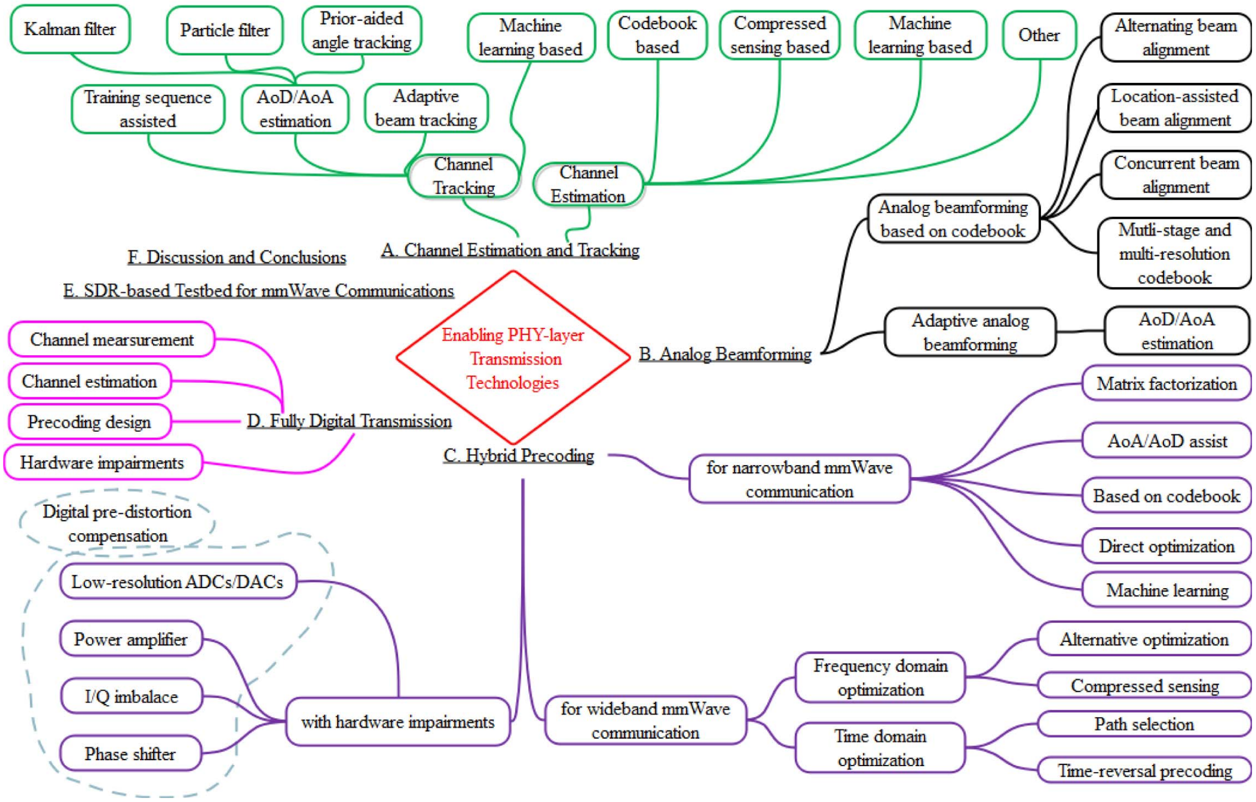


Fig. 13. ***Enabling PHY-layer transmission technologies discussed in this section.***

a beam squinting will happen within a relatively wide bandwidth. To alleviate this problem, in other words, to maintain a stable beam steering over a wide bandwidth, the true time delay method is proposed by using the delay line structures to ensure a stable time delay [90]. Thus, the equivalent phase delay is frequency-dependent, which matches well with the frequency-dependent phase delay requirement for stable beam steering [91]. Nevertheless, the aforementioned MBPAAs can also be supported by the true time delay method, with an enhancement of bandwidth.

The extraordinary growth of electronic devices drives the development of mmWave mobile connection technologies to support data-hungry applications. The mmWave antennas for UEs contribute to another emerging research hotspot in recent years, among which the integration of mmWave antennas into the UEs and UE-level phased antenna arrays is highly attractive [92]. The most important property of mmWave antennas in UEs is the mobility and coverage ability, which is severely reduced when considering the blockage of mmWave, such as the hand holding and body blockage. Hence, a phased array appears to be the first choice to solve the problem by using either beam scanning or beam switching [93]. Furthermore, two or three or even more phased array units can be inserted into a UE to enhance its coverage performance through a sectorial concept. However, the corresponding power consumption and hardware cost need further investigation [94].

IV. ENABLING PHY-LAYER TRANSMISSION TECHNOLOGIES

To efficiently exploit the potentials of multiantenna technologies, e.g., multiplexing, diversity, and array gain, it is required to carefully design multiantenna transceivers for wireless communication systems. Though the principle of designing a transceiver is not closely related to the specific carrier frequency, the design of antenna architectures needs to take into consideration the hardware cost and implementation complexity that depend on the specific carrier frequency. Furthermore, the specific design of transceiver schemes for precoding and combining depends on the hardware architecture, propagation environment, and practical requirements of various services. The distinct propagation characteristics between mmWave and microwave frequency bands lead to disparate signal processing methods for transceiver optimization [16]. For digital processing that adjusts digitally the signal phase and amplitude at baseband, each antenna element requires a dedicated baseband and RF hardware. However, in mmWave communication systems, it is impossible to equip with a dedicated baseband and RF hardware for each antenna element due to the prohibitively high cost and power consumption. Therefore, how to balance the hardware cost, implementation complexity, and system performance has attracted extensive interest in both industry and academia in the past few years. The main contents discussed in this section are illustrated in Fig. 13.

Table 12 mmWave Channel Estimation Summary

Antenna architecture	Methods	Estimated parameters	Comments	Ref.	YoP
Fully digital	Overlapped beam pattern	AoAs, AoDs, Path gains	A lot of beam training overhead. For each channel estimation, it is necessary to retrain the beams and run the corresponding algorithm.	[95]	2017
	Hierarchical codebook			[96]	2018
Fully connected	Top-P gain beam pairs			[97]	2018
	Compressed sensing			[98]	2014
				[99]	2018
Fully digital	Bayesian estimation	Channel coefficient		[100]	2019
	Compressed sensing	AoAs, Delay, Path gains		[101]	2020
Fully connected	Multiple signal classification method			[102]	2017
Lens array	Learned denoising-based approximate message passing neural network	Channel coefficient	A large amount of data collected is needed for model training and testing. Model training takes a long time.	[103]	2018
Fully connected	Fast and flexible denoising convolutional neural network			[104]	2019
Lens array	Fully convolutional denoising network and U-Net			[105]	2020
Fully connected	Convolutional neural network and spatial-frequency-temporal correlations			[106]	2019
	General iterative index detection	AoAs, Path gains	Running algorithm for each channel estimation.	[107]	2018
	Multiple frequency tones			[108]	2017

A. Channel Estimation and Tracking

1) Channel Estimation: To benefit from the potential gains provided by multiantennas, one of the most important elements is to obtain the CSI at the transceiver. Consequently, CSI estimation has been under extensive investigation for wireless communication systems. However, different from traditional MIMO communication systems operating at microwave frequency bands, the unique characteristics of mmWave propagation make the CSI estimation more challenging. The challenges mainly reflect twofold. First, the signal-to-noise ratio for channel estimation may be very low with the lack of array gains before establishing data transmission links due to the spatial angular sparsity and large path loss of mmWave. Second, constrained by the expensive hardware cost and considerable high power consumption, the number of RF chains is usually much smaller than that of antennas in a hybrid architecture system. It implies that each RF unit cannot obtain simultaneously the sampled signals from each antenna, i.e., can only obtain a combination of sampled signals from all antennas [14]. As a result, the conventional pilot-assisted channel estimation algorithms for fully digital systems cannot be directly applied to acquire the explicit CSI of mmWave communication systems. In recent years, how to efficiently and effectively estimate the CSI has attracted extensive attention. Table 12 lists some channel estimation methods for mmWave communication systems.

a) Codebook-based channel estimation: The first approach is to estimate an equivalent channel via codebook-based multistage beam training. The equivalent channel is the product of the adopted analog beams and the real PHY channel. Yet, the precision of this method mainly depends on the beamwidth and the mobility of terminals. To implement this approach, in general, a high training overhead is needed for pairing transceiver beams, which depends on the resolution of analog beam codebooks designed. Using the analog beamforming techniques, the most straightforward channel estimation method is to exhaustively search in all possible angular directions. After finishing beam training, a virtual channel matrix can be formed, whose entries represent the channel gains between the M transmit and N receive beams. Recalling the sparse propagation characteristics in the angular domain of mmWave, one can effectively generate the equivalent channel by identifying the transmit and receive direction pairs with maximum gain. To reduce the number of channel estimation measurements and improve the estimation accuracy, a fast mmWave MIMO channel estimation framework is developed by designing a set of novel overlapped beam patterns [95]. In the proposed scheme, the authors design a maximum likelihood detector to optimally extract the AoD and AoA information from the measurements and a linear minimum mean squared error channel estimator to estimate the channel coefficients by optimally combining the selected measurements in all stages. Xiao *et al.* [96] propose a multipath decomposition and recovery approach to estimate the mmWave channel by using hierarchical search based on a normal-resolution codebook. A top-P reconstruct approach is proposed to generate the channel matrix by exploiting the beam direction pairs with the top-P gain for mmWave communication systems [97].

b) Compressed sensing-based channel estimation: This method fully exploits the spatial angular sparsity of mmWave propagation to estimate the AoA, AoD, and complex path gains. Then, the channel matrix can be constructed via the obtained AoA, AoD, and complex path gains [98]. The most popular approach is to estimate the channel matrix by combining the dictionary matrix and beam training codebook with the compressed sensing theory. The fundamental idea of these approaches is to search multiple transmit/receive directions in each measurement by creating initial beam patterns [99]. By leveraging the inherent sparsity of the mmWave channel, the channel estimation problem is transformed into a reconstruction problem of compressible signals from a set of noisy linear measurements. Then, the entries of the unknown mmWave MIMO channel matrix are found via the generalized approximate message passing algorithm [100]. Recently, by exploiting the angle-delay sparsity of mmWave transmission, a compressive sensing-based channel esti-

Table 13 mmWave Channel Tracking Summary

Tracking method	Comments	Type		Ref.	YoP
		Theory	Platform		
Beam tracking is conducted during data transmission.	Large pilot overheads.	✓	✓	[63]	2009
A priori knowledge aided channel tracking.	Need prior data to excavate a temporal variation law of the physical direction. Tracking time-varying channels with low pilot overhead.	✓		[109]	2017
Noncoherent compressive tracking with signal strength received.	Need relatively slow feedback overhead from terminals.	✓	✓	[110]	2017
Leaky wave antenna based path discovery.	Transmitting distinct signals with unique signatures across different angles.	✓	✓	[111]	2020
Particle filtering based beam tracking.	Need to transmit a series of training pilots that depend on the number of beam pairs used at transceivers.	✓		[112]	2019
Auxiliary beam pair-assisted angle tracking.	Need to additional auxiliary beam pairs based on the conventional beam training.	✓		[113]	2018
Unscented Kalman filtering based channel tracking.	Need initial channel estimation information.	✓		[114]	2019
Machine learning based beam tracking.	Need a large number of training and test data.	✓	✓	[115]	2020
Multi-armed bandit based beam tracking.	Middle pilot overheads..	✓		[116]	2020
Graph neural network based channel tracking.	Need a large number of training and test data.	✓	✓	[117]	2020
Deep learning based channel tracking.		✓	✓	[118]	2020

mation algorithm is designed to estimate the channel of mmWave massive MIMO communication system, with taking beam squint into account [101]. Meanwhile, the classical multiple signal classification method is used to estimate the AoA/AoD. Then, the least-squares method is used to estimate the complex path gain. Different from its element-space counterpart, the beamspace multiple signal classification method may exhibit spectrum ambiguity caused by the beamformers [102].

c) Machine learning-based channel estimation: Recently, machine learning-based channel estimation methods arose to make full use of the inherent characteristics hidden in data/signals collected in an end-to-end manner. For example, considering the sparse mmWave channel matrix as a natural image, a learned denoising-based approximate message passing neural network is applied to construct the channel estimation model for beamspace mmWave systems [103]. However, the performance of this learning model is limited by the noise level. To address this problem, a fast and flexible denoising convolutional neural network is used to build a channel estimation framework for cell-free mmWave systems [104]. Furthermore, based on the aforementioned machine learning methods, a blind channel estimation algorithm with a fully convolutional denoising network and U-Net is developed to overcome their shortcomings [105]. By exploiting the spatial–frequency–temporal correlation, a deep convolutional neural network is designed to estimate the channel in mmWave communication systems [106]. These research results show that machine learning-based channel estimation methods are more capable to extract the inherent characteristics of the channel from a large amount of data collected and have the potential to estimate the channel more accurately with lower complexity. However, the fast changing of communication environments requires the deep learning model to be adaptive, that is, it must have strong scalability and generalization abilities.

d) Other channel estimation methods: In some special cases, the scatters may be abundant for mmWave communication, namely, mmWave channel may be correlative. The spatial correlation of the channel can be used to estimate the channel of mmWave MIMO systems with a hybrid antenna array structure. With the help of pilots, a general iterative index detection-based channel estimation algorithm is proposed for the uplink of mmWave multiuser communication system [107]. The strongest AoAs at BS and user sides are estimated by exploiting multiple frequency tones for the mmWave multiuser downlink system [108]. Then, the devices transmit orthogonal pilot symbols to BS along with the estimated strongest AoA directions for estimating the equivalent channel.

2) Channel Tracking: Due to the requirement of the directional propagation of mmWave, one may consider that mmWave communication is suitable only for a static communication environment, such as fixed D2D communication, as illustrated in Fig. 1. In practice, to accommodate the terminal mobility, real-time beam alignment and channel estimation should be executed frequently, which leads to high resource overhead. Furthermore, in mmWave frequency bands, the user mobility exacerbates Doppler effects and leads to very short channel coherence time. This means that mmWave channels vary quickly, even when considering the short symbol duration associated with large bandwidth. Therefore, for mmWave communication, there is no enough time to continuously repeat beam training from scratch. This implies that maintaining beams toward mobile users and adapting to frequent blockage require efficient and dynamic channel-tracking or path tracking algorithms. A comparison of the research on channel-tracking is listed in Table 13.

To support dynamic beam tracking, both 802.11ad and 802.11aj suggest adding automatic gain control subfield and beam training subfields (TRN-T/R) at the end of data frames to track channel variations [32], [33]. The beam tracking stage is an optional stage, that is used to track the changes in the transmit and receive weight vector due to channel variation over time [63]. An alternative solution for tracking the mmWave channel changes is to track the LoS path of the channel by utilizing the geometric relationship between the transmitter and receiver. Some prior knowledge can be used to track the angle, i.e., priori-aided angle tracking strategies, which includes two main steps. The first step is to acquire the temporal variation law of the AoD and AoA of the LoS path. Then, the support set (the index set of nonzero elements in a sparse vector) of the channel is predicted by jointly using the temporal variation law of the LoS path and the sparse structure of mmWave channels [109]. The core idea of path tracking is to filter the spatial propagation path. A noncoherent compressive tracking scheme is designed to estimate the dominant path between BS and user with very small beacon overhead at subsecond time scales [110]. One-shot path discovery scheme is studied via transmitting distinct signals with unique signatures across different angles such that each PHY path has its own signature [111]. Lim *et al.* [112] propose to use particle filtering approaches for tracking the time-varying beam channel to update the beamforming and combining vectors. An auxiliary beam pair-based high-resolution angle tracking strategy is investigated for mmWave wideband systems with mobility [113]. The authors further investigate the impact of the array calibration errors on the auxiliary beam pair design from the perspective of practical implementation. In addition, other beam tracking algorithms, such as adaptive beam tracking [114], are designed for mmWave communication systems.

In general, channel tracking aims to estimate the directions or locations of mmWave users in varying environments. In the case of high mobility of terminals, e.g., in the high-speed railway scenario, the conventional beam tracking strategies become inefficient. Tracking a user's trajectory and velocity helps predict his location changes, which further speeds up the beam tracking and adjustment in mobile mmWave networks. Machine learning methods have the ability to predict the user's location changes via recording a large amount of history trajectory data. Meanwhile, by sensing the change of the environment, the learned pattern of beam change is used to guide the beam alignment by using the ϵ-greedy strategy or the upper confidence bound strategy [116]. In addition, with a small amount of training overhead, the channel-tracking algorithms based on machine learning and initial channel estimation are also studied, such as graph neural network-based [117] and long short-term memory-based channel-tracking [118]. These researches show that making full use of the information of communication environments for channel-tracking is crucial for adapting the high dynamic communication scenarios. Meanwhile, studying real-time one-shot deep learning networks is also an important direction for mmWave communication systems due to the difficulty of obtaining massive training data and the demand for lightweight mobile devices with low-power consumption.

B. Analog Beamforming

Constrained by the high hardware cost and high power consumption of mmWave communication systems, early research on mmWave communication focuses on improving the propagation distance of mmWave at an acceptable hardware cost. Consequently, analog beamforming that is implemented using PS networks becomes a natural choice for mmWave communication systems. Analog beamforming is essentially a spatial filtering operation typically using an array of radiators to capture or radiate energy in a specific direction over its aperture. In general, the design of analog beamforming can be divided into two categories, i.e., one is based on the predefined codebook and the other is implemented via estimating AoA/AoD.

1) Analog Beamforming Based on Codebook: A codebook is a matrix in which each column specifies a beam weight vector that corresponds to a unique beam pattern. The goal of the design of analog beamforming based on codebook is to maximize certain criteria, such as the signal-to-interference-plus-noise ratio or signal-to-noise ratio, by identifying the best beam pair for data transmissions from the set of possible transceiver beam pairs. The optimal solution is to perform a brute force search over the set of possible transceiver beam pairs, but this requires too much over-the-air overhead to determine the best beam pair. Alternating beam alignment (training) between transceivers is one of the most commonly used methods [119]. To reduce the alignment overhead, three-stage protocol, i.e., D2D linking, sector-level searching, and beam-level searching, and two-stage protocol, i.e., sector-level searching and beam-level searching, have been adopted, respectively, by the 802.15.3c [30] and 802.11ad [32]. These two protocols still require significant alignment overheads to determine the best beam pair. As the constant antenna weights (amplitude and/or phase) are applied to the array elements to steer the main beam, even a slight beam misalignment between two communicating devices (for example, due to mobility) deteriorates system performance [120]. This leads to the frequent invocations of time-consuming mechanisms for beam realignment. To this end, some side information extracted from the data packets and the position of terminals may be used to speed up selecting the analog beam pair from the codebooks [121]. Another factor affecting beam alignment overhead is the predefined codebooks [122]. Therefore, properly designing codebook can efficiently promote the effectiveness of analog beam alignments, such as the multiresolution codebook [123] and multistage beamforming codebook [124]. By combining the multiresolution and reflection, the short-range indoor mmWave multiuser communication can be realized by properly designing the analog beam direction from the beamspace perspective [125]. Multibeam concurrent transmission is one of the promising solutions for mmWave networks to provide seamless handover, robustness to blockage, continuous connectivity, and massive access [126]. One of the major obstacles is the optimization of beam pair selection for mmWave multibeam concurrent transmission, especially for ultra-dense mmWave networks [127]. A parallel-adaptive beam

Table 14 Analog Beam Alignment Summary

Architecture	Scheme	Criterion	Mode	Ref.	YoP
Single RF chain	Three-stage downlink-uplink alternative beam alignment	Maximizing received power	Single-user	[63]	2009
	Two-stage downlink-uplink alternative beam alignment	Maximizing received power	Multi-user	[129]	2019
				[130]	2019
Multiple RF chains Fully connected	Interleave assisted beam alignment	Minimizing outage probability	Single-user, Multi-user	[119]	2018
Single RF	Location assisted alternative beam alignment	Maximizing received SNR	Single-user	[121]	2019
Multiple RF chains Fully connected	Alternative beam alignment, blockage control strategies and multi-user multi-beampower allocation	Maximizing sum rate	Multi-user	[122]	2019
	Multi-resolution codebook, adaptive multilevel beam alignment, sequence design	Maximizing received power	Single-user	[123]	2017
Single RF chain	Alternative beam alignment, Hierarchical codebook design	Minimizing delay		[124]	2016
Multiple RF chains Fully connected	Acquiring candidate beam pair links for heterogeneous network, Concurrent beam codebook design	Maximizing sum rate	Multi-user	[127]	2018
	Adaptive beam training protocols, Concurrent beam codebook design	Maximizing received power		[128]	2017

training protocol is proposed to significantly accelerate the link establishment by exploiting the structure features of a hybrid array antenna to scan multiple spatial sectors simultaneously [128]. A comparison of the aforementioned analog beam alignment for mmWave communication is presented in Table 14.

2) Adaptive Analog Beamforming: Adaptive antenna arrays utilize efficient signal-processing algorithms to continuously resolve the multipath, desired signals, and the interfering signals; then, the optimal beam weight vectors (amplitude and/or phase) are determined, and the corresponding analog beam can be obtained according to certain criteria. Specifically, for mobile communication systems, the time-varying AoA/AoD needs to be tracked continuously to constantly adjust the direction of the analog beam. Furthermore, the precision of the estimated AoA/AoD directly and seriously impacts the direction of adaptive analog beamforming. In other words, if the estimation precision of AoA/AoD can be further improved, the combined analog beam can be more precisely set to the incoming/departure direction [131]. To this end, there exist many studies to estimating AoA/AoD in order to improve the performance of analog beamforming communication systems. A high-accuracy AoA estimation with a single training symbol is designed to accelerate beam training by leveraging the emerging architecture of true-time-delay arrays and frequency-dependent probing beams [132]. A multiple carrier frequency tone-based technology is proposed to jointly estimate the AoAs of the strongest paths for the uplink multiuser mmWave communication systems [133]. Codebook-based auxiliary beam pair enabled AoD and AoA estimation is investigated to minimize the initial access delay for mmWave communication system with ULAs or UPAs [134]. Different from single ULA or UPA, the cross correlations between the gains of consecutive subarrays can be used to eliminate the ambiguities and enhance the tolerance to noise [135].

C. Hybrid Precoding

The theoretical maximum data rate of 37 917 Mb/s per spatial stream is achieved with the highest order modulation of 64 QAM, the biggest code rate of 7/8, and the bandwidth of 8.64 GHz in 802.11ay [34]. However, in practice, it is very difficult to realize the goal due to the prohibitive hardware cost and implementation complexity for ultrawide bandwidth communication systems with higher order modulation. Fortunately, MIMO technology is widely proved in practical communication systems, such as 802.11n/ac/aj, to be an effective and efficient method for achieving high data rates via spatial division multiplexing. Combining the MIMO and antenna array technologies is regarded as a promising way to balance the hardware cost and power consumption and to satisfy the high data rate demand.

When investigating the precoding/combining design for mmWave communication systems, it is necessary to jointly take into account three factors, i.e., precoding/combining with RF hardware constraints, the use of large-scale antenna arrays, and the limited scattering nature of mmWave channels [136]. Under these constraints, a hybrid architecture (hybrid precoding/combining) implementation at both digital and analog domains is regarded as a promising alternative, as well as has recently received significant attention from both industry and academia. The analog precoding/combining in the analog domain is implemented using PS networks, whereas the digital precoding/combining in the digital domain can be realized at baseband via simultaneously adjusting the phase and amplitude. However, the constant-module constraint and the cascading between the analog precoding/combining and digital precoding/combining result in the optimization to be nonconvex and more difficult to obtain the global optimal solution. Further research is required for efficiently solving the optimization problem for mmWave communication systems.

1) Hybrid Precoding for Narrowband mmWave Communication: Generally speaking, a transceiver should be designed to obtain the optimal performance of communication systems. To fully unleash the potential of mmWave, in recent years, many effective and efficient approaches are proposed to design a hybrid transceiver. Table 15 lists various existing studies for optimizing hybrid transceiver of narrowband mmWave communication systems.

a) Hybrid precoding via matrix factorization: Matrix factorization is one of the most commonly used methods to overcome the coupling between analog precoding

Table 15 Analog Beam Alignment Comparison

Architecture	Scheme	Requirements	Mode	Ref.	YoP
Fully connected	OMP based sparse precoding, OMP-MMSE based combining	Perfect CSI at transceivers	Single-user	[137]	2014
	Parallel-index-selection matrix inversion bypass simultaneous OMP based sparse precoding	Perfect CSI at transmitter	Single-user	[138]	2015
	Taylor's expansion based analog precoding, Least square based digital precoding	Perfect CSI at transmitter	Single-user	[139]	2017
Fully/Partially connected	Conjugate gradient algorithm for analog precoding, Least square based digital precoding	Perfect CSI at transmitter	Single-user	[140]	2016
Fully connected	Analytical expression for hybrid precoding at each update	Perfect CSI at transmitter	Single-user, multi-user	[141]	2019
	Kronecker decomposition based analog combining, MMSE-based digital combining	Perfect CSI at receiver	Multi-cell multi-user	[142]	2017
	Heuristic matrix decomposition hybrid precoding design	Perfect CSI at transceiver	Multi-user	[143]	2016
	AoA/AoD assisted analog precoding, BD/ZF based digital precoding	Perfect CSI at transceivers	Multi-user	[144]	2019
	Beam selection via iterative eigenvalue decomposition	Effective CSI at transceiver	Single-user	[145]	2016
	Microwave assisted beam selection	Effective CSI at transmitter	Single-user	[146]	2018
	Beam selection via beam alignment, ZF for digital precoding	Effective CSI at transmitter	Multi-user	[147]	2015
	Joint beam selection and digital precoding optimization	Eeffective CSI at transmitter	Multi-user	[148]	2017
	Joint beam selection and user scheduling	Effective CSI at transmitter	Multi-user	[149]	2017
	Beam selection, ZF for digital precoding optimization	Effective CSI at transmitter	Multi-user	[150]	2019
Fully/Partially connected	Energy efficient hybrid precoding design using PDD method	Perfect CSI at transmitter	Single-user	[151]	2017
Fully connected	Spectral efficiency maximization using PDD method for hybrid antenna architecture systems	Perfect CSI at transmitter	Multi-user	[152]	2018
	Spectral efficiency maximization using LISA method for hybrid antenna architecture systems	Perfect CSI at transmitter	Multi-user	[153]	2018
Lens array	Cross-entropy based hybrid precoding design	Perfect CSI at transmitter	Single-user	[154]	2019
Fully connected	Deep neural network based hybrid precoding design	Requiring a lot of training data and labels	Single-user	[155]	2019
Fully connected	Convolutional neural network based hybrid precoding design		Multi-user	[156]	2020

and digital precoding. First, the optimum fully digital precoding is obtained, and then, matrix factorization is used to obtain the analog precoding and digital precoding matrices [137]. Existing research outcomes demonstrate that the design of hybrid analog/digital precoders can be formulated as a sparsity constrained matrix reconstruction problem [138]. In exploiting the sparse-scattering structure of mmWave channels, the goal is to capture the "dominant" paths by choosing properly steering vectors. Various matrix factorization methods are proposed using Taylor's expansion [139], alternating minimization [140], and Kronecker decomposition [142], with the objective of achieving spectral efficiency close to that obtained with fully digital solutions. To realize the performance of fully digital antenna architecture, it is sufficient that the number of RF chains in a hybrid architecture is greater than or equal to twice the number of data streams [143].

b) AoA/AoD assisted hybrid precoding: Once the analog beams have steered at the "dominant" paths of the mmWave channel, the mmWave PHY channel can be transformed into a small dimension equivalent channel. Though this can reduce the computational complexity, how to effectively acquire the phase angle of strong path directions is still a challenging problem, especially for multiuser mmWave communication scenarios. It is necessary to investigate and develop joint beamforming and channel estimation techniques for single-user and multiuser mmWave communications under LoS or NLoS conditions. After obtaining the small dimension equivalent channel, the conventional MIMO precoding design methods can be directly used to optimize the digital domain precoding [144].

c) Codebook-based hybrid precoding: As pointed out in the approach of codebook-based channel estimation, one can obtain a virtual channel matrix once the beam training is finished [145]. Consequently, the design of a hybrid transceiver can be transformed into joint analog beam selection and digital precoding/combining design problem [146]. A single limited feedback hybrid precoding method is proposed for mmWave multiuser communication system with zero-forcing digital precoding [147]. Instead of adopting zero-forcing digital precoding, by exploiting the virtual channel matrix and the idea of antenna selection, He *et al.* [148] transform the design problem of hybrid precoding into a digital precoding optimization problem constrained with additional conditions on codeword selection for mmWave multiuser communication system. Following the idea of the virtual channel, a joint analog beam selection and user scheduling method is developed in [149]. By releasing the interuser interference, Sun and Qi [150] propose first a Hungarian-based codeword selection method and then using zero-forcing precoding to design the digital precoder with an equivalent channel.

d) Directly optimize hybrid precoding: Different from the aforementioned design methods, to better understand the optimal hybrid precoding/combining design, especially for multiuser mmWave communication systems, some novel methods are investigated to directly address the optimization problem for mmWave communication systems. The optimization of hybrid transceiver can be studied by regarding the product of analog precoder/combiner and digital precoder/combiner as a whole based on the penalty dual decomposition method. Then, an alternative optimization method can be used to maximize spectral and energy efficiencies for mmWave communication systems. Following this idea, the maximization problems of energy efficiency and spectrum efficiency are investigated, respectively, for mmWave single-user [151] and multiuser communication systems [152]. The linear successive allocation method that is proposed for the fully digital precoding in multiuser MIMO systems is extended to address the transceiver design problem of mmWave multiuser systems [153].

e) Machine learning-based hybrid precoding: Due to the ability of deep learning to process massive data and solve complicated nonlinear problems, some deep learning-based hybrid precoding/combining methods are designed to speed up the optimization method based on the conventional optimization theory. The idea of cross-entropy optimization developed for machine learning applications is utilized to design the hybrid precoding for mmWave systems with lens array and low-resolution ADCs [154]. A framework applying deep neural networks to design hybrid precoding is studied for mmWave MIMO systems [155]. The convolutional neural network is used to design the precoder/combiners for mmWave multiuser MIMO systems using the exhaustive search algorithm to select the analog precoder and combiners as output labels [156]. The aforementioned studies focus on designing end-to-end deep neural networks to learn the mapping between the input and the output and to approach an optimal or suboptimal solution to a conventional optimization problem. This kind of deep learning method belongs to the class of data-driven supervised learning networks. However, in general, it is hard to find the optimal or suboptimal solution to the optimization problems in mmWave communication systems. Meanwhile, for wireless communication networks, it is difficult to obtain a large amount of training data for constructing a deep learning model. Therefore, data and model jointly driven deep learning model become an emerging direction for mmWave communication networks.

2) Hybrid Precoding for Wideband mmWave Communication: For wideband mmWave communication with frequency selectivity channels, a potential problem of wideband hybrid precoding is to overcome channel impairments. In mmWave OFDM systems, the analog precoders and combiners are the same for all subcarriers, while the digital precoders and combiners are different for each subcarrier. This makes the design of hybrid precoders and combiners more challenging compared with narrowband mmWave systems. For the design of hybrid precoder/combiner for wideband mmWave systems, the existing literature can be divided mainly into two categories from the viewpoint of the time–frequency domain.

a) Transceiver design in frequency domain: The coupling among variables in the frequency domain is generally expressed as product form. Generally, alternative optimization is an effective approach to releasing the coupling relations. In particular, one can first divide the optimization variables into some subsets so that the optimization problem can be easily solved relative to each subset. Then, alternative optimization is carried out between those subsets. For example, for a given analog precoding matrix, the digital precoder of each subcarrier has an analytical expression for wideband mmWave single-user systems with aiming to maximize the spectrum efficiency only under power constraint [157]. Based on the analytical expression, one can focus on designing the analog precoder subject to certain constraints and maximizing a certain objective [158]. Following these ideas, the sparse-scattering nature of the mmWave channel is further utilized to study the hybrid precoding design for both single-user [159] and multiuser [160] mmWave wideband system under the power constraint per-subcarrier. In addition, the idea of cross-entropy optimization developed for machine learning applications is also utilized to design the hybrid precoding for wideband mmWave systems [161]. However, the aforementioned references mainly focus on maximizing the spectrum efficiency under simple power constraints and constant modulus constraints. This implies that how to design a more efficient hybrid transceiver is still challenging for a wideband mmWave communication system with more complicated constraints.

b) Transceiver design in time domain: The existence of large path loss of mmWave leads to a limited number of strong propagation paths, i.e., the transmitter and receiver are only coupled through a small number of dominant beams, which is typically much smaller than the signal dimensions in antenna domain. From the viewpoint of channel propagation in the time domain, the analog beam is to select the dominant path for transferring signals. Exploiting this observation, a low-complexity path division multiplexing is proposed for point-to-point mmWave communication [162]. Meanwhile, the time-reversal transmission that exploits the delay difference between different paths is designed to filter out the strongest path as the desired transmission path with regarding another path as interference path [163]. Following this idea, hybrid precoding using time delay precompensation is investigated for single-user and multiuser mmWave wideband systems [164].

3) Robust Hybrid Precoding/Combining Design: The fundament of hybrid precoding/combining is to acquire the CSI for mmWave communication systems. However, in practice, it is very difficult to acquire the perfect CSI at transmitter, especially for mmWave communication system with digital–analog hybrid antenna array architecture, due to various factors, such as estimation/quantization errors, pilot contamination, and feedback delays. This implies that the research on robust hybrid precoding/combining is imperative via taking into account the serious interference and CSI errors for mmWave communication systems [165]. For example, for a full-duplex mmWave MIMO relay system, a robust joint transceiver algorithm is proposed by taking into account the stochastic CSI errors [166]. A robust hybrid beamforming scheme is studied via taking the correlation between the channel estimation errors into account for mmWave communication systems [167].

Table 16 Hybrid Transceiver With Considering Hardware Impairments

Hardware impairments					Scheme	Conclusion	Ref.	YoP
ADC	DAC	PA	I/Q	PS				
✓					Hybrid and digital beamforming receivers	• The low resolution ADC digital beamforming is robust to small automatic gain control imperfections; In the low SNR regime, the performance of digital beamforming even with $1-2$ bit resolution outperforms hybrid beamforming;	[170]	2017
✓					Bayesian optimal data detector	• Adding a few low-resolution RF chains to original unquantized systems can obtain significant gains;	[171]	2018
✓					Bayesian Channel Estimation	• In terms of the channel estimation accuracy, the low-resolution ADCs lead to a small performance gap compared to the high-resolution ADCs when the signal-to-noise ratio (SNR) is low;	[172]	2018
✓					User Scheduling	• The channel structure in the beamspace, in addition to the channel magnitude and orthogonality, plays a key role in maximizing the achievable rates of scheduled users;	[173]	2019
		✓			Constant envelope precoding	• Constant envelope precoding is an effective way to make the PA work near the saturate region;	[174]	2018
	✓	✓			Energy efficient quantized hybrid architecture transmitters	• Hybrid precoding with partially connected and digital precoding are the most energy- and spectral-efficient solutions, respectively;	[175]	2018
		✓			Digital pre-distortion techniques	•Digital pre-distortion is an effective linearization approach for the PA used in mmWave systmes;	[176]–[179]	2020
		✓			SC for mmWave communication	• SC helps to improve the efficiency of power amplifiers;	[180]	2019
			✓		Compensating transmitter I/Q imbalance	• I/Q imbalance can substantially affect the system performance;	[181], [182]	2017
			✓		Hybrid beamforming with I/Q imbalance	• I/Q imbalance limits the achievable sum rate to a finite ceiling;	[183]	2018
				✓	Evaluating phase shifter quantization effect	• The quantization of phases cause a significant degradation to the system performance;	[184]	2015
				✓		• For a small number of quantization bits, the precoder implemented using two phase shifters for each coefficient is a good approximation of the unquantized one;	[185]	2017
				✓	Design of hybrid precoders and combiners	• The proposed algorithms can offer a performance improvement to the existing low-resolution hybrid beamforming schemes;	[186]	2018
				✓	Transmit antenna selection and analog beamforming	• Antenna selection can improve the performance in terms of spectral efficiency;	[187]	2018
				✓	Dynamic subarrays and hardware efficient low-resolution PSs	• Multiple antenna and multi-user diversities help to make up for the loss led by low low-resolution PSs;	[188] [189]	2018 2020

4) Hybrid Precoding With Hardware Impairments: The specific system performance is determined mainly by the hardware technologies adopted in practical communication systems. Though the ideal hardware implementation technologies can achieve the optimal system performance, the expensive hardware cost and power consumption are unaffordable [168]. For example, the power consumption of a typical ADC scales linearly with the bandwidth and grows exponentially with the quantization bits. Consequently, high-resolution ADC chains are the most power-hungry elements at the receive side. On the transmit side, the power expenditure is dominated by PAs that are usually required to operate within the high linearity regime to avoid the distortion of signals. On the other hand, the cheap hardware components are particularly prone to degrade the system performance due to the impairments existing in any transceiver, e.g., the nonlinearity of PA, in-phase/quadrature (I/Q) imbalance, PN, and quantization errors [169]. Therefore, how to obtain a tradeoff between the system performance and hardware cost along with power consumption has attracted extensive attention in both industry and academia. Table 16 lists some transceiver design schemes with taking into account the hardware impairment for mmWave communication systems.

a) Low-resolution ADCs/DACs: On the one hand, mmWave propagation experiences high attenuation, and most scattered reflections become too attenuated, i.e., mmWave channel is dominated by a sparse set of reflectors. As a result, approximate mmWave channel rank-1 matrix representations arise with a notable probability. On the other hand, the signal-to-noise ratio is very low before beam alignment, and a very stringent low-power constraint is required at the receiver. This means that the large-scale antenna array is imperative to compensate for the large path loss, i.e., improve the signal-to-noise ratio for mmWave communication systems. However, due to the large bandwidth and high rate sampling, the analog front end of the receiver with a large number of antennas becomes especially power-hungry. In particular, since the power dissipation at ADCs scales linearly with the sampling rate and exponentially with the number of bits per sample, it may not be desirable to operate the system with high-resolution ADCs. Therefore, to reduce the power consumption, one of the most widely concerned issues is the design of a hybrid combiner with low-resolution ADCs for mmWave communication systems [170]. A mixed-ADC architecture with low-resolution RF chains and high-resolution ADCs is shown to be a viable architecture for mmWave MIMO communication systems [171]. In addition, improving the quality of the estimated CSI is also an effective way to promote the performance of mmWave communication systems with low-resolution ADCs. The studies in [172] have shown that one can achieve similar or even better performance with a smaller number of RF chains and low-resolution ADCs by jointly using the pilots and data. For mmWave communication system with low-resolution ADCs, the channels of users scheduled need to have as many propagation paths as possible with unique AoAs and even power distribution in the beamspace in order to maximize the achievable rate for a given channel gain [173]. However, how to effectively exploit low-resolution devices is still a hot issue for mmWave communication with aiming to balance the system performance and the hardware cost together with power consumption.

b) Hardware impairment of PAs: In mmWave communication systems, PA is a key component for improving the signal-to-noise ratio and the coverage of mmWave communication. However, to support spatial division multiplexing, the linear combination of multiple streams may lead to a higher peak-to-average power ratio. To overcome this challenge, constant envelope precoding is regarded as a promising and powerful way for improving the PAs efficiency of mmWave communication [174]. On the other hand, employing low-resolution DACs can relax the linearity requirement, allowing the PAs to operate closer to saturation, thus increasing their efficiency [175]. To overcome the serious nonlinearity impact on signals, digital predistortion techniques achieve competitiveness and have earned wide applications due to their low costs and high accuracy [176]. A detailed signal and distortion modeling is carried out in broadband multiuser hybrid MIMO systems with a bank of nonlinear PAs in each subarray while also taking the inevitable crosstalk between the antenna/PA branches into account [177]. Meanwhile, a practical power scalable beam-oriented digital predistortion scheme is designed to further resolve the hardware implementation issue encountered in mmWave transmitters with hybrid antenna array architecture [178]. A multibeam digital predistortion technique is proposed to resolve the issues of PA's nonlinear distortion and multibeam interference with mmWave analog beamforming transmitters in multiuser scenario [179]. In addition, SC modulation is regarded as a powerful and promising method for mmWave communication to guarantee a low peak-to-average power ratio of the transmit signals and allow a highly efficient power amplification [180].

c) Hardware impairment of I/Q imbalance: I/Q imbalance is one of the common down-conversion and up-conversion impairments of analog front-end in direct-conversion (zero-IF) transceiver. Physically, when the baseband signal is up-converted in the transmitter or when the RF signal is down-converted in the receiver, the signals in the I/Q branches have slight differences in their amplitude and phase responses, e.g., due to manufacturing tolerances. The I/Q imbalance is negligible relative to the sampling interval for microwave systems, but it becomes significant and can substantially affect the system performance for mmWave systems. To fully realize the potential of mmWave communication systems, one has to handle the I/Q imbalance in the transceiver. The I/Q imbalance compensation at transmitter was investigated, respectively, for mmWave SC frequency-domain equalization systems [181] and mmWave OFDM communication systems [182]. A hybrid precoding algorithm considering I/Q imbalance is studied for mmWave massive MIMO systems at both the transmitter and receiver [183].

d) Hardware impairment of PSs: In mmWave communication systems, there are two basic types of PSs for mmWave systems: active PSs and passive PSs. Both types of PSs are costly and experience phase errors, including deterministic errors and random errors, due to the manufacturing tolerances and material imperfections. The deterministic errors can be corrected through appropriate manufacturing, while the random errors can have a multiplicative effect on the beam pattern and need to be compensated algorithmically [72]. On the other hand, the analog precoders/combiners are implemented via a PS network that is controlled digitally with a finite number of values, depending on the quantization bits. The quantization effect of PSs on mmWave beamforming is evaluated in [184]. The results show that the quantization of phases causes a significant degradation to the system performance. Therefore, it is necessary to take into account the quantization effect of phases in designing hybrid transceivers for mmWave communication systems [185]. Wang *et al.* [186] investigate the practical design of hybrid precoders and combiners with low-resolution PSs in mmWave MIMO systems. The antenna selection technology is utilized to improve the spectral efficiency of the mmWave system with low-resolution PSs [187]. Deng *et al.* [188] investigate the multiuser beamforming gains with different phase-quantization levels and subarray geometries. By dynamically connecting each RF chain to a nonoverlap subarray via a switch network and PSs, the performance loss incurred by using low-resolution PSs can be compensated by the multiple antennae and multiuser diversities [189].

D. Fully Digital Transmission

It is well known that deploying a large number of antennas at transmitter and/or receiver (massive MIMO) can significantly improve the spectral and energy efficiency of wireless networks. Furthermore, adopting simple beamforming strategies, such as maximum ratio transmission or zero-forcing precoding, can obtain these performance gains in a rich scattering environment [190]. In addition, as mmWave has an extremely short wavelength, it becomes possible to pack a large number of antenna elements into a small area. Meanwhile, as the cost of mmWave hardware decreases, fully digital mmWave massive MIMO becomes a promising way to improve the performance of future mmWave communication systems. To better understand the propagation of fully digital mmWave massive MIMO communication systems, some channel measurement activities are on different mmWave frequency bands, such as 11, 16, 28, 36, and 44 GHz, for fully digital mmWave massive MIMO communication systems [42].

Though a hybrid architecture with multiple RF chains can enable multiuser/ multidirectional beamforming, its performance is limited by the number of RF-chains.

To overcome the shortcomings of hybrid architecture, fully digital architecture where each antenna element is attached to a separate pair of ADCs has been recently investigated [74]. This architecture brings all the advantages of digital beamforming in terms of fast beam management and optimality of beamforming, but it has the highest power consumption at ADCs and the baseband processer for a given bit resolution and sampling rate [191]. To reduce the power consumption incurred by ADCs, digital beamforming with low-resolution ADCs becomes a promising way for mmWave massive MIMO communication system with fully digital architecture. Furthermore, the studies have shown that the performance loss due to the coarse quantization of low-resolution ADCs can be overcome with a large number of receive antennas. The studies further show that digital beamforming is more energy-efficient than hybrid beamforming for multiuser communication [192]. In order to reduce the power consumption of input/output interfaces between the RF integrated circuit and baseband modem, a novel fully digital architecture with blind beam tracking and spatial compression is developed for mmWave communication systems with fully digital beamforming architecture [193].

To make full use of the potential benefits of MIMO systems, most studies on precoding techniques assume the perfect CSI at the transmitter. However, in practice, it is impossible to obtain the perfect CSI before aligning the transceiver direction for mmWave communication systems with fully digital beamforming architecture [194]. To overcome the difficulty of obtaining perfect CSI at the transmitter, an orthogonal random precoding scheme is proposed to extend cell coverage in the downlink of mmWave massive MIMO systems with fully digital beamforming architecture [195]. Wang *et al.* [196] propose uplink and downlink channel estimation strategies by analyzing the spatial- and frequency-wideband effects (beam squint effects) in mmWave massive MIMO systems.

E. SDR-Based Testbed for mmWave Communications

The rapid development of communication technologies makes building experimental platforms or testbeds a challenging task, especially to meet the hardware requirements of new standards. Software-defined radio (SDR) provides the flexibility, cost efficiency, and power for rapidly studying and validating new wireless communication technologies. Liu *et al.* [115] carry out an experiment to collect raw mmWave signal data from the National Instruments (NI) mmWave transceiver system and analyze the characteristics of the mmWave signals transmitted. The experimental results show that the prediction accuracy of users' locations obtained by machine learning methods increases with the training time epochs. As an SDR-based testbed-level experimental example of mmWave communications, a compact and highly programmable 28-GHz phased array subsystem is developed for 28-GHz channel sounding measurements [197]. A fully programmable testbed of the PHY, MAC, and Network layers, enabling mmWave communication over 2-GHz wide channels in the 60-GHz frequency band, is built by using the NI mmWave transceiver, where a user-configurable 12-element phased array antenna from SiBeam is equipped [198]. A highly flexible experimental MIMO platform is designed to accommodate the bandwidth of variable ranges from 160 MHz to 2 GHz for either 802.11ac/ax or 802.11 ad/ay [199]. This testbed is built on the RF system on a chip platform that integrates multiple ADCs/DACs with gigasampling rates, two multicore processors, and programmable logic.

F. Discussion and Conclusion

In this section, we review the progress of enabling PHY-layer transmission technologies and point out the future PHY-layer study directions for mmWave communication systems.

1) We summarize the studies on the channel estimation and tracking for mmWave communication systems. The unique characteristics of mmWave propagation make the channel estimation more challenging due to the lack of array gains and the fact that each RF unit cannot obtain simultaneously the sampled signals from each antenna. Though a large number of studies have been carried out for channel estimation, how to efficiently estimate channels is still challenging for mmWave massive MIMO communication systems. Furthermore, spatial multiplexing may be used to improve the spectral efficiency in mmWave massive MIMO communication systems. However, spatial multiplexing is largely limited by the rank of the channel matrix, which depends on spatial multipath propagation exploiting scattering environment and so on. The directional transmission with a narrow beam may reduce the coverage of scatters and then reduce the rank of the channel matrix. This feature is different from the conventional MIMO communication systems operating in below 6-GHz frequency bands. Therefore, studying in-depth the rank of channels will help the research of mmWave spatial multiplexing transmission technologies for mmWave massive MIMO communication systems. In some special environments, NLoS propagation may be capable of supporting wireless transmission. In other words, for mmWave massive MIMO communication systems, the channel matrix may possess a different rank for different narrow beam configurations in a different wireless environment. Meanwhile, some new communication technologies, such as the intelligent reflection surface, can be used to enrich the rank of the channels of mmWave communication [200].
2) We review the analog beamforming schemes. Many studies focus on the design of analog beam

codebooks and the beam training mechanism based on the designed codebooks. In addition, to adapt to the change of environment and the mobility of terminals, adaptive analog beamforming has been extensively studied via dynamically tracking the propagation channel changes. However, due to the lack of the ability to provide multiplexing gain, the analog antenna array gradually moves toward the hybrid architecture and fully digital architecture for mmWave communication systems.

3) The advances of enabling PHY-layer transmission technologies are reviewed from three aspects for mmWave communication system with hybrid architecture. Though the research on hybrid precoding and combining has attracted extensive attention, most of the research focuses on the design of hybrid precoding and combining of mmWave communication systems with fully connected and partially connected architecture. Only a few works study the design of hybrid precoding and combining for mmWave communication system with dynamic combination between RF chains and antennas. This is because it depends on the channel change of communication environments and the self-adaptive ability of the transceiver. The design of hybrid precoding and combining has also been carried out for mmWave communication systems with Lens antenna architecture.
4) Hardware impairment is an important factor affecting the performance of communication systems, especially mmWave communication systems. There are a few papers focusing on the comprehensive study of the impact of hardware impairment on mmWave communication systems and the corresponding hardware impairment compensation methods. In particular, the digital predistortion technique is an enabler for mitigating the impact of hardware impairment on the performance of communication systems. Some researchers have explored many novel methods to reduce the PA nonlinear impact on the performance of the mmWave communication system. However, we still need to study some novel techniques based on digital predistortion to reduce the impacts on the performance of the mmWave communication system by comprehensively taking into account the aforementioned hardware impairments.
5) Motivated by the successful application of machine learning, especially deep learning, in the image processing field, machine learning-based mmWave communication technologies, including machine learning-based channel estimation, channel tracking, hybrid precoding, and so on, have been attracted extensive attention from both industry and academia. To obtain an effective machine learning-based communication model, we need to collect a large number of training and test data for the off-line training. However, the high dynamic and complex characteristics of wireless environments make it very difficult to obtain the training and test data. In the future, it is one of the key points to improve the scalability, generalization, and real time of communication technologies based on machine learning. At the same time, the research of distributed cooperative communication technologies with data privacy protection ability is also one of the research focuses of communication technologies based on machine learning. In addition, in wireless networks, the kinds of communication nodes and communication traffic may be rich and diverse. Therefore, how to design an effective deep learning model supporting more heterogeneous networks is also important for further improving the performance of deep learning algorithms.
6) An emerging fully digital mmWave massive antenna architecture has been regarded as a promising method to compensate for the large path loss and penetration loss of mmWave with the reduction of mmWave hardware cost. At present, one focuses on studying the design of transceiver with lower resolution hardware for mmWave communication system with fully digital architecture. However, when employing fully digital architecture, several pressing challenges, including channel estimation, beam training, feedback, hardware cost, and signal processing, need to be overcome. The research on these aspects is still in its infancy.
7) SDR-based platforms are an efficient development tool for studying novel wireless communication technologies and adapting to the diverse and rapid changing requirements of wireless systems. Some SDR-based platforms have been developed for speeding up the validation of new wireless communication technologies. However, they cannot be regularly used as general-purpose research platforms due to their cost and highly optimization design, especially for the research of high-frequency communication technologies. Therefore, more flexible and affordable SDR-based testbeds are needed to be developed for catering to the emergence of new standards and technologies.

V. EMERGING USE CASES OF mmWave COMMUNICATION

From the viewpoint of the quality of service, the large path loss and weak penetration may be disadvantages of mmWave communication systems. However, from the communication security perspective, they may be favorable factors for some special application cases of mmWave communications. At the same time, the directional transmission with antenna arrays also provides a favorable mechanism for achieving interference management, energy harvesting, and security communication. Consequently, these factors give birth to many new research topics.

A. Emerging Use Cases

1) Ultradense mmWave Communication: With the development of information and communication technologies, human life and society will be increasingly digitized, hyperconnected, and globally data-driven, such as eHealth and autonomous vehicles. These emerging requirements drive the communication network to support ubiquitous device connectivity. Among the appealing approaches to realize these ambitious goals, network densification is shown to be the most promising one by deploying more BSs with smaller coverage. The ultradense deployment, however, involves high capital and operational expenditures for network operators to connect more cellular BSs via backhaul connections [201]. Meanwhile, interference management is also another challenging problem for ultradense networks. From the perspective of backhaul and interference management, the directional transmission and large path loss are considered as advantages. This is because they reduce the likelihood of cochannel interference and increase the frequency reuse density. The directional transmission along with the D2D communication can provide Gb/s throughput with reducing the interference of concurrent access and backhaul transmissions [202]. In addition, properly selecting the transmitting and receiving beam pair and allocating the transmission power can significantly improve the network performance of mmWave D2D communication systems [203].

2) UAV mmWave Communication: Recently, UAVs communication emerges as a supplement for terrestrial cellular communication to enhance the quality of user experience. The UAV communication has the potential to establish wireless links in unexpected communication scenarios, such as to help with data offloading in sudden traffic hotspots, ubiquitous coverage against severe shadowing, and prompt service recovery after natural disasters. Different from terrestrial cellular communication, the UAV BS moves around and can be placed at desired locations based on demand in UAV communication networks. However, the movement of UAV BSs brings more difficulties to the UAV mmWave communication, such as making the beamforming training and tracking more complex. In addition, the inherent challenges encountered in fixed BS mmWave communication, such as large path loss and directional transmission, also exist in UAVs mmWave communication even though the chances for LoS links increase [204]. Therefore, efficient communication mechanisms need to be investigated and developed, including beamforming training and tracking in the presence of a high Doppler effect [205]. To make full advantage of the motion characteristics of UAV BSs, intelligent cruising and beamforming training and tracking algorithms have the ability to effectively improve the mmWave coverage range and the quality of the propagation channel by adaptively adjusting the position of UAV BSs [206]. By virtue of the flexibility of dynamic beam adjustment, the NOMA technology has the potential to further enhance the system capacity of UAV mmWave communication [207]. In addition, improving the coverage and transmission signal quality should help to enhance the PHY-layer security of UAV mmWave communication systems [208].

3) Green mmWave Communication: It is reported that the total energy consumed by the infrastructure of cellular wireless networks, wired communication networks, and the Internet takes up more than 3% of the worldwide electric energy consumption nowadays, and the portion is expected to increase rapidly in the future [209]. Motivated by this observation, one of the major 5G research challenges is to improve the energy efficiency 1000 times. In other words, in addition to enhancing network throughput, wireless communication systems should reduce energy consumption. On the other hand, the development of battery technology is much slower than the increase in energy consumption; therefore, the mobile terminals in wireless systems necessitate energy saving [210]. Therefore, how to balance energy efficiency and spectral efficiency becomes a focus of many research activities. The ultradense networks combined with mmWave technology are expected to increase both energy efficiency and spectral efficiency [211]. The energy coverage probability, average harvested power, and overall (energy-and-information) coverage probability are analyzed by using stochastic geometry for a typical wireless-powered device in terms of the antenna geometry parameters, BS density, and channel parameters. For a given user population, the network-wide energy coverage can be maximized by optimizing the antenna geometry parameters [212].

4) PHY-Layer Security mmWave Communication: In the era of acquiring information at anytime and anywhere, personal privacy and information security have become key issues to be considered in the process of communication technology research. At the same time, with the enhancement of hardware computing power and the development of big-data processing technologies, the traditional computation-based cryptography techniques have become less secure and less reliable, especially for a wireless communication system with a broadcast nature. Hence, how to achieve PHY-layer security communication is essential research for wireless communication [213]. To achieve PHY-layer security communication, the existing solutions include controlling the signal energy leakage to the eavesdropper and adding some artificial noises in the desired signal for jamming potential eavesdropper. In mmWave communication systems with large path loss and directional transmission, the limited coverage range is a perceived advantage, which may reduce the opportunities for exposing protected content. The beamwidth of analog precoding vector depends on the number of antennas and the angles of analog precoding vectors, which requires to be carefully designed for reducing or eliminating the signal energy leakage to eavesdroppers [214]. Artificial noise-assisted hybrid precoding design is another powerful way for PHY-layer security in mmWave communication systems [215]. The closed-form expressions of the connection probability for maximum ratio transmission and artificial noise beamforming are obtained for a multi-input single-output mmWave system, where multiple single-antenna eavesdroppers are randomly located [216]. The stochastic geometry approach is used to evaluate performance measures, such as the connection outage probability, secrecy outage probability, and achievable average secrecy rate for mmWave-overlaid microwave cellular networks [217].

5) Content-Centric mmWave Communication: Low-latency data delivery is one of three key performance indices for the 5G, beyond 5G, and 6G wireless communication systems. In particular, the reliability requirement of the factory automation and telesurgery is $1 - 10^{-9}$ with the lowest end-to-end latency being less than 1 ms. Other services, e.g., smart grids, intelligent transportation systems, and process automation, have more relaxed reliability requirements of packet loss rate of 10^{-3}–10^{-5} with latencies between 1 and 100 ms [218]. Usually, in a practical system, the delivery latency depends not only on the source location of requested files and the capabilities of baseband signal processing but also on the transmission data rate. On the one hand, introducing the cache at the network edge, i.e., caching frequently requested files at the network edge, has the potential to meet the demand of millisecond-level delivery delay by reducing both the burden on fronthaul links and the content delivery delay [219]. On the other hand, increasing the transmission bandwidth is also a powerful tool to increase the transmission rate. This implies that the delivery delay can be reduced. Combining these two points, content-centric (cache-enabled) mmWave communication becomes naturally a potential way to achieve content delivery with low latency [220]. Meanwhile, different content-centric transmission modes can lead to different received signal strengths such that different user association strategies exert different effects on system performance. Hence, efficient MAC and interference management strategies should be developed taking into account the content cache status and narrow-beam transmission mechanism for content-centric multimode wireless communication networks [221].

6) Intelligent mmWave Communication: The directional transmission and sensitivity of mmWave signals to blockage greatly impact the coverage and reliability of mmWave communication and pose more technological challenges for the mmWave system. These factors provide more degree of freedom for user association and beam alignment with considering network environment [222]. This drives the research of context-aware communication, intelligent user association, intelligent beam alignment, intelligent resource allocation including transmit power, user scheduling, and beam allocation for mmWave communication systems. For example, position-assisted beam alignment is more efficient than the traditional alternative beam alignment [223]. Most of the existing research on the design of hybrid transceivers assumes that the CSI is perfectly known at the transmitter and receiver. However, this assumption is unlikely true in practical mmWave systems. To unleash the requirement, one approach is to exploit the history data information to learn the CSI based on machine learning, especially long short-term memory learning [224]. Besides, the directional transmission of mmWave makes the cell association more challenging compared with the omnidirectional transmission. The research shows that exploiting the context information will help to improve the spectral efficiency of mmWave communication systems [225].

7) mmWave Sensing and Imaging: We note that the ultra-wideband and directional transmission are two notable characteristics of mmWave communication systems. The ultrawideband and directional communication of mmWave enable cm-resolution and angular imaging information. These bring a chance for wireless sensing and imaging using mmWave communication signals. Recently, mmWave sensing and imaging have attracted extensive attention from both industry and academia [226]. However, to effectively realize mmWave sensing and imaging, mmWave systems require much larger apertures (20–200 cm). This implies that the need for a massive number of sensors to completely build up a high-resolution image of the scene is still a major challenge for mmWave sensing and imaging systems. The emergence of mmWave communication infrastructure in 5G and 6G cellular systems further brings great opportunities to mmWave sensing and imaging [227]. Guan *et al.* [228] designed a prototype system for 3-D imaging using mmWave 5G signal. Yanik *et al.* [229] jointly exploit different mechanical scanners and the commercially available MIMO mmWave radar sensors to facilitate various synthetic aperture radar techniques. Meanwhile, they propose a novel synchronization mechanism between MIMO mmWave sensors and the scanners in the proposed testbed.

B. Discussion and Conclusion

Though a lot of research activities have been carried out on these emerging use cases, there are still many issues to be further studied.

1) The spatial sharing mechanism defined in 802.11ad [32] has the ability to manage the interference of ultradense networks and support D2D application via clustering mechanism. However, it requires a coordination controller to cooperatively schedule the spatial sharing communication pairs. Furthermore, the coordination controller requests the terminals to perform and report spectrum and radio resource measurements for assessing the possibility to perform spatial sharing and interference mitigation. In addition, the mobility of terminals requires frequent changes of beam direction. These factors

make the implementation of the spatial sharing mechanism difficult and even impossible. Hence, a more efficient spatial sharing mechanism needs to be studied from the perspective of time domain and beam domain with taking the mobility of terminals and the dynamics of network environments.

2) The mobilities of UAV BSs and terminals make the beam training and tracking more complex. A series of existing 802.11 standards focus on short-distance static or slow mobile terminal communication as the main communication scenario. Though there are some studies on beam alignment for high-speed railway and UAV mmWave communication, these research results have not been standardized at present. Therefore, these factors need to be considered in the development of new mmWave communication standards, such as in future mmWave cellular communication technology specifications.
3) The energy efficiency of wireless communication depends on many factors, such as the transmission rate, the hardware structures, and the carrier frequency. For mmWave communication, though increasing transmission bandwidth and adopting directional transmission can improve the spectral efficiency, it does not necessarily improve the energy efficiency [230]. How to achieve really energy-efficient communication is still challenging for the designer of mmWave communication systems. Therefore, for mmWave communication, one should study not only the energy-efficient transmission scheme but also the energy-efficient hardware design and implementation. The latter is more important for extensive applications of mmWave communication.
4) The limited coverage range due to the large path loss and weak penetration is a perceived advantage, which may reduce the opportunities for exposing protected content. On the other hand, it may also give a chance for the eavesdropper to obtain the protected content, once the eavesdropper locates in the coverage of the main lobe of the beam. The existing research on PSmC mainly focuses on the transmission scheme from the perspective of a secure transmission rate without fully utilizing the characteristics of mmWave. How to achieve really PSmC needs to be studied, accounting for the characteristics of mmWave propagation and directional transmission.
5) The research on cache-enabled mmWave communication and intelligent mmWave communication is still in its infancy. The introduction of directional transmission and caching popular content at the network edge and mobile terminals makes the resource allocation, user association, interference management, and beam alignment more challenging for mmWave communication systems. Making the mobile terminal capable of learning the information of the surrounding environment is an important means to improve the spectrum efficiency of mmWave communication. However, many challenging technical problems still need in-depth research for future mmWave communication systems [231].
6) With the development of mmWave communication in 5G and 6G wireless systems, more and more mmWave devices have the ability to achieve ultrahigh-resolution sensing and imaging. Reusing mmWave infrastructure for sensing and imaging, the radar functions would need to be added in hardware and multiplexed (in time/frequency/code) with communication functions, thereby increasing cost and reducing network data throughput. These may require control or modify the control of BS or communications waveforms that may not be allowed in 5G protocols. This means that we need to take these new requirements of mmWave sensing and imaging into account in the B5G/6G protocol development process.

VI. CONCLUSION

This article provides a comprehensive overview of the state of the art of research on mmWave communication, including the standardization of mmWave communication, antenna architecture, and enabling PHY-layer transmission technologies, as well as some emerging use cases of mmWave communication. The researches have shown that mmWave communication is a promising solution to provide high data rate content delivery for future wireless communication systems due to the abundant available spectrum resource in mmWave frequency bands of 30–300 GHz. However, a large number of channel measurements have shown that the large path loss and expensive hardware cost become the main obstacles for the practical application of mmWave communication. To compensate for the large path loss and weak penetration, large-scale analog antenna array and massive MIMO antenna architecture are adopted for mmWave communication systems. In general, a fully analog antenna array only bring diversity and array gain but cannot provide multiplex gain. In addition, the conventional MIMO system requires dedicated baseband and RF hardware per antenna element, which causes high cost and power consumption of the mixed analog/digital signal components for mmWave communication systems. Consequently, digital/analog hybrid antenna array architecture becomes an efficient approach to balance the system performance and hardware cost together with power consumption. This scheme combining with hardware constraints brings various new challenges for designing transceivers of mmWave communication systems that have attracted extensive studies in both industry and academia.

In recent years, a large number of R&D activities have been carried out to investigate mmWave communication technologies. Meanwhile, a series of technology specifications have been established for some mmWave use cases. However, there are still many opening research problems relating to channel characteristic analysis and baseband signal processing when mmWave is used in WPAN, WLAN, cellular networks, VNs, or wearable networks, and so on. Furthermore, new engineering solutions are required to realize high data rate transmission with the acceptable cost for the emerging applications and use cases. In particular, from the perspective of antenna design and baseband signal processing, some issues need to be further studied and explored.

1) *Design of mmWave antennas:* The research and implementation of the MBAs still have great challenges and opportunities. As compared in Section III, FCMBPAA has a better performance than PCMBPAA in terms of power efficiency, aperture efficiency, and wide-angle coverage, at the cost of more complex architecture and hardware. The implementation of such a complex architecture is a pressing issue on its application in mmWave communications, the same with DCMBPAA. The reflector- or lens-based MBAs exhibit better performance of high-gain beams and wide-angle coverage with a simple structure. However, there are three issues to be solved. First, the number of RF chains is equal to the number of beams; thus, the hardware cost is high for large-scale beam cases. Second, the PA in each RF chain can only be operated in one beam; thus, the PAs cannot be fully utilized in scenarios with spares beams, leading to low power efficiency. Finally, the large form factors must be kept as the air-fed scheme is used, which will bring problems during the installation and maintenance.
2) *Characterization of mmWave channel:* A large number of channel measurement activities focus on evaluating the propagation characteristics of mmWave, such as the path loss, blockage, AoA, and AoD, and constructing the channel models. The measurement results show that the mmWave channel possesses spatial sparsity in the angular domain. Consequently, directional transmission and reception are considered a necessary way for mmWave communication systems. For the directional transmission of mmWave massive MIMO communication systems, what we need to study is the rank of a directional transmission channel or how to effectively achieve the spatial multiplexing mechanism.
3) *Baseband signal processing of mmWave communication:* The main motivation of utilizing mmWave is the abundant spectral resource at mmWave frequency bands. Meanwhile, to achieve the gigabits transmission rate, 802.11ad/aj/ay will adopt GHz transmission bandwidth and sampling rate. Consequently, the data throughput of baseband signal processing increases drastically for the mmWave system. For example, the data throughput is up to 42 Gb/s for an SC mmWave system with a 2.16-GHz bandwidth, the quadrature sampling rate of 1.76 GSamples/s, and ADC resolution of 12 bits. Furthermore, the data throughput would theoretically be hundreds of Gb/s for mmWave massive MIMO systems with multiple RF chains, especially for fully digital structure mmWave systems. How to effectively complete the baseband signal processing within the limited time and hardware cost is a challenging problem for both software and hardware design.
4) *Advanced hardware impairment mitigation:* Compared to the current RF-based systems, the main challenge pertaining to the implementation of mmWave systems is the considerable impact of hardware impairments that become more serious with an increasing carrier frequency. Though many studies have focused on investigating the impact of hardware impairments of mmWave systems, such as low-resolution ADCs, nonlinear power amplify, I/Q imbalance, and the quantization of PSs, there is limited study on evaluating the overall impact of hardware impairments on mmWave systems. In addition, for wideband SC mmWave communication systems, it is necessary to investigate the impacts of in-band jitter and various filter implementations, such as pulse filtering, on mmWave systems. Digital predistortion is an effective way to compensate for the hardware impairments, but its computational complexity will be further increased and may even suspend its utilization for the wideband SC mmWave systems.
5) *mmWave massive MIMO intelligent communication:* With the introduction of cache at the network edge and devices, as well as mmWave massive MIMO and ultradense networks, more and more resources availability and the dynamic change of environments make the mmWave communication network become more complex and difficult. Providing the communication terminals with abilities of self-learning, self-optimization, self-configuration, and self-adaptation is a key trend of future wireless communication systems. Meanwhile, the rapid development of machine learning, such as reinforcement learning, deep learning, and graph neural network, provides a strong theoretical support for the development of intelligent communication. However, the scalability, generalization, and real-time communication technologies based on machine learning may be the research hot spot for mmWave communication. At the same time, the research of distributed cooperative communication technologies with data privacy protection ability is also one of the research focuses of communication technologies based on machine learning. ■

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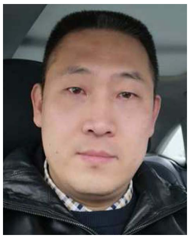

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