Millimeter Wave Communication: A Comprehensive Survey

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***Abstract*—Millimeter wave (mmWave) communication has raised increasing attentions from both academia and industry due to its exceptional advantages. Compared with existing wireless communication techniques, such as WiFi and 4G, mmWave communications adopt much higher carrier frequencies and thus come with advantages including huge bandwidth, narrow beam, high transmission quality, and strong detection ability. These advantages can well address difficult situations caused by recent popular applications using wireless technologies. For example, mmWave communications can significantly alleviate the skyrocketing traffic demand of wireless communication from video streaming. Meanwhile, mmWave communications have several natural disadvantages, e.g., severe signal attenuation, easily blocked by obstacles, and small coverage, due to its short wavelengths. Hence, the major challenge is how to overcome its shortcomings while fully utilizing its advantages. In this paper, we present a taxonomy based on the layered model and give an extensive review on mmWave communications. Specially, we divide existing efforts into four categories that investigate: physical layer, medium access control (MAC) layer, network layer, and cross layer optimization, respectively. First, we present an overview of some technical details in physical layer. Second, we summarize available literature in MAC layer that pertains to protocols and scheduling schemes. Third, we make an in-depth survey of related research work in network layer, providing brain storming and methodology for enhancing the capacity and coverage of mmWave networks. Fourth, we analyze available research work related to cross layer allocation/optimization for mmWave communications. Fifth, we make a review of mmWave applications to illustrate how mmWave technology can be employed to satisfy other services. At the end of each section described above, we point out the inadequacy of existing work and identify the future work. Sixth, we present some available resources for mmWave communications, including related books about mmWave, commonly used mmWave frequencies, existing protocols based on mmWave, and experimental platforms. Finally, we have a simple summary and point out several promising future research directions.**

***Index Terms*—mmWave communications, beamforming, short wavelengths, antenna array, severe attenuation.**

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I. Introduction

NOWADAYS, more and more bandwidth intensive applications are emerging in daily routines of mobile users (e.g., HDTV, UHDV) [1]. Wireless data traffic is projected to skyrocket 10000 fold within the next 20 years [2]. To tackle this incredible increase, one of the most efficient resolutions is to move the data transmissions into an unused nontraditional spectrum where enormous bandwidths are available, such as millimeter wave (mmWave). The mmWave bands roughly corresponding to frequencies from 30GHz to 300GHz have drawn considerable attention because of huge bandwidth. mmWave communications have several merits compared with existing wireless technologies, which are described as follows.

- Extremely wide bandwidths: Compared with existing wireless networks, mmWave communications employ much higher frequencies (30-300GHz) as carrier frequencies. Hence, it has much more abundant spectrum resource (270GHz), making itself quite alluring under the conditions of intensive spectrum.
- Small element sizes: Owing to short wavelengths, mmWave devices enable large antenna arrays to be packed in small physical dimension.
- Narrow beams: With the same antenna size, it is possible to pack more antenna elements at mmWave frequencies than at microwave. Therefore, the formed beam can be narrower, which can further facilitate the development of other applications, such as detection radars.

However, mmWave communications also suffer from several drawbacks. Due to much higher carrier frequencies compared to conventional wireless techniques, severe attenuation will occur caused by oxygen absorption, which is shown in Fig. 1. From this figure, it can be observed that in some special bands such as 35GHz, 94GHz, 140GHz, and 220GHz, mmWave propagation experiences relatively small attenuation. Thus, long distance communication can be realized in these mmWave bands, which is well suitable for peer to peer communication. However, in the 60GHz, 120GHz, 180GHz bands, mmWave signals attenuate severely as high as 15dB/km, which are known as “attenuation peak”. In general,

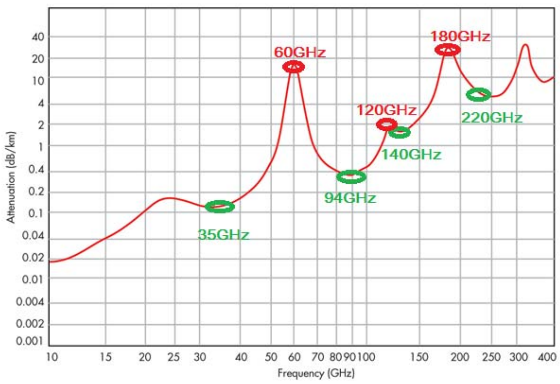

Fig. 1. Atmospheric and molecular absorption at mmWave frequencies [9], [10].

these bands are employed by covert network and system for multipath diversity so as to satisfy the requirements of network safety factor. Meanwhile, mmWave signals will experience poor diffraction when encountering blockages owing to the short wavelengths [3]. These two defects significantly shorten the transmission range of mmWave signals and easily bring mmWave links to the disconnected state. Thanks to the rapid progress in complementary metal-oxide-semiconductor (CMOS) radio frequency (RF) integrated circuits [4], [5], beamforming based on large-scale mmWave antenna arrays has been widely exploited to extend the coverage of mmWave networks [6], [7]. In the meantime, interference in mmWave based networks can be substantially cut down based on highly directional beams, rendering mmWave networks noise-limited rather than interference-limited in many cases [8].

Yet, many unresolved problems in the physical layer, medium access control (MAC) layer, and network layer induced by its unique characteristics hamper the realization of mmWave communications to full advantage. In the physical layer, extensive research related to the construction of mmWave channels has been carried out [11]–[13]. For instance, owing to widely divergent propagation features compared to LTE, mmWave channels of 28GHz, 38GHz, 60GHz, and 73GHz covering line-of-sight (LOS) and non-line-of-sight (NLOS) are built for both indoor and outdoor environments, such as building offices and dense urban environments. For mmWave circuit components and antenna design, the non-linearity and phase noise become much more serious due to much higher operating frequencies [14]–[16]. Effective strategies are needed to combat these defects [17]–[20]. With much smaller wavelengthes, large-scale antenna arrays with more than 100 elements are designed, based on which beamforming can be achieved to provide high link gain. Meanwhile, protocols in MAC layer should be redesigned since propagation characteristics in physical layer have changed [21]. Therefore, new designed MAC protocols should be adopted to support highly directional transmission links, extreme low latencies, and high peak data rates [22]–[24]. In terms of network layer, majority of existing research work concentrates on multi-hop routing and relay placement so as to enhance the coverage and capacity of mmWave networks [25]–[27]. For the actual use cases of mmWave communications, many application scenarios have been enumerated, such as data traffic delivery in dense wearable networks, or object detecting and tracking at centimeter accuracy [28]–[30].

Meanwhile, several survey papers containing different aspects of mmWave technology have been published in recent years [9], [31]–[35]. Wang *et al.* [32] discuss the technical challenges such as large-scale attenuation, atmospheric absorption, phase noise, limited gain amplifiers in the design of mmWave frameworks. They have also investigated the critical metrics which can characterize multimedia QoS based on mmWave communications. Finally, they propose a QoS-aware multimedia scheduling scheme to realize the trade-off between performance and complexity. Rangan *et al.* [33] investigate the deployment strategies of small mmWave cells in urban environments. Research work in [9] and [31] explores the utilization of mmWave communications in 5G networks. They have pointed out the feasibility, advantages, and challenges if employing mmWave communications in future wireless networks. Recently, Rappaport *et al.* [34] present a comprehensive survey of mmWave radio propagation models to date. They carry out a detailed elaboration of various models in terms of path loss model, line-of-sight probability, and building penetration. Xiao *et al.* [35] make a review of mobile networks based on mmWave communications, including recent channel measurements and models, MIMO, and access and backhaul schemes. In addition, they have also introduced the standardization and deployment efforts for mmWave mobile networks.

In comparison to existing surveys in the mmWave field, the outline of the contributions of this paper is presented as:

- We conduct a more in-depth and comprehensive analysis and summary of mmWave communications, including physical layer, MAC layer, network layer, cross-layer optimization, and use cases, to enable interested individuals to have a quick and overall insight.
- Due to the rapid development of mmWave technology, a large amount of research work on mmWave communications has been completed [36]–[38] these years. Therefore, we incorporate these research efforts into this paper, in order to facilitate the understanding of mmWave development trends.
- We provide several use cases (e.g., wearable devices) to illustrate how mmWave communications are employed to satisfy the requirements of other services based on its unique features.
- We also present available mmWave resources, which include books about mmWave, commonly used mmWave frequencies, mmWave based protocols, and experimental platforms.

The rest of this paper is organized as follows: Section II presents a comparison between WiFi at sub 6GHz and at mmWave, as well as comparison between cellular networks at sub 6GHz and at mmWave band. Section III introduces the proposed taxonomy. In Section IV, a classification and analysis of mmWave communications in physical layer is carried out. Sections V and VI describe the development of mmWave communications in MAC layer and network layer, respectively. Compared to studies on single layer, we present certain relative research work on cross layer of mmWave communications in Section VII. Subsequently, after obtaining a comprehensive understanding of mmWave, the application of mmWave communications is discussed in Section VIII. Meanwhile, available mmWave resources are introduced in Section IX. Finally, we conclude this paper and provide several future research directions in Section X.

II. Comparison Between mmWave and Other Wireless Technologies

In recent years, the wireless communication technology enjoys a rapid development, accompanied by the update of wireless techniques. In this section, we will briefly introduce two mainstream wireless communication techniques, including WiFi and 4G LTE. In addition, simple comparison between WiFi at sub 6GHz and at mmWave band will also be presented, as well as the comparison between cellular networks at sub 6GHz and at mmWave band.

A. WiFi

Conventional WiFi is a wireless communication technology that allows electronic devices to be connected to a wireless local area network (WLAN), typically using the 2.4G Ultra High Frequency (UHF) or 5G SuperHigh Frequency (SHF) RF band. As one of the most widely utilized wireless technologies, WiFi improves interoperability between wireless network products based on IEEE 802.11 standards. Yet one of the serious problems with WiFi lies in its poor security [39]. For example, hacker shows how to use unmanned aircraft to easily get access to all information of phone users with open WiFi. Moreover, WiFi brings high power consumption, restricting its application in the field of smart home.

B. 4G LTE

The fourth generation mobile communication system (4G), integrated with 3G and WLAN, is able to transfer large amounts of data, high-quality audio, video, and images. In many respects, it has unique superiority. First, based on wide network spectrum, transmission data rates can be greatly improved compared to 3G. Second, on the basis of high data rate, high quality communication can be realized, as well as bidirectional downloading and on-line fighting game. Third, in order to make 4G communication acceptable as soon as possible, it supports global roaming, open interface, interconnection with various kinds of networks, terminal diversification. Nevertheless, it faces with the problems such as various standards, limited capacity, slow facilities update and so on.

C. Comparison

Traditional 802.11 protocol is designed for 2.4GHz WiFi, which is based on the modulation mode of frequency-hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). It can support up to 2Mbps data rate. Next, 802.11a and 802.11b are published, operating at 5GHz and 2.4GHz, respectively. 802.11a protocol, which is based on orthogonal frequency division multiplexing (OFDM), can support maximum data rate of 54Mbps, while 802.11b can only deliver up to 11M data per second. Finally, in 802.11g protocol, the same maximum bandwidth based on the same modulation mode with 802.11a can be provided. The difference between them is the carrier frequency since 802.11g operates at 2.4GHz. Instead of employing 2.4GHz and 5GHz frequency bands, 802.11ad is developed at the carrier frequency of 60GHz, which belongs to mmWave frequency band. Based on different modulation modes, it can support different maximum data rates, respectively as 7Gbps and 4.6Gpbs. Thus, it can realize wireless high definition audio and video data delivery in the family. However, compared to WiFi protocols at sub 6GHz, the coverage of 802.11ad based networks is much smaller owing to poor diffraction and severe attenuation of 60GHz signals [40], [41]. From above description, we find that bandwidth provided by WiFi is much narrower than that of mmWave. Existing wireless communication technologies cannot alleviate the enormous pressure from exponential growth of data traffic. Detailed comparison between these WiFi protocols is shown in Table I.

In recent years, explosive wireless data traffic produced by various kinds of applications has already congested conventional 4G LTE networks [8]. As a promising candidate, mmWave communications can provide multiple orders of magnitude data rates than LTE cellular networks. Yet, due to near-field losses and blocking, the transmission range of mmWave signals is greatly shortened. Therefore, beamforming based on large-scale mmWave antenna arrays has been exploited to extend the coverage, which is entirely different from the transmission mode in LTE cellular networks. The formed directional beams can substantially cut down the interference in mmWave cellular networks, always rendering mmWave cellular networks noise-limited rather than interference-limited in LTE cellular networks. However, novel strategies should be designed for beam adaption under dynamic mmWave cellular networks, in case of beam misalignment.

III. Taxonomy

The taxonomy about mmWave communications can be captured in Fig. 2. As shown in this figure, we categorize available literature related to mmWave communications into research in physical layer, research in MAC layer, research in network layer, cross layer optimization, and use cases of mmWave. Subsequently, we introduce some available resources about mmWave in terms of related books, commonly used frequencies, mmWave protocols, and experimental platforms.

A. Research on mmWave Communications

Research in Physical Layer: Available literature under this category can be divided into the design of circuit components and antennas, beam selection schemes, precoding, MIMO, channel model, modulation mode, NOMA, and security in the physical layer. Much research work has been performed to design novel mmWave antenna arrays and power amplifiers or beam alignment and selection schemes, thus achieving high gain and then enhancement of network capacity and coverage.

TABLE I
COMPARISON BETWEEN DIFFERENT WIFI STANDARDS

WiFi protocol	Frequency	Modulation mode	Maximum data rate
Traditional 802.11	2.4GHz	FHSS or DSSS	2Mbps
802.11a	5GHz	OFDM	54Mbps
802.11b	2.4GHz	HR-DSSS	11Mbps
802.11g	2.4GHz	OFDM	54Mbps
802.11ad	60GHz	OFDM or single carrier modulation	7Gbps or 4.6Gbps

Research in MAC Layer: In MAC layer, according to the proposed schemes tailored for different types of networks, this paper presents and summarizes protocols in ad hoc networks, mesh networks, WPANs, and cellular networks, respectively. For WPANs, majority of research work in MAC layer prefers to design novel MAC protocols, aiming at improving the spatial reuse and throughput. However, for mmWave cellular networks, efficient protocols are necessary for the management of initial access, mobility, and handover.

Research in Network Layer: Existing studies in network layer of mmWave networks are classified into framework design, relay deployment strategies, routing schemes, and combination of mmWave with LTE or WiFi, all of which aim at improving robustness to blockage, reducing transmission latency, and enhancing coverage and capacity.

Cross Layer Optimization: Cross layer optimization about mmWave communications has also been proverbially investigated. In this part, we mainly review available literature related to cross layer optimization between different layers in mmWave communications, in order to further optimize mmWave communication systems. For example, information interaction between different layers of mmWave communications can render proposed protocols and schemes more accurate and efficient.

Use Cases of mmWave Communications: In the view of unique features of mmWave, mmWave applications can be categorized into mmWave communications for wearable devices, mmWave communications in the virtual reality, mmWave communications in vehicular networks, mmWave in satellite communications and 5G networks, and mmWave for imaging, tracking, and detecting. Combining these areas with mmWave technology, it can realize more accurate and satisfactory operation and greatly boost the performance. Consequently, it is envisioned that mmWave communications will be applied in more areas.

B. Available Resources of mmWave

With continuous development, the number of papers and books about mmWave technology is increasing, facilitating researchers to enter the field of interest more easily and quickly. Therefore, we have a comprehensive review of available mmWave resources. First, we list several popular books, from which we are able to have a thoughtful understanding of mmWave. Second, we analyze and summarize a few frequencies commonly utilized in mmWave communications. Detailed comparison among these frequencies is presented. Third, we briefly present several well-known mmWave protocols, such as IEEE 802.11ad and IEEE 802.15.3c. Finally, we have introduced several experimental platforms applied for mmWave based experiments.

Next, we will analyze and summarize existing research work according to the taxonomy.

IV. RESEARCH IN PHYSICAL LAYER

Compared with existing wireless technologies, mmWave communications occupy much higher carrier frequencies, resulting in severe attenuation of mmWave signals caused by oxygen absorption. Therefore, how to design novel mmWave antennas, precoding and beamforming schemes has become a research hotspot, so as to increase the gain and extend the coverage range. In this section, we review the papers about design of mmWave circuit components, antenna arrays, precoding, beamforming, channel model, MIMO, non-orthogonal multiple access (NOMA), and security in the physical layer of mmWave communications.

A. Circuit Components

In order to realize multi-Gbps data rates, high-dimension modulations such as M-order phase shift key (MPSK) and M-order quadrature amplitude modulation (M-QAM) are widely employed to improve the spectral efficiency [42], [43]. Coupled with high-order modulation mmWave signals, huge bandwidth, and high peak-to-average power ratio (PAPR), mmWave communications are susceptible to nonlinear distortions [44] and multipath propagations. Meanwhile, mmWave power amplifier (PA) always suffers from nonlinear distortion inherently due to hardware manufacturing imperfection. Thus, the symbols will be expressed in error with a great chance, resulting in the increase of bit error ratio (BER) and performance deteriorations.

1) Nonlinear Distortion: To address nonlinear distortions, many investigations have been conducted in PAs of mmWave communication systems. Gerhard and Knoechel [45] improve the output power back-off efficiency through Chireix output coupling of two PAs and an input differential phase adjustment. The core of this scheme is to set the operational power away from the PAs saturation point, consequently alleviating the influence of nonlinear distortions. Yet, this kind of strategy also brings a remarkable decline in the received SNR at the receivers. Another conventional strategy to combat the nonlinear distortion is digital pre-distortion. Research work in both [46] and [17] is dedicated to design effective digital pre-distorters for mmWave transmitters. Different from [46],

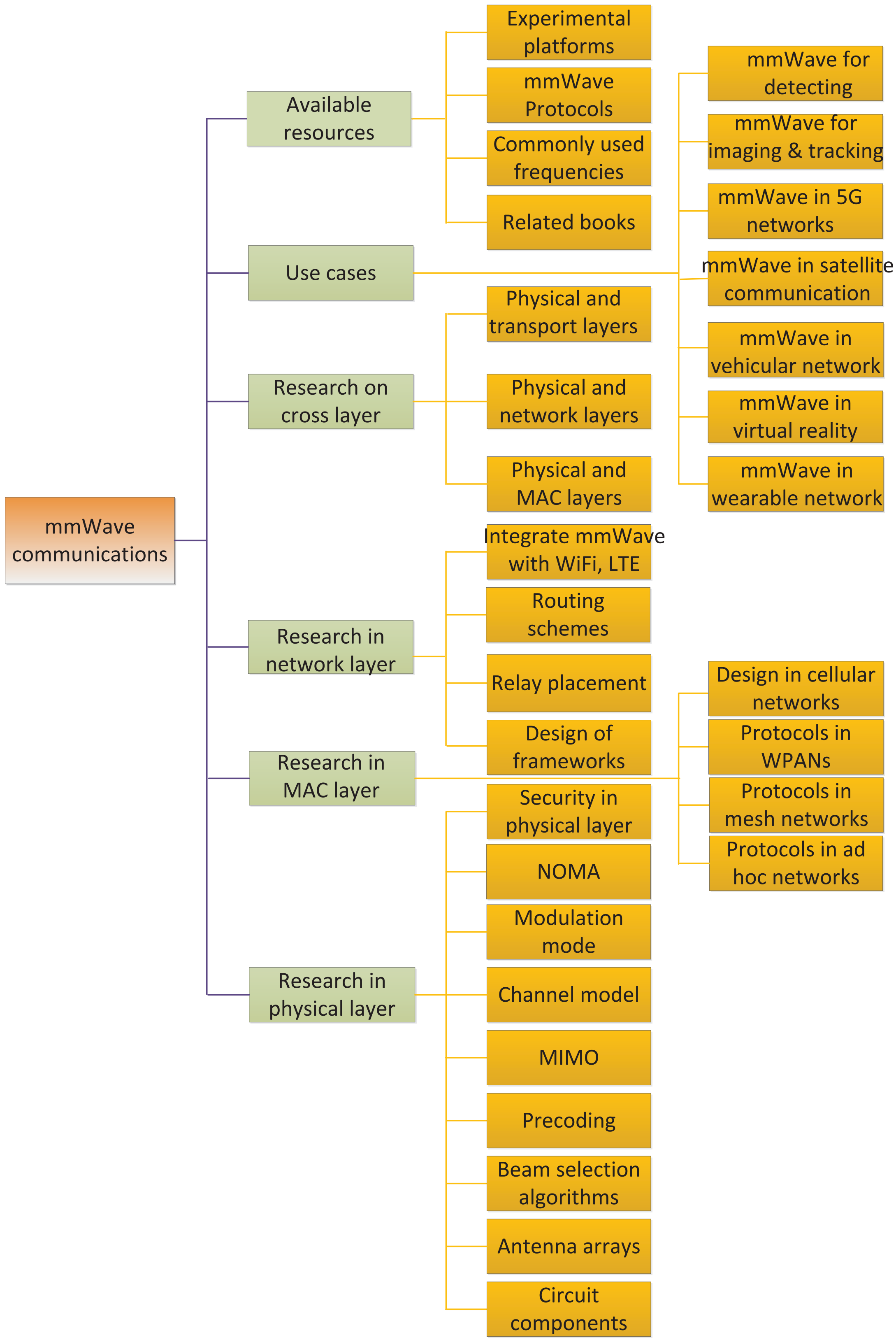

Fig. 2. The taxonomy of mmWave studies in this paper.

Fan *et al.* [17] regard the transmitter as a whole and only process the baseband input and PA output since mmWave transceivers are usually highly integrated. Hence, they propose a nonlinearity pre-distortion scheme for mmWave transmitters, which is based on a joint in-phase and quadrature imbalance. However, these schemes are designed for baseband signal processing, which implies that the radio frequency signals should be down-converted through an analog-to-digital converter. Then, they are calibrated by a feedback control loop. Obviously, these schemes may require large amount of computation and cannot be utilized practically.

Unlike addressing nonlinear distortion at the transmitters, researchers make determined efforts to calibrate nonlinear distortion at the receivers. As stated by [47], it is the first attempt to decrease the influence of PA nonlinearity at the receiver-end. Specifically, a demodulation strategy sets the points of distorted constellation (DC) as its own center points, instead of the standard constellation (SC). An estimation algorithm based on data-aided (DA) maximum likelihood (ML) is developed to derive the DC. The proposed scheme aiming at combating PA nonlinearity shows a BER performance close to the ideal PA case. Further, Li *et al.* [18] propose a nonlinear equalization algorithm to decode the unknown symbols at the receiver, which is contaminated not only by nonlinear distortions, but also multipath interferences. In particular, the particle filtering combined with Monte-Carlo sequential importance sampling analyzes the involved posterior density, and the non-analytical distribution can be acquired by random measures based on evolving probability-mass. Based on these steps, a local linearization detector model can be built to prepare for the practical design of a sequential detector.

Furthermore, additional steps have been executed at both the sending and receiving ends, thus mitigating the nonlinear distortion. As the first attempt, constant envelope OFDM (CE-OFDM), which is based on phased modulation, can transform the OFDM signal to another signal type with efficient power amplification [48]. At the receiver, phase demodulation is performed before the OFDM demodulator. By this way, the transformation through the phase modulation will result in 0dB PAPR constant envelope signals well tailored for nonlinear, efficient amplification. Based on CE-OFDM, Sacchi *et al.* [49] demonstrate that combined with trellis-coded modulations, CE-OFDM can provide a robust link performance with respect to bit-error-rate and packet-error-rate.

Different from waveform design for terrestrial mmWave communications, Sanctis *et al.* [50] make a detailed comparison of waveforms utilized for satellite communications at EHF frequency bands, in order to overcome nonlinear distortions and phase noise. When phased noise is at a moderate level such as in Q band, constant envelope multicarrier waveforms such as CE-OFDM and CE-SC-FDMA are the most promising candidates compared to UWB based standards. However, TH-UWB seems to be more suitable for the waveform design of satellite communication when phase noise level is relatively high such as in W band.

2) Phase Noise: As another huge challenge in the design of circuit components, phase noise, which degrades the performance of channel estimation and bit-error-rate (BER), poses great challenge to mmWave communications due to high oscillation frequency. Therefore, a tradeoff between phase noise and frequency tuning range should be made for frequency synthesis in the mmWave band. Existing methodology to combat phase noise can be classified into two categories: (i) Direct synthesis. (ii) Indirect synthesis. Direct synthesis is a technique that sets the frequency of local oscillator the same with the voltage-controlled oscillator (VCO) fundamental (f_0), or higher than f_0.

For instance, Li *et al.* [19] propose a 60 GHz voltage-controlled oscillator with an inductive division LC tank based on 90 nm CMOS. The inductive division can effectively cut down the phase noise with the increase of signal amplitude, as well as widening the tuning range. Under the condition of 0.7V supply, it can realize a tuning scope ranging from 53.2 GHz to 58.4 GHz, consuming 8.1 mW. At 58.4 GHz, the phase noise can be as low as -91 dBc/Hz at 1 MHz offset. Further, Xi *et al.* [51] introduce the circuit topologies and design strategies for low-phase-noise CMOS mmWave Quadrature VCO (QVCO) and VCOs since QVCO also plays a crucial role in mmWave IC design. In particular, a transformer enabling extra phase shift is embedded in QVCO. It decouples phase noise from the relationship of phase error, thus mitigating the impact of phase noise. The QVCO can achieve the lowest phase noise of -119.2 dBc/Hz at 10 MHz offset of a 56.2 GHz carrier and a tuning range of 9.1%.

Then, for indirect synthesis, its main idea is to utilize harmonic-mode VCO and higher order harmonics. The employment of *N*-push operation which combines the VCO and divider in the mmWave band is investigated in [52]. If it is integrated with a phase-locked loop (PLL), wider tuning scope can be obtained based on the proposed combination than traditional mmWave PLLs by applying injection locked frequency dividers. Using 130nm IBM CMOS technology, multiple versions of the triple push oscillator are implemented and characterized. A 55GHz-65GHz tuning range can be achieved based on a 206pH tank inductance.

However, these methods still remain a matter of debate. Consequently, Shirazi *et al.* [20] propose a self-mixing VCO (SMV) architecture, which is referred to as H-VCO architecture. This is because H-VCO can realize higher frequency tuning range and lower phase noise simultaneously. It can generate both the first (f_0) and second harmonic ($2f_0$), which can be combined to acquire the desired third-harmonic at mmWave frequency band. As the core of H-VCO, a Class-C push-push topology is employed so as to improve the second-harmonic content and mixing efficiency, thus contributing to the reduction of phase noise. Compared to conventional VCOs, H-VCO demonstrates a superior performance in terms of frequency tuning range and phase noise.

B. Antenna Arrays

After the presentation of circuit designs, we then review available research work on the design of another kind of mmWave hardware-antenna arrays, illustrating how to offer high gain through antenna design. The extremely short wavelengths of mmWave (e.g., 10.7 mm at 28GHz, 5 mm at 60GHz, and 1 mm at 300GHz) provide enormous potential for mmWave antenna arrays that are adaptive with high gain, cost-effective to fabricate and integrate in mass-produced consumer electronic products. Low cost and high gain can be realized with physically small antennas. From the cost perspective, mmWave antennas can be directly integrated with other

TABLE II
CLASSIFICATION OF MILLIMETER WAVE ANTENNAS

Antenna type	Gain	Advantage	Disadvantage	Application
Reflector antenna	$\leq 97dBi$	Small size, simple structure, high gain and antenna efficiency, low noise temperature, good antenna radiation directivity	High cost	Radar, radio navigation, electronic warfare, telemetry, radio astronomy and meteorology
Lens antenna	–	Small side lobe and rear lobe, wide band and high directivity	High profile	Military satellite and multi beam applications
Horn antenna	$\leq 30dBi$	Simple structure, wide frequency band, high power capacity, good radiation characteristics, fairly sharp main lobe, small side lobe	Low gain and low level of side lobes	Feed of the large radio telescope, reflector antenna of satellite ground station, reflector antennas used in microwave relay communication system
On-chip integrated antenna	$\leq 29.2dBi$	Lowest cost, high degree of integration, compact structure, high reliability, and mass production	Small metal conductivity, substrate of low resistivity and high dielectric	60GHz radio systems for commercial use
Microstrip antenna	$\leq 28.5dBi$	Low profile, light weight, low cost, easy to mass production and microwave integration	Narrow band, low radiation efficiency, small power capacity	Microwave radar sensor

portions of a transceiver and fabricated with either packaging or integrated circuit production technology. This is a stark departure from all existing wireless systems, which rely on coaxial cables, transmission lines, and printed circuit boards to connect antennas with the transmitter or receiver circuits in modern cellphones, laptops, and base stations.

As shown in Table II, we classify conventional mmWave antennas into five types: reflector antennas, lens antennas, horn antennas, on-chip integrated antennas, and microstrip antenna. First of all, we investigate the development of reflector antennas, lens antennas, horn antennas successively.

1) Aperture Antennas: Reflector antenna forms a desired radiation pattern by a reflector based on the scattering effect of electromagnetic waves. In the mid of 1980s, Evans *et al.* [53] design a telescope named James Clerk Maxwell using mmWave reflector antenna. Its maximum operating frequency is up to 750GHz. When setting the wavelength as 0.4mm, the antenna gain is equal to 97dBi. The main reflector is composed of 276 plates distributed in 7 rings, which is made by light weight double honeycomb aluminum structure. In 2009, a novel method for improving the cross-polarization and beam efficiency of an offset parabolic reflector antenna is proposed [16], aiming at space borne radiometric applications. Its core is to utilize a special multi-mode primary feed (tri-mode conjugate matched feed) to illuminate the offset parabolic reflector antenna.

mmWave lens antenna is a kind of antennas capable of converting a spherical wave or cylindrical wave of an electromagnetic wave, a point source or a line source into a plane wave to obtain a pen shape, a sector, or other shape beam. Design of lens antenna has received extensive attention since it can greatly reduce signal processing complexity and RF chain cost without notable performance degradation [54], [55]. Work in [54] proposes a new communication architecture-continuous aperture phased MIMO, referred to as CAP-MIMO. Using a high-resolution discrete lens array, it enables a continuous aperture phased-MIMO operation. Based on the theoretical foundations of [54], Brady *et al.* [55] study and address the problems about modeling, design, and analysis of the physically realizable CAP-MIMO system in detail.

Contrast to the studies in [54] and [55], which treat the EM lens and the antenna array separately by modeling the lens as an approximate spatial discrete Fourier transform (DFT) filter, a systematic designed framework regards the lens antenna array as an integrated component [56]. In the framework, detailed array configuration is presented and corresponding array response is derived. Under these conditions, the signal power of each multi-path is concentrated upon one single element of the lens antenna array at both ends. Then, a low-complexity transceiver design based on path division multiplexing (PDM) is put forward under multi-paths of arbitrary angle of arrival (AoA)/departure (AoD). It can be applied for both narrow-band and wide-band communications.

Horn antenna is a kind of antennas whose shape is similar to circular or rectangular cross section with tapered opening. In [57], a horn-like antenna-in-package method based on a multi-layer substrate is proposed to achieve a 10dB impedance bandwidth from 55 to 68GHz and a stable gain of 6dBi. Although this scheme exhibits superior performance over conventional high-gain aperture antennas, most of them still suffer from either low gain or high cost. Therefore, Liao *et al.* [58] design a kind of differential aperture antennas formed by an H-shaped opening cavity. In the opening cavity, there exists a long cross-shaped patch fed differentially by two grounded coplanar waveguides (GCPWs) since GCPW brings low radiation loss, ensuring a high gain at broadside. Meanwhile, its height in mmWave band is as low as most of commercially available laminates, thus the proposed aperture antenna is compatible with standard planar circuit technology and very suitable for various mmWave applications. Finally, through extensive simulations, it demonstrates many obvious merits such as low cost, low profile, compact size, and compatible with standard planar circuit processes. It also can provide high gain and wide bandwidth.

The above three kinds of antennas belong to aperture antennas. Aperture antennas are widely employed in various applications such as point-to-point communications, relay aided communications, and radars, because of their high gain, wide bandwidth, and simple structure.

2) mmWave Microstrip Antenna: As another kind of traditional mmWave antennas, microstrip antenna is a kind of antennas that utilizes microstrip or coaxial probe to patch feed. In convention, application of mmWave microstrip antenna in specific systems is restricted by its narrow bandwidth. Consequently, Firdausi and Alaydrus [36] propose a multi-layer structure for mmWave microstrip antenna, which consists of three layers. Two rectangular microstrip patches are installed in the middle layer, and they are fed by an electromagnetic coupling provided by the bottom layer. For the top layer, a gridded structure with 6×3 rectangular microstrip patches is constructed to improve the antenna gain. Calculation results show that coupled with 8.65dBi gain, mmWave microstrip antenna can work efficiently in three frequency bands with the range of 40GHz-80GHz.

3) mmWave On-Chip Antenna: However, above antennas are not the most promising alternatives for commercial mmWave antennas due to high manufacturing cost, large size and the inability to integrate with solid state devices. Thanks to the rapid development of integration technology, researchers shift their focus to on-chip integrated mmWave antennas since it has several appealing advantages such as low profile, light weight, compact structure, structural consistency, easy fabrication and integration with solid state devices.

In [59], a new type of antenna fabrication for on-chip antennas is proposed in the conditions of low temperatures. It is compatible with CMOS integrated circuit technology. Based on this technology, novel vertical structures with controllable azimuth and elevation angles (with respect to the wafer plane) can be constructed, as well as flexibility of shaping the antenna profile and length. Different from [59], Chuang *et al.* [60] present a novel Micro-Electro-Mechanical Systems (MEMS) movable plate concept appropriate for vertical on-chip antennas. This method is completely compatible with CMOS processes and is neither restrictive of operating frequency nor antenna type while achieving high efficiency. Besides, it is capable of polarization diversity (horizontal or vertical polarization) relative to the substrate plane.

4) mmWave Phased Antenna: Another product of the rapid development of integration technique is mmWave phased array antennas, which can accommodate tens or even hundreds of elements and be prevalently deployed in mmWave networks. They are critical and essential for mobile base stations, real-time mmWave imaging or detecting systems, MIMO applications, and radar anti-collision systems due to the fast beam steering and low cost.

In [61], a fully integrated 77GHz phased-array transceiver is introduced for the first time. The SiGe transceiver employs a phase-shifting model based on local LO-path to realize beam alignment. The proposed scheme for phase shifting can adapt to various frequencies and elements. Meanwhile, Natarajan *et al.* [62] present a 60GHz phased-array receiver design for both LOS and NLOS links, aiming at high gain based on single carrier and OFDM. However, for future potential applications, the requirements for mmWave array design mainly involve wide bandwidth and adequate gain [63]. Thus, Briqech *et al.* [64] propose a 16-element phased array using a low-cost piezoelectric transducer-controlled phase shifter, which is suitable for the frequency range of 55-65GHz. The phased array is fed with an amplitude taper wideband Y-junction power divider, and integrated with a single printed circuit board substrate. Simulation results illustrate that the impedance bandwidth is less than -10dB with a gain of 20dB while bringing low radiation losses.

C. Beam Alignment and Selection Algorithm

Thanks to the speedy development of mmWave antennas, beamforming (BF) based on large scale antenna arrays has been explored in several popular protocols, such as IEEE 802.15.3c (TG3c) for indoor wireless personal area networks (WPAN) and IEEE 802.11ad (TGad) for wireless local area networks (WLAN). Consequently, high BF gains can be obtained to compensate for severe signal attenuation caused by penetration loss, rain effect, and atmospheric absorption [65], [66].

1) Digital or Analog Beamforming: In traditional MIMO systems, which is based on digital beamforming, each element in antenna arrays generates one individual radio-frequency (RF) chain, then going through a separate digital-to-analog (D/A) convertor and an analog-to-digital (A/D) convertor successively. Subsequently, we can obtain the corresponding digital signal through adjusting its phase and amplitude at a controllable precision. Nevertheless, this conventional technique may not be suitable for mmWave communication systems due to high cost and substantial power consumption [33], [67].

Instead, techniques of analog beamforming and hybrid analog/digital beamforming are widely utilized to realize multi-stream/multi-user transmission. Unlike digital beamforming, in the process of analog-only beamforming a single RF chain is shared by all antenna elements, coupled with constant-amplitude constraint on their weights. Analog beamforming has been extensively explored in mmWave MIMO OFDM systems [68], [69].

Via *et al.* [68] develop a beamforming scheme for transmitters and receivers under the OFDM mode. In particular, under the assumption of perfect channel knowledge at the receiver end, a beamforming criterion is designed, highly depending on a setting parameter ℓ. ℓ, which considers most beamformer design matrixes, makes a tradeoff between the energy of the equivalent SISO channel and its spectral flatness. It can be transformed into a non-convex optimization problem and solved by semidefinite relaxation techniques. When setting ℓ to a particular value, the mean square error (MSE) can be minimized, and the received signal-to-noise ratio (SNR) can be maximized. However, perfect channel information can not be obtained in the majority of cases due to the high variability of mmWave channels. Therefore, in [69], a non-iterative symbol-wise beamforming scheme for MIMO-OFDM systems is proposed based on imperfect channel information at transmitters or receivers. A beamforming scheme based on limited feedback combined with a codebook design is developed for a spatially correlated frequency selective channel. The proposed scheme just brings acceptable capacity loss compared to symbol-wise beamforming scheme with perfect channel knowledge. Yet, it demonstrates a robust performance to the channel uncertainty. Above beamforming schemes aim at OFDM systems.

However, related research shows that single carrier based mode may be a more promising candidate for mmWave communications [70]. Hence, Li *et al.* [71] investigate the optimization of joint base station and user equipment analog beamforming vectors in order to minimize the MSE of baseband equalized signal. And this optimization problem can be well addressed by an iterative local gradient descent algorithm. It demonstrates a gain of more than 2dB at a BER of 10^{-4} compared to conventional iterative algorithm for beamforming.

2) Hybrid Analog/Digital Beamforming: Compared to analog or digital only beamforming strategy, hybrid analog/digital beamforming is another commonly utilized beamforming scheme in mmWave communication systems, which is shown in Fig. 3. Transmitted signals are firstly processed through phase shifters in the digital domain, requiring no RF chains. Therefore, the dimension of signals can be greatly cut down. The post-processed signals go through a conventional analog beamforming in order to construct mmWave MIMO systems in a much lower complexity. The core of hybrid beamforming is to divide the precoding between analog and digital domains, which can make an efficient tradeoff between the low-complexity yet limited-performance analog beamforming and the high-complexity good-performance fully digital precoding [72], [73]. Meanwhile, it enables RF chains less than the number of antenna elements.

Assuming perfect channel knowledge at the transmitter, Ayach *et al.* [72] explore the utilization of transmit precoding and receiver combining based on large antenna arrays. According to the spatial features of mmWave channels, the precoding/combining problem is formulated as a sparse reconstruction problem. Utilizing basis pursuit, effective schemes are designed to accurately approximate optimal unconstrained precoders and combiners. Naturally, an optimal performance can be achieved even based on low-cost RF hardware. In the meantime, Sohrabi and Yu [74] also investigate the precoder and receiver design to maximize the spectral efficiency when hybrid beamforming is employed at both transmitters and receivers. Especially, the proposed hybrid beamforming

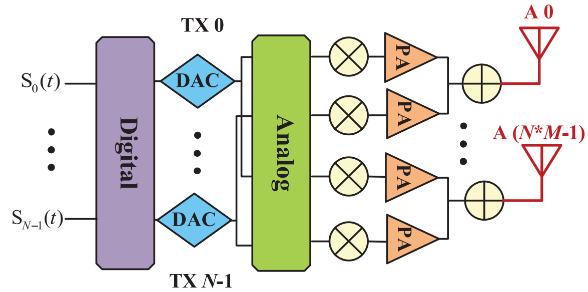

Fig. 3. The structure of hybrid analog/digital beamforming technology for mmWave communications.

demonstrates the same performance with the fully-digital beamforming scheme when the number of RF chains is greater than or equal to twice the number of data streams.

Nevertheless, acquisition of perfect channel information at the transmitter is a hard task in actual scenarios [75]. Consequently, in [76], a hybrid beamforming schemes combined with codebooks based on limited channel feedback is developed for mmWave communications. First of all, the initial hybrid precoding scheme can be obtained based on a given RF codebook. Subsequently, based on the hybrid precoding scheme, efficient hybrid analog/digital codebooks are proposed for spatial multiplexing, thus improving the multiplexing efficiency. Finally, a near-optimal greedy frequency selective hybrid beamforming strategy can be derived according to Gram-Schmidt orthogonalization.

D. Precoding

Beamforming with multiple data streams, known as precoding, can be done digitally at baseband in traditional multi-antenna systems to further improve mmWave spectral efficiency. It makes a compromise between hardware complexity and system performance in mmWave systems. Precoding employs large antenna arrays to achieve high gains with low cost and cheap hardware. For example, analog precoding is often implemented with phase shifters [70], [77], which sets constant modulus constraints to the elements of RF precoder. Much research work has been carried out for analog precoding in low-complexity transmitting terminal equipments [78]–[80].

1) Analog Precoding: However, these methods provide limited antenna gain and suboptimal performance without regard to mmWave MIMO systems equipped with large antenna arrays. In other words, these methods do not utilize the structure of mmWave MIMO channels. Therefore, in [81], a low hardware-complexity precoding scheme is proposed based on the structure of realistic mmWave channels. A clustered channel model is built to capture both the limited scattering at high frequency and antenna correlation for single-user precoding in a practical transceiver architecture. It can be modeled as a sparsity-constrained signal recovery problem under the constraints of RF hardware, large antenna arrays, and limited scattering nature of mmWave channels. Then, based on orthogonal matching pursuit, an algorithmic precoding scheme takes an optimal unconstrained precoder as input, instead of directly maximizing mutual information. The capacity of mmWave communication systems can be nearly fulfilled based on the proposed precoding scheme.

2) Hybrid Precoding: In order to multiplex several data streams and perform beamforming more accurately, the concept of hybrid precoding is introduced to meet these requirements [7], [72]. It consists of precoding in both analog and digital domains. Then, the technique of transmitter precoding and receiver combining is developed in [72]. According to the spatial structure of mmWave channels on the premise of the availability of channel knowledge at the transmitter, the precoding/combining problem is converted into a sparse reconstruction problem. However, demands for accurate channel information usually cannot be satisfied due to channel variability caused by weather conditions and blockages.

Accordingly, how to design hybrid precoding schemes with limited feedback is a valuable research issue. For downlink multiuser mmWave systems, Alkhateeb *et al.* [82] recommend the combination of analog and digital processing, inspired by the power consumption of complete radio frequency and mixed signal hardware. Under the conditions of small training and feedback overhead, the low-complexity hybrid analog/digital precoding scheme configures precoders at the transmitters and analog combiners at multiple receivers. Compared to analog-only beamforming solutions, the proposed scheme can provide higher data rates and nearly optimal performance with the unconstrained digital beamforming using relatively small codebooks.

Above research work has concentrated on hybrid precoding for narrow-band mmWave systems, yet mmWave communications enable multi-Gbps data rates between devices. Consequently, mmWave systems will likely operate on wide-band channels with frequency selectivity. Alkhateeb and Heath [76] propose a novel hybrid analog/digital precoding strategy for wide-band mmWave systems with limited feedback channels between transmitters and receivers. It is based on the hybrid analog/digital codebooks and Gram-Schmidt orthogonalization. And hybrid analog/digital codebooks for spatial multiplexing in wide-band mmWave systems can be derived according to an optimal hybrid precoding scheme.

Finally, unlike above hybrid precoding schemes considering full-array structure, a near-optimal, low-complexity iterative hybrid precoding scheme using realistic sub-array structure is proposed in [83]. Specifically, the capacity optimization problem is divided into a series of ones easier to be handled by considering the antenna array one by one, meaning that precoding for each antenna array corresponding to one RF chain will be designed separately rather than jointly. Similar to [83], Gao *et al.* [84] design an energy-efficient and successive interference cancelation (SIC)-based hybrid precoding scheme for sub-connected architecture. The main idea of this proposed scheme is to decompose the total achievable rate optimization problem under non-convex constraints into a series of simple sub-rate optimization problems. The complexity of SIC-based hybrid precoding is only about 10% as complex as that of recently proposed spatially sparse precoding. Meanwhile, it shows a superior performance in energy efficiency compared to the spatially sparse precoding and fully digital precoding.

E. MIMO

High-gain beamforming combined with MIMO is expected to overcome severe attenuation in mmWave communications [85], [86]. In particular, MIMO can offer high multiplexing gains, which in turn contributes to orders of magnitude increase in spectral and energy efficiency. Thus, the combination of mmWave and MIMO can provide significant capacity gain and improvement of link reliability over mmWave networks without MIMO [87], [88]. In conclusion, mmWave communications integrated with MIMO plays a crucial role in future 5G mmWave networks.

Thomas and Vook [89] demonstrate a mmWave cellular network with densely deployed small cells leveraging single-user (SU) MIMO, thus providing much larger network capacity compared to existing cellular systems. Accordingly, a natural question is raised, that is whether multi-user (MU) MIMO can bring significant capacity gains for mmWave based networks. Therefore, Vook *et al.* [87] extend the research work in [89]. They investigate the performance of both single and multi-user MIMO in 72GHz mmWave systems. Superior performance based on MU-MIMO can be achieved compared to SU-MIMO, which is determined by the scheduling scheme, user density, and the number of transmitted streams per user. For instance, MU-MIMO set with two streams per user demonstrates a much superior performance over MU-MIMO based on only one stream per user.

With regard to spatial modulation (SM) for MIMO, space shift keying (SSK) is employed to text and analyze the performance of spatial modulation in MIMO systems [90]. As the simplest form of SM, SSK combined with MIMO can work efficiently under the conditions of LOS propagation in mmWave communications systems.

F. Channel Model

After forming mmWave beams, determined efforts have been made to explore the propagation characteristics of these formed beams. Unlike signal propagation in the microwave frequency band, mmWave signals attenuate much more severely, and the performance of mmWave links will experience a fast decline when encountering obstacles. Substantial research work has been carried out to construct mmWave channel models in actual environments with regard to the height of transmitter and receiver, reflection, and blockage. For instance, 3GPP builds TR 38.900 and TR 38.901 channel models for above 6GHz frequency, which cover path gain, spatial and delay characteristics of the channel [91]. Existing research work can be divided into two parts: indoor channel model and outdoor channel model.

1) Indoor mmWave Channel Model: For indoor channel construction, Nie *et al.* [11] conduct propagation measurements for 73GHz mmWave indoor channel in a typical office environment on the 9th floor of 2 MetroTech Center, Brooklyn, NY, USA. Transmitters are located at 2.5m height and receivers are located at a height of 1.5m. It can observed that 73GHz indoor channels do not vary much from UHF channels. In addition, most receiver locations have at least a few distinct angles of arrival with multipath energy. For the omnidirectional indoor model, extensive experimental results show that a better line-of-sight (LOS) path loss exponent can be obtained than free space owing to reflections in an office environment. For non-line-of-sight (NLOS) channels, the value of loss exponent is measured as 3.1, which is almost the same with that of common NLOS UHF channels.

Instead of channel measurements at 73GHz, Xu *et al.* [12] concentrate on 60GHz indoor channel measurements and model construction. Power delay profiles (PDPs) and power angle profiles (PAPs) have been widely measured in indoor environments, based on which detailed multipath structure can be deduced. Finally, a conclusion can be reached: propagation characteristics have a strong relationship with the multipath channel structures, which is determined by image based ray tracing techniques for line-of-sight (LOS) applications. For NLOS propagation reflected by walls, the metallic structure of composite walls must be considered when building mmWave channels.

Furthermore, as the quality of mmWave links will be greatly influenced by indoor human activity, Haneda *et al.* [92] present a preliminary overview of 5G channel models in both indoor offices and shopping malls. It is observed that small mmWave wavelengthes bring an increased sensitivity of the propagation models to the scale of the environment. Meanwhile, the penetration loss highly relies on the material and increases with mmWave frequency. Based on these analysis, Collonge *et al.* [93] conduct extensive measurements about the influence of human activity on indoor 60GHz channels. When the LOS link is shadowed by a person, signal strength will decrease by more than 20dB. Besides, mmWave channels are "unavailable" for about 1% or 2% of the duration time of 100ms in the presence of one to five persons.

2) Outdoor mmWave Channel Model: In addition to research on indoor channel models, recent research shows that the transmission range of mmWave communications can be up to and even exceed 200m in outdoor environments [13], [65], [94]. Therefore, outdoor statistical channel characterization and modeling ignite a research upsurge [95]–[97]. Firstly, 73GHz propagation measurements in New York City are performed [97]. The authors have built a preliminary 3GPP-style 3D mmWave channel model, employing the ray tracer to determine elevation model parameters. Furthermore, based on large amounts of real-world measurements at 28 and 73GHz in New York, Akdeniz *et al.* [96] develop spatial statistical channel models for both 28GHz and 73GHz mmWave cellular networks. It is found that in dense urban environments with many NLOS mmWave links, strong mmWave signals can be detected even 100-200m away from mmWave base stations.

Aiming at the designed channel model tailored for wider frequency, Kyro *et al.* [95] carry out the measurement campaign of 71-76 and 81-86GHz in a street canyon scenario. The mean values of root mean square delay, which is an important parameter for very broadband radio channels, is derived to be the values ranging from 0.089ns to 0.125ns. The results are almost the same with that of actual measurements. Furthermore, Haneda *et al.* [98] build mmWave channels with the frequency range from 6GHz to 100GHz for outdoor urban microcellular and macrocellular environments. It takes incorporating path loss, shadow fading, LOS probability, penetration, and blockage models into consideration. Experimental results verify that different materials in building construction introduce different penetration loss. For example, conventional glass is relatively transparent with a rather weak increase of loss, and the loss will increase with frequency due to conductivity losses. However, energy-efficient glass can bring additional loss that can be as high as 40dB even at lower mmWave frequencies. Other materials like concrete or brick have losses that increase rapidly with frequency. Meanwhile, considering two kinds of blockages: dynamic blockage such as cars and humans and geometry-induced blockage such as buildings. The effect of dynamic blockage is equal to transient additional loss on the paths that intercept the moving object. However, the influence of geometry-induced blockage on propagation channels highly depends on diffraction and sometimes by diffuse scattering. Comparison of different kinds of actual channel models are shown in table III.

G. Modulation Mode

Subsequently, in order to reduce the bit error and improve the spectrum efficiency based on the designed channel models, orthogonal frequency division multiplexing (OFDM) has been widely employed in mmWave communication systems, including issued standards such as the IEEE 802.15.3c and the IEEE 802.11ad or available literature [99], [100]. It can realize high spectral efficiency for all kinds of links, which consists of uplink, downlink, sidelink, and backhual [101]. Meanwhile, a straightforward utilization of MIMO is enabled combined with OFDM, consequently further enhancing the spectral efficiency. OFDM based communication systems can be robust against phase noise, which is especially critical for mmWave communications operating at much higher carrier frequencies. Nevertheless, the use of OFDM will result in high peak-to-average-power-ratio (PAPR) and then high transmission power consumption since low PAPR will contribute to high power efficiency. It is known that high PAPR caused by OFDM can be extensively cut down through various well-known techniques proposed in [102], just compromising the overall performance in a minor way. Therefore, OFDM combined with PAPR reduction techniques is an attractive scheme for future wireless systems.

1) OFDM: In mmWave communications, orthogonality among sub-channels in the OFDM based communication systems can not be maintained due to the severe nonlinearity in low-resolution analog-to-digital converters. Hence, Wang *et al.* [103] design an efficient algorithm for data detection when applying low-resolution ADCs and OFDM. Besides, they have also developed a power allocation (PA) strategy aiming at the minimization of average symbol error rate. Detailed analysis verifies that the proposed detector can reach the fundamental limit of the Bayesian optimal design. Simulation results further confirm the accuracy of the analytical results and show that the performance of designed detector combined with PA scheme close to the OFDM system with infinite-resolution ADC can be realized.

TABLE III
COMPARISON OF DIFFERENT KINDS OF CHANNEL MODELS

Ref.	Frequency	Applicable scenario	Evaluated parameter
[11]	73GHz	Office environment	Directional and omnidirectional path loss, propagation characteristics such as number of multipath components, RMS delay, and spatial characteristics
[12]	60GHz	Indoor and short-range outdoor environments	Power delay profiles (PDPs) and power angle profiles (PAPs)
[92]	6-100GHz	Office and shopping mall	Path loss, delay spread and angular spread and the multipath richness
[93]	60GHz	Indoor environments	Attenuation and coherence bandwidth caused by blockage
[97]	73GHz	Urban dense environments	Azimuth, elevation, and polarization
[96]	28 and 73GHz	Urban dense environments	Path loss, number of spatial clusters, angular dispersion, and outage
[95]	71-76 and 81-86GHz	Street canyon scenarios	Excess delay, power level, and angular distribution of multipath components
[98]	6-100GHz	Urban microcells and macrocells	path loss, shadow fading, LOS probability, penetration and blockage

Despite that OFDM is one of the most promising modulation techniques in 5G mmWave communications, it has several shortcomings that contradict with the requirements of 5G technology, such as high peak-to-average-power ratio, cyclic prefix (CP) redundancy, complex amplifiers. Consequently, other appropriate alternatives, including generalized frequency division multiplexing (GFDM), filter bank multi-carrier (FBMC), universal filtered multi-carrier (UFMC), are proposed to provide substantially improved performance compared to the OFDM design. The commonality of the three solutions is to work without CP or just with zero padding prefix (ZP) and then enhance the spectral efficiency by adding filters. Correspondingly, the complexity will be increased in the process of reception and transmission in order to mitigate the influence of inter symbol interference (ISI) or inter carriers interference (ICI).

2) GFDM: To make GFDM satisfy the requirements of various application scenarios, Ferreira *et al.* [104] propose a GFDM based flexible data frame, which is in line with the specific demands of different 5G applications. In addition, when employing GFDM in spatial multiplexing based wireless systems, the inherent interference caused by GFDM such as ISI, ICI, and inter-antenna interference (IAI) will occur, thus bringing a huge challenge to the design of the receiver. Therefore, a parallel interference cancellation (MMSE-PIC) iterative receiver structure with the prominent minimum mean squared error is designed to reduce these interference. Meanwhile, a formulation is derived to simplify the practical implementation. It verifies that the complexity of GFDM based MMSE-PIC demapper scales linearly with the quantity of sub-carriers, as well as a superior performance compared to OFDM mapper except for frame error rate. In conclusion, waveform design and code design should be combined to fully utilize the GFDM based MMSE-PIC receiver structure.

3) FBMC: As another prospective alternative, FBMC is a modulation technique in which sub-carriers are processed by filters so as to restrain the sidelobes of the signals. Obviously, the bandwidth will also be limited. The reason why FBMC is employed in 5G networks lies in its ability to cope with network asynchronism [105], robustness to frequency misalignments [106], full utilization of frequency white spaces in dynamic spectrum access and cognitive radio networks [107]. Hosseini *et al.* [108] combine the wavelet-based spectrum sensing (WPSS) and FBMC modulation to improve the data rate and capacity in mmWave heterogeneous networks. WPSS can adapt the sub-carriers to alleviate the spectral leakage and interference, and wavelet-based FBMC can suppress the sidelobes. It outperforms Fourier-based spectral sensing in terms of power spectral density, detection probabilities, and bit error rate.

4) UFMC: Compared to FBMC, UFMC filters the subbands to realize suppression of spectral sidelobes, improved robustness against time and frequency synchronization, instead of sub-carriers. Furthermore, UFMC based filtering length is considerably shorter than that of FBMC. This is because UFMC conducts the filtering for each sub-band based on wider bandwidth than sub-carrier. Consequently, UFMC is more suitable for M2M applications, in which there exist many short-burst flows. Meanwhile, it does not utilize any CP. Instead, it exploits ZP to improve the spectrum efficiency. However, this distinguishing feature renders UFMC much more sensitive to time misalignment compared with CP-based OFDM waveform.

5) NOMA: Adopting power multiplexing, NOMA is able to further improve the spectrum efficiency based on OFDM. It can satisfy the requirements of low latency, high reliability, massive connectivity, improved fairness, and high throughput in heterogeneous networks. NOMA access technique enables that different users share the same degrees of freedom (DoF) through superposition, and multiple user detection (MUD) can be utilized to separate these interfered users. This mechanism is completely different from traditional orthogonal multiple access (OMA) technique, which follows the rule that users with better channel quality have a higher priority to be served first. NOMA can boost the number of links based on the technique of controllable symbol collision in the same DoF. Hence, network capacity can be enhanced. Meanwhile, users with various kinds of quality of service can be multiplexed on the same DoF, thus improving the latency and fairness.

Recent research work has already explored mmWave and NOMA, individually. Nevertheless, thorough performance evaluation has not been performed about combination of these two techniques. Therefore, Marcano and Christiansen [109] make an attempt to investigate the combination of NOMA and mmWave cells. Compared to OMA, up to 70% network capacity gain can be acquired based on NOMA. However, when applying NOMA, the SINR will decrease by 12dB over OMA in order to achieve a target block error rate. Meanwhile, compared to conventional NOMA technique, the distinguishing feature of mmWave-NOMA is that beamforming is a crucial technique in mmWave communications. Xiao *et al.* [35] point out that based on single-beam forming, the performance of mmWave-NOMA systems is compromised due to relative angles between NOMA users. Yet, when applying multi-beam forming, superior performance like robustness can be obtained. They have also discussed and proposed a joint design of intertwined power allocation and user pairing.

Further, Zhang *et al.* [110] investigate the combination of NOMA, mmWave, and MIMO. The network capacity can be derived based on two regimes: (i) Noise-dominated and low signal to noise ratio (SNR) regime, (ii) Interference-dominated and high-SNR regime. It demonstrates that significant capacity improvements realized in this integrated system, which is also verified through extensive simulations.

Different from system throughput improvements based on NOMA, Hanif *et al.* [111] focus on downlink sum rate optimization by applying NOMA in multiple-input single-output (MISO) systems. This problem can be well addressed by a minimization-maximization algorithm (MMA). NOMA based data transmission rate outperforms the conventional orthogonal multiple access schemes, especially under the circumstances of low transmitting signal-to-ratio.

H. Security in Physical Layer

Above description, mainly focusing on reducing the bit error rate and improving the spectrum efficiency and system capacity, is related to the critical techniques in physical layer of mmWave communications. However, owing to the broadcast nature of mmWave communications, it is vulnerable to wiretapping. Hence, mmWave communication security recently gains more and more attention especially for mmWave MIMO systems. Previous research focuses on conventional microwave networks. It adjusts the antenna steering orientation to exploit the maximum directivity gain while reducing the signal leakage to eavesdroppers or radiates the artificial noise (AN) for jamming potential eavesdroppers [112], [113]. But for mmWave communications, these strategies do not seem applicable owing to the unique features. Due to be susceptible to blockage, the influence of inconspicuous objects on mmWave security is explored in [114]. It shows that even reflectors at a scale of centimeter can render the information loaded on the directional beam wiretapped by eavesdropper. More sophisticated reflectors like metal surfaces will result in a broader range where the attacker can locate. Further, the received signal strength acquired by potential attackers is the same with that of legitimate recipient, leading to a small influence on the recipient's performance. Next, we will review the available literature related to the security of physical layer in mmWave communications.

Firstly, security assessment about different types of mmWave networks has been conducted. Wang and Wang [115] evaluate the network-wide physical layer security performance of downlink transmissions in mmWave cellular networks. They compute the secure connectivity probability and average number of perfect transmission links per unit area in a noise-limited mmWave network. The research is performed under the scene of both non-colluding and colluding eavesdroppers. When allocating power to artificial noise (AN) and designing the security policies for mmWave communication systems, both the array pattern and intensity of eavesdroppers should be taken into consideration. Unlike secrecy performance evaluation in mmWave cellular networks, Zhu *et al.* [116] investigate the physical layer security in mmWave ad hoc networks, accounting for various factors such as mmWave channel features, random blockages, antenna gains, and AN. A tractable scheme is proposed to evaluate the secrecy performance when deploying uniform linear array. It reveals that when setting relatively low transmitting power, lower carrier frequency can realize superior secrecy performance. With the increase in transmitting power, higher carrier frequencies are needed to obtain a higher secrecy rate. Meanwhile, AN may be ineffective for improving the secrecy performance in mmWave ad hoc networks.

Subsequently, effective schemes are presented to explain how to improve the secure performance of mmWave communication systems, such as employing RF precoding [117], [118]. In [117], a directional four-symbol modulation repeats the switch operation of phase shifters in a phased array, minimizing the bit error rate (BER) of a LOS channel in a desired direction and maximizing the BER in other directions.

Valliappan *et al.* [118] propose an Antenna Subset Modulation (ASM) scheme for point-to-point secure wireless communications. ASM modulates the radiation pattern at symbol rate by driving only a subset of antenna arrays, resulting in a directional radiation pattern that projects a sharply defined constellation in the desired direction. Nevertheless, it is based on one strict assumption: paths from legitimate receivers to eavesdroppers are line-of-sight (LOS). However, since mmWave links are prone to being broken by obstacles, non-line-of-sight (NLOS) mmWave links are likely to be frequently selective.

In [119], a novel RF precoder is designed to improve the security performance in physical layer. It is configured with two degrees of channel knowledge at transmitters. For full channel knowledge, RF precoder maximizes the secrecy rate with two algorithms. These two algorithms are based on semi-definite relaxation and gradient ascent, respectively. For partial channel knowledge, such as just the angles of departure (AoDs), RF precoder maximizes the secrecy rate under secrecy outage constraints. The proposed scheme can converge quickly, and demonstrate a superior performance over existing secrecy schemes.

I. Conclusion of mmWave in Physical Layer

In this part, we make a review of mmWave communications and point out the future work in physical layer.

- The development of mmWave circuit components is firstly introduced. In PAs, non-linear distortion is inevitable due to imperfect artificial manufacturing and high PAPR. Therefore, based on the CE-OFDM strategy, corresponding operations at both the transmitting and receiving ends can be more effective to mitigate the influence of non-linear distortion compared to processing at transmitting-only or receiving-only end. To combat phase noise induced by VCOs, an effective scheme is to devise VCOs with high quality factor and low loss inductor based on accuracy noise models.
- The classification of mmWave antenna arrays has been presented mainly according to the development. Due to small wavelengths, the transmission loss caused by medium is very large, which is an enormous challenge in the mmWave antenna design. For mmWave antennas embedded in base stations, an effective method is to adopt substrate integrated antennas due to two reasons, respectively as small loss induced by air waveguide transmission and microstrip antenna technique that can be produced on a large scale. Then, for mmWave antenna design at mobile terminals, antennas should be directly integrated in the package, since embedded antennas in the chip bring excessive loss and extra cost.
- In this section, we mainly review the literature related to analog beamforming and hybrid beamforming. It can be concluded that hybrid beamforming will be most likely to be applied in 5G cellular networks. However, there exist several pressing challenges to overcome when employing hybrid beamforming, including RF chains determination, channel estimation, and beam training and feedback. Under the constraints of fixed number of multiplexed streams and antenna elements, hardware complexity, and power consumption, the relationship between channel capacity optimization and the number of RF chains is worth studying. It is known that perfect channel information can not be acquired in most scenarios. Consequently, the space sparsity between mmWave channels can be utilized to reduce the number of estimated channel parameters, which in turn simplifies the channel matrix, signal processing, and thus the overall system design. Finally, in order to adapt to dynamic channel conditions, UE localization and tracking should be utilized since conventional beam training and feedback will result in too much overhead in terms of time and processing.
- We have also presented the precoding schemes. Majority of them focuses on realizing low-complexity schemes according to the perfect information of channels and antenna arrays. Nevertheless, wireless channel state varies over time, especially in outdoor scenarios. Instant channel information acquisition is a bottleneck for precoding schemes. Then, for future work, the exploitation of space sparsity between mmWave channels or relatively high channel prediction model provides a promising solution.
- As a critical component in physical layer, the establishment of mmWave channel models becomes particularly important. However, completely different from traditional microwave signals, mmWave signals experience severe attenuation and poor diffraction. In addition, mmWave links are usually highly directional. These features render mmWave channels much more susceptible to environments. Consequently, mmWave channel models should be built in indoor and outdoor scenarios, respectively. Signal reflection by the wall and furniture, the obstruction of moving people should be considered in the process of indoor mmWave channel construction. For outdoor mmWave channel models, reflection by nearby buildings and obstruction of moving people are crucial factors since NLOS mmWave links occupy the dominant component, especially in crowded outdoor environments.
- MIMO, especially for massive MIMO, can further improve the spectrum efficiency and channel capacity for cellular networks. However, channel model construction for massive MIMO is still in its infancy. Coupled with large scale antennas in both base station and UE, multi flows can be transmitted at the same time between the sending and receiving ends. Hence, the problem about how to quantify the relation and interference among these flows renders the channel model construction for massive MIMO more challenging. For future work, channel characteristics can be obtained based on statistical beam domain, thus building mmWave channel models for massive MIMO. Another conventional problem for massive MIMO is that channel information becomes much more difficult to be obtained compared to single flow. Hence, two different methods can be adopted. Firstly, the sparsity of mmWave beam domain and doppler expansion characteristics can be utilized to reduce the dimension of channel information matrix. Secondly, statistical channel information can be exploited to optimize the pilot design, thus providing high-precision instantaneous channel estimation knowledge. Finally, a typical problem for massive MIMO is how to optimize multiuser air division multiple access systems based on the acquired channel information. Under the premise of obtaining statistical channel information at transmitters, low complexity and high performance can be realized through appropriate resource allocation in the beam domain.
- Subsequently, modulation modes like OFDM and several other alternatives such as GFDM, FBMC, and UFMC has been presented. However, based on OFDM, the multichannel transmission efficiency needs to be improved since 5G will be applied to Internet of things. For example, an implementation of OFDM based windowing is effective to reduce interference between adjacent bands.

- Security research in mmWave communications is a promising direction in the absence of in-depth investigation. Due to the broadcast nature of mmWave communications, mmWave signals are susceptible to wiretapping. Compared to microwave communication security, beamforming and precoding provide a useful mechanism to improve security and privacy for mmWave communications, especially for medium and long range outdoor communications.

V. Research in MAC Layer

Based on critical techniques in physical layer like NOMA, there may exist a large amount of users sharing the same wireless physical link, then problems about how to avoid collision and mitigate interference among users are raised in MAC layer. Compared to traditional wireless communication technologies, mmWave communications allow more concurrent links due to its narrow beam. This feature motivates an interesting research topic for mmWave communications, namely concurrent links scheduling for interference mitigation and capacity enhancement in MAC layer. We classify exiting research work into four groups, and each group centers around one of the network types, which includes ad hoc networks, mesh networks, WPANs, and cellular networks.

A. Protocols in Ad Hoc Networks

In mmWave ad hoc networks, interference among transmission links can be greatly cut down due to narrow beams. Thus, it introduces the concept of noise-limited wireless networks as opposed to the interference-limited ones. However, existing MAC protocols ignore the difference between these two regimes, which may bring great decrease in performance. Novel MAC protocols considering both noise-limited and interference-limited regimes can be more conducive to capture the characteristics of mmWave networks [120]. Specifically, tractable closed-form expressions, operating under slotted ALOHA and TDMA, are derived as functions of collision probability, per-link throughput, and area spectral efficiency in mmWave ad hoc networks. When transferring from a noise-limited regime to an interference-limited regime, performance of mmWave ad hoc networks can be affected, which depends on density of transmitters, density and size of obstacles.

Previous research work on mmWave ad hoc networks usually assumes that nodes operate in both directional and omnidirectional modes. This assumption causes the asymmetry-in-gain problem. It means that this mechanism will bring deafness and collision problems to existing MAC protocols since nodes do not have accurate information about their neighbors. In fact, nodes can only sense one direction at any given time instance. Consequently, it becomes quite difficult for them to accurately set its directional network-allocation vector (DNAV) for all ongoing communication links. To solve the above problems, Shihab *et al.* [121] propose a novel wireless distributed protocol named DtDMAC for device-to-device communications. In this protocol, each node is equipped with only one directional antenna. Thus, the asymmetry-in-gain problem can be addressed effectively, which in turn mitigates the impact of deafness and collision.

B. Protocols in Mesh Networks

In addition to ad hoc networks, the application of mmWave communications in outdoor mesh networks with relatively short ranges of 100-200m also holds potential for quickly deployed broadband extension of the Internet. In this section, we will review some papers that focus on design guidelines such as interference minimization, deafness mitigation among concurrent links [122], [123].

For interference minimization, Mudumbai *et al.* [122] build an architecture for outdoor mesh networks operating in the 60GHz band. They take narrow beamwidth and oxygen absorption into consideration, and analyze how much interference can be cut down. Detailed analysis demonstrates that interference caused by uncoordinated transmission links can be ignored when designing mmWave mesh networks. By contrast, design of half-duplex transmission scheme is the real challenge. Based on the preliminary analysis and results in [122], Singh *et al.* [123] play a vanguard role in characterizing the spatial interference of mmWave mesh networks and quantitatively analyzes a pseudowired abstraction in the design of MAC protocols. Firstly, they extract and analyze the spatial interference statistics among multiple concurrent links. Subsequently, an analytical framework is constructed for half-duplex transmission scheme to acquire the collision probability, which is a function of antenna patterns and density of simultaneously transmitting nodes. It concludes that highly directional mmWave links can indeed be modeled as pseudowire. Packet losses caused by failed coordination are an order of magnitude higher than those due to collisions, intensifying the demand for more sophisticated coordination mechanisms.

For deafness mitigation, Singh *et al.* [24] derive an approximate time division multiplexed (TDM) scheduling scheme in a distributed MAC protocol to address the "deafness" problem. Time has been divided into transmitting or receiving slots. They have already been stored successfully for a given neighbor and assigned properly. At the same time, partial slots are abandoned for being placed into a per-neighbor blacklist. Feedback from all active neighbors of one node constitutes the node's transmitting and receiving history. It can be applied into implicit coordination and persistent use for a given slot. In comparison to previous distributed MAC protocols, TDM can adaptively accommodate changes in demand for simple learning rules embedded in all nodes and relieve the pressure of frequent control message exchanges.

C. Protocols in WPANs

As another typical kind of networks, wireless personal area networks (WPANs) can also provide peer-to-peer connection for short-range communication systems. Combining ultra-wideband wireless communications (UWB) with mmWave communications, Time Division Multiple Access (TDMA) based standards about multi-gigabit data rates can be realized in WPANs, such as ECMA-387, IEEE 802.15.3c. In order to exploit concurrent transmissions (spatial reuse) to expand the capacity of mmWave WPANs, two mainstream types of MAC protocols have been developed: Centralized MAC protocols and distributed MAC protocols.

1) Centralized MAC Protocols: In centralized MAC protocols, a piconet coordinator (PNC) is set up to schedule all transmission links according to continuous collection of device information. Gong *et al.* [124] present a new centralized directional CSMA/CA protocol designed specifically for 60GHz WPANs since conventional CSMA/CA protocols cannot match well with directional antennas. First of all, they analyze the influence of impaired carrier sensing when applying directional antennas to conventional MAC protocols. Based on these analysis, a central coordinator is set up to distribute network allocation vector (NAV) information, extending conventional CSMA/CA frameworks. Meanwhile, another centralized MAC protocol named multi-hop relay directional MAC (MRDMAC) also aims at multi gigabit indoor WPANs [41]. It applies the conventional AP-based single hop MAC architecture in order to maintain the primary connection. Then, a sequential polling policy is responsible for scheduling the majority of transmission links passing through the PNC. PNC selects an intermediate node to forward data traffic if one link to the PNC is broken owing to blockages.

Nevertheless, under-utilized spatial reuse causes degraded performance since most links go through the PNC. Research work in [125]–[127] proposes distinctive solutions to address this problem. In [125], a frame-based directive MAC protocol (FDMAC) fully exploits collision-free concurrent transmission links to improve the spatial reuse efficiency in mmWave WPANs. It consists of one PNC and multiple devices (DEVs). Network time is divided into a sequence of non-overlapping intervals, termed frames, which include two phases: scheduling phase and transmission phase. In the scheduling phase, PNC acquires traffic information from DEVs and develops a concurrent links scheduling strategy according to greedy coloring (GC) algorithm, which is based on graph coloring. Next, during the transmission phase, DEVs start concurrent transmission according to the strategy. Chen *et al.* [126] also design an IEEE 802.11 based scheduling scheme with the same purpose as [125]. Firstly, they derive proper conditions to enable spatial reuse. Then, a practical scheduling algorithm is proposed according to these conditions. They evaluate the performance of the scheme using both idealistic and realistic antennas to demonstrate its high efficiency.

2) Distributed MAC Protocols: Motivated by the fact that high medium utilization can be realized by highly directional links in mmWave communications, especially in the 60GHz band, distributed MAC protocols are another promising candidate. Niu *et al.* [127] propose a channel transmission rate aware MAC protocol, referred to as RDMAC. In the protocol, a heuristic algorithm is responsible for the measurement of channel transmission rates. Another heuristic scheduling algorithm with short delay and low computing complexity is proposed to derive a near-optimal scheduling scheme for all of these channels. From another prospective, Kwon *et al.* [128] propose a coverage adaptive directional MAC (abbreviated to CAD-MAC) for mmWave WPANs. It assigns sectors based on variable device locations. CAD-MAC outperforms existing MAC protocols in terms of network throughput and energy efficiency.

D. Protocols in Cellular Networks

Compared to above network types that are suitable for short-range communications, mmWave cellular networks can accommodate more UEs and support longer transmission distance. As the first standard for mmWave cellular networks, 3GPP NR is a standardization effort to bring 5G visions into commercialization [129]. It redesigns the fundamental techniques such as numerologies, channel coding, and MIMO, since mmWave cellular networks are completely different from microwave cellular networks. Problems become even more challenging in MAC layer of mmWave cellular networks. For instance, initial access and handover must be taken into consideration in MAC layer design for mmWave cellular networks. In this section, we mainly provide a literature review about the protocol design for initial access, mobility management, and handover. Meanwhile, as a crucial technique to enhance the spectrum utilization, capacity, and robustness of mmWave cellular networks, Device-to-Device (D2D) communications enabling direct connection and communication between UEs without base stations are also presented.

1) Protocols Designed for Initial Access: Initial access and mobility management are two of the most fundamental functions in MAC layer of mmWave cellular networks. They specify the access of UE to the cellular networks and maintain the established wireless links. In particular, initial access is composed of two steps, respectively as cell search on the downlink and random access on the uplink. Once the UE appears in cellular networks for the first time, it will start the initial synchronization process, as well as extraction of system information. Subsequently, it carries out the operation of random access, coupled with the status being marked as active in cellular networks. After these two steps, the UE can access to the mmWave cellular networks successfully. However, mmWave communications heavily depend on directional links to combat severe attenuation, significantly complicating the initial access. Initial access in mmWave cellular networks has already been studied in several standard protocols. For instance, The Verizon 5G forum [130] has investigated the initial access technique for mmWave cellular networks. In particular, base stations employ beam sweeping to carry out cell search. Then, the beam reference signal can be leveraged to select the appropriate beam directions of base stations by UEs.

In addition to standardization efforts for initial access in mmWave cellular networks, extensive research work has also been dedicated to the initial access in cellular networks. Jeong *et al.* [131] propose a strategy that sequentially searches all the possible transmit-receive beam directions, which is also referred to as the exhaustive process. However, it always brings considerable time cost. Hence, Desai *et al.* [132] decompose the beam alignment procedure into two consecutive steps to avoid heavy time overhead. Firstly, base stations perform an exhaustive search over wide beams. Then, it searches narrow beams based on wide beam search. Detailed comparison between these two strategies demonstrates that the delay caused by hierarchical search is shorter than exhaustive search in general. Yet exhaustive research based scheme contributes to a wider coverage for cell-edge users.

Finally, as a simple broadcast based strategy for mmWave communications, directional codebooks with limited feedback can also be utilized for initial user discovery [133]. It is based on two observations: (i) a physical interpretation between beamformer structures and the AoD/AoA of dominant path can capture the scattering features. (ii) The codebook scope designed for best beam alignment is restricted by a virtual subarray architecture, which is within a couple of dB of the best tradeoff curve at all useful beam broadening factors. The proposed scheme based discovery time shows a smooth roll-off in performance with the reduction of link margin. Nevertheless, the low complexity for initial access will render it an alluring scheme for future mmWave systems. Further, in [134], a comprehensive summary based on four representative initial access protocols, which utilizes various combinations of directional and omnidirectional transmission and reception, reveals that the initial discovery delay will become shorter when more obstacles are set in existing environments. Yet, the user-perceived downlink throughput remains almost the same.

2) Protocols Designed for Mobility Management and Handover: In mmWave cellular networks, interference mitigation with highly directional transmissions comes at the expense of much more complexity in handling mobility and handover. The reasons are listed as below. Firstly, compared to existing LTE cellular networks, mmWave base stations will be deployed more densely due to limited coverage of mmWave communications, which implies that more frequent handovers will occur in mmWave cellular networks. Secondly, mmWave signals are vulnerable to random obstacles compared to microwave signals in LTE networks. For example, mmWave signals can be completely obstructed by materials such as brick and mortar, and even human body can cause a 35dB signal strength degradation. Finally, unlike omnidirectional radiation mode in LTE networks, small movements of obstacles or even orientation change of mmWave devices can easily render the highly directional mmWave links disconnected [135].

Consequently, after successful access, efficient strategies related to mobility management and handover should be devised to enhance the robustness of mmWave links in cellular networks. In convention, a natural method is multi-connectivity. It means that each mobile device builds connections to several base stations, possibly including 5G mmWave stations and LTE stations. Then, whenever mmWave links are broken, UEs can select another appropriate established link to preserve the connection [136], [137]. For instance, corresponding solutions in [138]–[141] are mainly about the multi-connectivity framework design in mmWave cellular networks, so as to be free of interruptions of handover or link failures. In particular, Tesema *et al.* [140] design a low layer multi-connectivity structure for 5G mmWave Ultra Dense Network, which is characterized by the variability of signal strength at the receiver. The problem about management of a set of connected cells can be formulated and then addressed by the numerical method. Compared to single-connectivity scheme, the proposed multi-connectivity shows a superior performance in terms of link failures and cell-edge throughput. Unlike research work in [140], Giordani *et al.* [138], [139] focus on the link direction tracking when establishing multi links. To solve this challenge, an measurement system combined with a local coordinator operating in the legacy band is developed to realize continuous monitoring of mmWave link state.

Further, Polese *et al.* [141] propose a dual connectivity and handover scheme applied for mmWave cellular networks. In the scheme, a LTE base station will be utilized as both fallback and coordinator, and another link attached to the mmWave base station is responsible for service delivery. In comparison with above multi-connectivity schemes, the proposed scheme applies an uplink sounding strategy to realize seamless link switch and a dynamic time-to-trigger (TTT) adaptation to improve the efficiency of switch decision. In addition, a local coordinator, which is deployed closely to the cells, is utilized to manage the traffic between the cells. This mechanism can substantially reduce the handover delay in case of link failures or handover.

3) D2D Communications: Device-to-Device (D2D) communications are a kind of technology that allows terminals to communicate directly with the reuse of cell resources. It can be applied in mobile cellular networks to improve resource utilization and network capacity [142]. However, D2D communications, which occupy the same carrier frequencies with today's cellular systems, can cause severe interference to users in cellular networks. By contrast, in mmWave cellular networks, owing to highly directional links, not only do D2D communications bring almost no interference to mmWave cellular systems, but also it contributes to improve robustness to blockage [41], [143]. Niu *et al.* [144] propose a scheduling scheme for popular content downloading in mmWave small cells, which is referred to as PCDS. In PCDS, a path selection algorithm constructs and maintains multi-hop paths by making full use of D2D communications and concurrent transmissions. The optimization problem about multi-hop transmission scheduling scheme is modeled as a mixed-integer linear programming (MILP), the aim of which is to minimize the content delivery time from the AP to all users. Numerous simulation results under various traffic patterns verify that compared to other protocols, PCDS demonstrates a superior performance in terms of delay and capacity.

E. Conclusion of mmWave in MAC Layer

In this section, we have summarized available literature of mmWave communications in MAC layer, including MAC protocols and scheduling schemes for ad hoc networks, mesh networks, WPANs, and cellular networks. Table IV summarizes several well-known MAC protocols mentioned above. Efficient scheduling schemes based on concurrent transmission links should be developed to realize interference mitigation and spatial reuse improvement. In particular, highly directional links can be modeled as pseudowired in outdoor mmWave mesh networks, implying that the interference among nonadjacent

TABLE IV
COMPARISON AMONG EXISTING MAC PROTOCOLS

Protocol	Network type	Frequency	Mode	TDMA-based
DtDMAC	Ad hoc network	60GHz	Distributed	No
FDMAC		60GHz	Centralized	No
MRDMAC	WPAN	60GHz	Centralized	No
RDMAC	WPAN	60GHz	Centralized	No
CAD-MAC	WPAN	60GHz	Centralized	Yes
PCDS	Cellular network	60GHz	Distributed	No

links can be ignored. Meanwhile, the information of antenna patterns can also be negligible for outdoor mmWave mesh networks. However, the assumption of pseudowired can not hold in indoor mesh networks due to limited transmission range. Thus, different scheduling schemes should be designed for mesh networks in different scenarios.

For mmWave WPANs, majority of existing MAC protocols are based on the request-to-send/clear-to-send (RTS/CTS) and network allocation vector (NAV) of the IEEE 802.11 distributed coordination function mechanism. Yet, mmWave WPANs may demand reservation based directional protocols due to the requirements of QoS. Besides, hidden node problems and deafness induced by asymmetric gains of directional antennas are also pressing problems that need to be resolved. Consequently, effective coordination mechanism among USs is critical to alleviate the impact of the deafness problem.

Finally, we have made a comprehensive review related to the design challenges of MAC protocols in cellular networks, such as initial access, mobility management, and handover, which is caused by highly directional links. Based on the utilization of both omnidirectional microwave and directional mmWave communications, these problems can be handled in a simple yet effective way. For example, the UE connecting to multi nearby cells can realize seamless handover when the microcell base station is responsible for beam tracking.

VI. RESEARCH IN NETWORK LAYER

In network layer, it can provide security management, routing management, and network management. Among them, routing is one important function in network layer of wireless networks, and routing algorithms are the core of routing. For mmWave communications, proper routing strategies can overcome the blockage problem, thus enhancing the robustness of mmWave links [26], [145]. In addition, multi-hop relaying is indispensable to extend the transmission range of mmWave communications. Finally, by adopting appropriate routing strategies, interference among these concurrent links can be minimized so as to enhance network throughput [146]. Before introducing routing schemes, we will present the research work related to mmWave network framework construction and relay deployment, since they are the foundation of routing strategies. After the introduction of routing schemes, we review some available papers about the integration of mmWave with WiFi or LTE networks, which can well illustrate the complementary advantages of different wireless technologies.

A. Design of Frameworks

The conventional methodology to avoid traffic congestion and enhance the capacity is to build efficient system frameworks based on the propagation features. Therefore, in this subsection, we mainly introduce the framework design for the next generation network and data center network.

1) Frameworks for Next Generation Network: In recent years, with explosive growth of wireless data, it brings substantial pressure on conventional cellular networks. In result, the fifth generation (5G) network has been proposed to meet these requirements. 5G consists of three key technologies-mmWave mobile broadband [70], massive MIMO [147], and small cells [148].

Nevertheless, applying these technologies to 5G communications is challenging. For example, both mmWave and massive MIMO systems require new hardware at base stations, and system framework needs to be redesigned due to mmWave's unique features. Therefore, Pi *et al.* [149] propose a mmWave gigabit broadband (MGB) framework for 5G network. It regards both mobile broadband small cells and fixed broadband access points as small cells and allows small cells to be deployed anywhere within the area coverage. The MGB framework can provide gigabit-per-second links to small cells in a particular area. Dense small cells contribute to much higher spectral efficiency by providing beneficial channel conditions. As an effective solution for gigabit-per-second fixed broadband and mobile broadband, MGB system can provide 1Gb/s peak rate and 100Mb/s average throughput to 96 small cells within 1km radius at a probability of 99%.

Different from utilizing 39GHz mmWave band in [149], Zhu *et al.* [150] deploy 60GHz mmWave picocells to augment existing cellular networks to satisfy the requirements of orders of magnitude increase in wireless data traffic. Some common myths about 60GHz outdoor communications such as small coverage, high sensitivity to blockage are dispelled. It proves that with high transmitting power and efficient collaboration between base stations, the coverage range of mmWave communications can reach nearly 200m and the probability of link connectivity is more than 95%. Therefore, an architecture named "picoclouds", which is depicted in Fig. 4, has been designed to deliver up to 72Gbps data rate for each mmWave base station. However, this work is just the beginning of 60GHz outdoor communications. There still exist some details to be implemented, including cross-layer modeling, user tracking, control plane, picocloud architecture, protocol design, and hardware design.

Furthermore, combined with another technology-software defined network (SDN), Akyildiz *et al.* [151] construct a software-defined architecture, referred to as SoftAir, for next generation cellular networks. In conventional cellular systems, hardware-based architectures are inflexible and closed. It becomes quite difficult to deploy new standards and techniques in cellular networks. In SoftAir, based on the network function

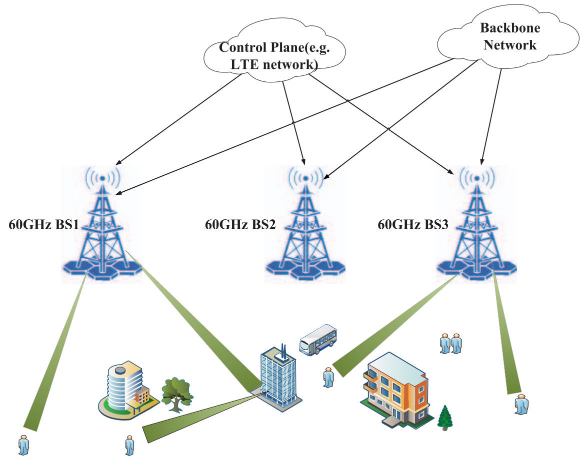

Fig. 4. A potential 60GHz picocell architecture.

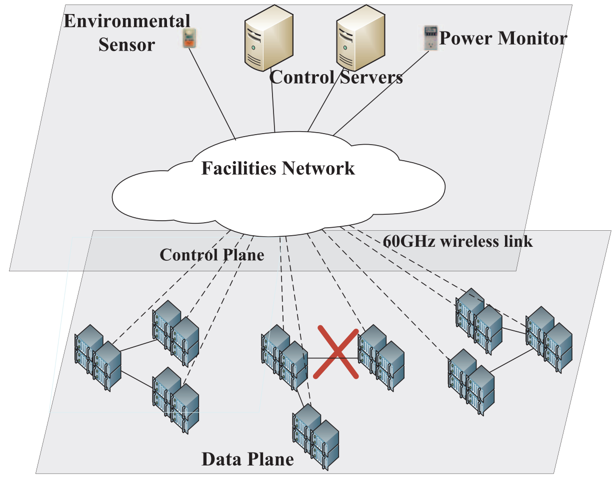

Fig. 5. A facilities network providing robust delivery of control traffic in a data center.

of cloudification and virtualization, a scalable, flexible and resilient network architecture is built, which makes deployment of standards and techniques much more quickly and conveniently. In addition, they investigate the techniques of fine-grained base station decomposition, seamless incorporation of openflow, mobility-aware control traffic balancing, and resource-efficient network virtualization in detail.

2) Frameworks for Data Center: In the meantime, with the rapid growth of cloud-based services, multicast traffic in data centers is rising sharply, resulting in link congestion and then decline in quality of service. Performance of conventional data centers is subject to network topologies and complex wiring. Therefore, researchers have made an attempt to combine wired links with 60GHz mmWave links in data centers [152], [153]. In [153], detailed analysis proves that the minimization optimization of total multicast traffic is NP-hard. Therefore, two heuristic algorithms with low complexity are proposed to address the tree construction problem and the maintenance problem, respectively. Based on practical parameter settings and extensive simulations, it demonstrates that the proposed framework is effective in relieving the pressure of massive multicast traffic in data centers.

From another perspective, Zhu *et al.* [152] build a low-latency facilities network architecture named Angora for data centers. Angora is decoupled from the wired network, mainly responsible for managing and controlling data center networks. Even sometimes networks suffer from congestion or hardware faults, the facilities network still runs normally, which is shown in Fig. 5. In Angora, a location-aware ID assignment based scheme can allocate wireless links so as to greatly reduce interference among nearby directional links. Furthermore, Angora can support arbitrary network sizes and routing schemes based on Kautz graphs.

Completely applying 60GHz wireless links, instead of cables, to construct wire-free data centers is also a feasible scheme [154], [155]. For example, Vardhan *et al.* [155] emulate various data center network (DCN) architectures such as 3-tier and fat-tree utilizing 60GHz links. It shows that wireless data centers become more flexible and cost-effective. In particular, applying beamforming and beamsteering, point-to-point LOS links between transceivers and receivers can be realized. Based on the imitation and analysis of [155], Shin *et al.* [154] build a wire-free data center based on Cayley graphs [156], in which wireless transceivers integrated within servers are deployed rather than wired switching fabric. Moreover, they design a new geographic routing protocol to schedule 60GHz wireless links, matching well with a practical rack-level hardware topology. Comparison among these frameworks is illustrated in Table V. It can be observed that framework designs in [149] and [150] aim at 5G network, which is based on 39GHz and 60GHz mmWave, respectively. However, research work in [152]–[154] develops data center networks leveraging 60GHz mmWave links.

B. Relay Placement

When the system framework is fixed, effective relay placement strategies are expected to address the challenges such as severe attenuation and blockages. Free space loss of 60GHz mmWave signals can be up to 21.6dB under the mode of omnidirectional communications, which is much worse than that of the 5GHz band. Accordingly, large scale mmWave antenna arrays have been utilized to establish directional paths. Nevertheless, these paths are always vulnerable to be broken due to obstacles. In result, relays are deployed to extend the coverage range and improve robustness to link failures. If there exists no LOS connectivity between the transmitter and receiver, then traffic can be switched to the relay, through which information can arrive at the destination. If LOS links are blocked by obstacles, the paths by relays can act as back-up links to complete transmissions, as illustrated in Fig. 6.

In mmWave WPANs, two major problems are needed to be addressed: how to place these relays from a set of candidate locations under the constraints of bandwidth and robustness (RMRP) and how to place the relays to maximize network utility under the condition of a fixed number of relays (RMURP). Zheng *et al.* [27] establish two vertex-disjoint paths between each pair of transmitter and receiver. In particular, one path is named the primary path, and another path is named the secondary path. Therefore, seamless switching to the secondary

TABLE V
COMPARISON AMONG PROPOSED FRAMEWORKS

Ref.	Frequency	Application	Advantage
[149]	39GHz	5G	Last mile solution for gigabit-per-second fixed broadband and small cell backhaul solution for gigabit-per-second mobile broadband
[150]	60GHz	5G	Improvement in network capacity
[153]	60GHz	Data center including wired and wireless links	Minimization of total multicast traffic
[152]	60GHz	Data center including wired and wireless links	Low-latency, robust, and flexible facilities networks
[154]	60GHz	Wire-free data center	High aggregate bandwidth, low latency, and high fault tolerance networks

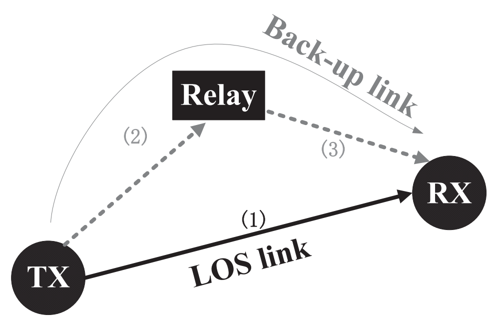

Fig. 6. mmWave relay deployment.

path can be realized whenever the performance of primary path degrades substantially. Furthermore, the D-norm uncertainty model is applied to maintain the links when encountering concurrent (worst-case) failures of a subset of primary paths [157]. Based on linear relaxation and duality theorem of linear programming, RMRP and RMURP can be modeled as the mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) problems, respectively. Bisector search algorithm and generalized benders decomposition algorithm are combined to well address the RMURP problem. However, it does not consider interference among concurrent directional links. Then, in [158], a more realistic interference model is built. In the model, a classic directional antenna radiation pattern [122] is utilized to reduce interference and improve spatial reuse. As well as [27], RMRP and RMURP in mmWave WPANs are modeled to improve the robustness against link failure. They are proved to be NP-hard. Based on bisection search, a heuristic algorithm is proposed to solve RMURP with a near-optimal performance.

Previous research has shown that network throughput is influenced by the time cost for relay operating [159]. Hence, time slot based scheduling schemes for relay operation are designed to further improve the throughput of mmWave WPANs [160], [161]. Scheduling for transmission paths from relay to destination and from source to relay will be executed in the same time slot, rather than allocate extra time slot for relay operation. mmWave features such as high path loss and beamforming have been fully utilized, contributing to enough space isolation among nearby links. Then, network throughput maximization is formulated into an integer optimization problem. And it is converted to a max-weight matching problem, which can be solved by the Kuhn-Munkres algorithm. 25% improvement in network capacity can be obtained in comparison to random scheduling method.

C. Routing Scheme

Then, we will introduce the routing schemes for mmWave networks, which are based on the relay deployment. Existing research work mainly can be divided into two kinds: Routing scheme for mmWave WPAN and cellular network and routing scheme for data center.

1) Routing Scheme for mmWave WPAN and Cellular Network: It is known that the coverage range of mmWave communications is dramatically restricted owing to obstacles and oxygen absorption. For example, when encountering brick walls, the strength of mmWave signals will decrease by as much as 178dB [65]. Accordingly, reflection plays a more dominant role than diffraction in received signal power of mmWave communications, making non-line-of-sight (NLOS) links quite promising for realizing high data rates. In order to adapt to these changes, routing schemes in the network layer of mmWave communications should make changes accordingly [25], [41], [162], [163]. Singh *et al.* [41] build a diffraction-based model to select transmission paths according to the locations of stationary and moving obstacles. Since mmWave links are easily broken by obstacles, employment of a small quantity of relay nodes can be effective to maintain mmWave network connections in a centralized WPAN. Hence, in [162], a multi-hop concurrent link scheduling scheme adopts the relay strategy to improve throughput in WPANs. Whenever one link is broken, an appropriate relay node will be selected to forward data traffic.

Different from the purpose of enhancing network capacity, Kim and Molisch [25] propose a multi-hop routing protocol with special emphasis on the maximization of video transmission quality since video streaming in cellular applications becomes increasingly prevalent. Numerous results show that the protocol can achieve around 33% better performance than existing max-min routing scheme. However, it ignores the fading and interference problem caused by multi-hop D2D communication. Therefore, Eshraghi *et al.* [163] set up pre-planned relays to ensure seamless line-of-sight (LOS) coverage if mobile phones can not relay data in the proposed mmWave D2D multi-hop routing for multimedia applications. In this protocol, the sum quality of uncompressed high definition (HD) video flow is maximized, which is one of the most popular form of mobile data traffic. The optimization problem is transformed into a mixed integer nonlinear programming (MINLP) problem and it can be solved by a suboptimal algorithm.

2) Routing Scheme for Data Center: Nowadays, data centers have been widely deployed, providing powerful computing and storage for various kinds of applications. Yet massive distributed applications running in data centers may result in link congestion with potentially tens of thousands of servers installed in hundreds of racks. Deploying wired networks and modifying configurations brings about high complexity and heavy overhead. Consequently, research on network topologies has been carried out to reduce cost and avoid congestion in data centers [164], [165]. However, operations such as planning, deploying, testing, and repairing in any large-scale wired networks still require measurable overhead. Therefore, 60GHz wireless links are suggested to be applied in data centers for its convenient management and high bandwidth as shown in 7. Utilizing steered-beam based mmWave links, Katayama *et al.* [166] construct a wireless packet-switching network structure for data centers. Direct wireless links connecting adjacent rows of racks can greatly reduce the transmission latency. Furthermore, it can lower the equipment and reconfiguration cost because cables and switches are replaced by 60GHz links.

With dissimilar goal, Halperin *et al.* [167] augment wired network with 60GHz links in order to relieve hotspots in oversubscribed data center networks. Numerous experiments in this paper verify that 60GHz links are suitable for being applied in data centers in terms of interference and link reliability. It also proves that only a small part of top-of-rack switches and links suffer from congestion at any time, implying that a few 60GHz links are enough for relieving hotspots. According to the experiments and analysis, they build a data center structure coupled with a set of beneficial flyways and routes in both direct and indirect ways. The completion time of bandwidth hungry applications can be shortened by 45% in 95% of the cases through numerous experiments.

However, there still exist some limitations in this work. First, 60GHz directional links may suffer signal leakage and produce interference to other links near the intended target receiver. Hence, the number of concurrent links should be reduced, as well as network throughput. Second, these LOS mmWave links between transmitters and receivers can be easily broken by obstacles.

Therefore, Zhou *et al.* [26] construct a 3D beamforming framework using 60GHz links in data centers based on previous efforts [167], [168]. In the 3D beamforming framework, indirect LOS 60GHz links between most or all rack pairs can be established by a signal reflection plane, avoiding blockages in the transmission path and minimizing interference among concurrent links. A link scheduling scheme is utilized to schedule concurrent links in 3D beamforming systems. It takes accumulative interference and antenna alignment delay into consideration so as to maximize the capacity and reduce the delay. Performance evaluation among wired data centers, data centers based on 2D beamforming, and data centers based on 3D beamforming is shown in Fig. 8 and Fig. 9. From Fig. 8, we can observe that with the increase of the size of the biggest flow, the delay time can be shortened by more than half when employing 3D beamforming. However, 2D beamforming systems can address only a few hotspots. It just brings a limited time overhead reduction. From Fig. 9, with the increase of bisection bandwidth for wired network, the reduction of total completion time in 3D beamforming systems ranges from more than 50% to slightly less than 40%. This is because more overflow traffic is consumed by wired network and less traffic is left for 60GHz wireless links.

D. Combination of mmWave Communications and LTE, WiFi

In addition to the above strategies, another conventional strategy to enhance the robustness of mmWave communications is by the assistance of the existing LTE or WiFi. It is acknowledged that future 5G communication systems have a strong desire for novel air interfaces operating at higher frequency bands due to worse propagation features. Silva *et al.* [169] construct a radio access network (RAN) architecture, in which a tight integration of the air interface with LTE can realize cross-air interface optimizations such as resource allocation, fast mobility, and multi-connectivity. In addition, an integration layer based on air interfaces is developed to enhance the coverage and capacity of 5G networks.

1) Combination of mmWave Communications and LTE: Based on the trial efforts in [169], dual-mode base stations that can make full use of mmWave and microwave resources are designed to address the uncertainty problem in conventional mmWave base stations. In particular, Semiari *et al.* [170] propose a dual-mode scheduling scheme at both mmWave and microwave bands, which can be formulated as an optimization problem with minimum unsatisfied relations. It enables several user applications (UAs) to run on each user equipment (UE) at the same time, aiming to maximize the QoS per UA according to a set of context information like the channel state information. Then, a scheduling scheme is proposed to address the formulated problem, in which different strategies are designed for mmWave and microwave band. It can work effectively with regard to the number of satisfied UAs and QoS over these two kinds of frequency bands, and be converged in polynomial time.

Meanwhile, Omar *et al.* [171] evaluate the coverage and rate performance based on hybrid base stations at both mmWave and sub 6GHz bands, which are deployed in suburban environments such as university campuses. The actual buildings within the campus are modeled as blockages, and different densities of base stations are deployed according to different densities of outdoor users. It is verified that mmWave cellular networks are predominantly restricted by noise caused by large bandwidth, rather than interference-limited in conventional UHF networks. Combined with dense deployment of hybrid base stations, broader coverage and higher date rates can be achieved compared to stand-alone UHF networks.

Fig. 7. mmWave assisted communications in data center.

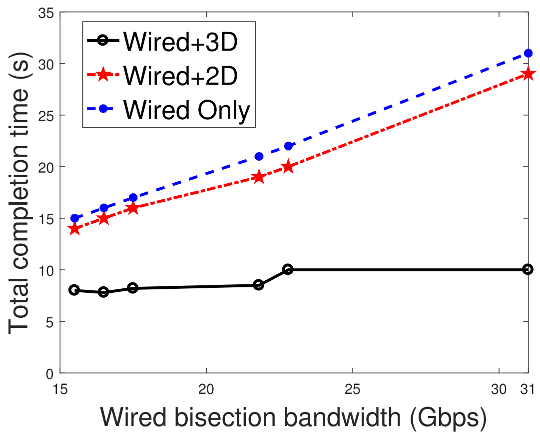

Fig. 8. Total Completion Time.

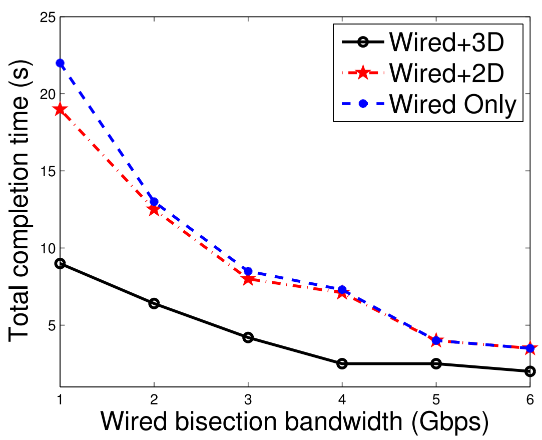

Fig. 9. Overall impact of adding beamforming links.

2) Combination of mmWave Communications and WiFi: Besides, research work has also explored the combination of mmWave and WiFi. As a critical technique in mmWave communications, beamforming has been employed to overcome the challenge caused by propagation characteristics. However, traditional beamforming training (BT), which is based on exhaustively searching all beam settings in all possible directions, will bring excessive delay and considerable power consumption. Accurate positioning can mitigate the overhead induced by mmWave link establishment, discovery, and association since mmWave networks are location-driven systems. Therefore, Mubarak *et al.* [172] develop a paradigm for mmWave small cell BT, discovery and association based on WiFi localization, especially under urban outdoor circumstances. Combined with WiFi localization, the complexity of link establishment and beam discovery can be substantially reduced compared to conventional schemes. Further, integrated with multi-band chipsets, Sur *et al.* [38] design an IEEE 802.11-compliant system named MUST, which can support seamless, high-speed mmWave links. Firstly, a WiFi-assisted 60GHz link adaptation scheme is designed for best beam prediction and rate setting in physical layer, yet without any time overhead. Then, a proactive blockage detection and switching algorithm is proposed to realize fast path switching when blockage occurs, which just brings a latency less than 10ms. MUST can acquire 25-60% throughput enhancement compared to state-of-art schemes, as well as nearly 2 orders of magnitude cross-band switching latency reduction.

Chandra *et al.* [173] realize intelligent coordination and cooperation between mmWave and WiFi from another point of view. They construct a 60GHz picocellular network architecture coupled with WiFi, which is referred to as CogCell. In particular, 60GHz mmWave communications are utilized for data delivery, while WiFi acts as the control plane because of its robust coverage. When mmWave links are in poor connectivity, WiFi can serve as a candidate to relay data traffic.

E. Conclusion of mmWave in Network Layer

In this section, we have introduced and summarized existing research work on network layer of mmWave communications. In the framework design for data centers, mmWave links are exploited to avoid traffic congestion and realize low latency delivery, thus building a more flexible and resilient data center network. However, due to the unreliability of wireless signals, especially for mmWave communications, a fault-tolerant framework is also needed to recover from packet loss or link failure. For cellular networks, frameworks should be more flexible since it is hard to deploy novel standards and techniques in LTE cellular networks. Hence, combined with SDN, which renders mmWave networks more like a software based architecture, rather than hardware based, flexible and resilient operations in future cellular networks can be provided to deploy new standards and techniques more quickly and conveniently.

When the network framework is fixed, an effective method to extend the coverage range and improve the robustness of mmWave communications is to deploy relay nodes. As mentioned above, the optimization of relay placement can be divided into two subproblems, respectively as RMRP and RMURP. However, when considering minimizing interference brought by these relays, this optimization scheme will be transformed into a NP-hard problem. Addressing the NP-hard problem always brings excessive time overhead. Therefore, on the premise of guaranteeing the system performance like throughput or coverage, the primary objective of designed algorithms is to reduce the time overhead, thus enabling to provide a backup link quickly when relay nodes are needed.

For routing schemes, the conventional target is to avoid traffic congestion, reduce the interference and delivery time. Nevertheless, problems become more complex in mmWave networks. For example, the routing scheme should be determined as soon as possible when encountering blockages, and NLOS links may occupy the majority component in the received signal. Consequently, mmWave links reflected by walls, furniture, and buildings should be taken into account when developing routing schemes. Utilizing the location of buildings, or indoor walls and furniture through environment perception or adding the reflection settings, routing strategies based on NLOS paths can be employed to overcome the blockage and interference problems, as well as reduce the time cost.

At last, we have presented certain research work on the combination of mmWave and LTE or WiFi to explore how to enhance the performance of mmWave networks leveraging existing LTE and WiFi networks. However, related studies just start. Several critical problems remain unresolved. For instance, the topology of mmWave base stations (BS) and LTE BSs or WiFi APs should be determined at the lowest expenditure while fully utilizing the robustness of LTE and WiFi signals. Next, efficient cooperative communication among mmWave BS, LTE BS, and the UE is also worth studying since available cooperative mechanisms are just tailored for simple systems.

VII. Research on Cross Layer

Naturally, research on cross layer has also been conducted in order to further optimize mmWave communication systems. Available literature is mainly dedicated to cross-layer resource allocation/optimization in mmWave communications.

A. Cross Layer Optimization Between MAC Layer and Physical Layer

MAC layer in mmWave communications requires to be redesigned so as to enable directional transmission, low delay, and super high data rate in physical layer. Therefore, Yildirim and Liu [174] propose a cross-layer neighbor-discovery scheme embedded in MAC layer, so as to adapt to directional links in 60GHz networks. Specifically, linear and circular polarization and their different responses to reflection in the physical layer are utilized to realize synchronization between the transmitter and receiver. The difference in response can judge whether there exists a LOS path between the receiver and transmitter. Thus, the direction of neighbour devices can be determined based on these obtained information. Further, Singh *et al.* [41] introduce a cross-layer model and design for 60GHz mmWave WPANs. The model accounts for two distinguishing features, respectively as directional mmWave links and blockage. According to the design, a diffraction-based model is built to determine mmWave link connectivity, thus in favor of the design of MAC layer protocol. It is shown that multi-hop MAC protocol based on these models is effective to maintain high network utilization with low overhead.

Different from interference analysis in conventional UHF networks, interference in mmWave networks is mainly caused by concurrent directional mmWave links. In [175], a cross-layer model is built for interference and coexistence analysis in mmWave WPANs, in which realistic 60GHz channel and high-speed physical layer design are taken into consideration. Based on the proposed model, it is observed that the interferer has to be angularly located at least 1.3 times the victim's beamwidth away from the victim's antenna pointing direction, so as to minimize the interference to the victim receiver.

B. Cross Layer Optimization Between Network Layer and Physical Layer

For cross-layer optimization between physical layer and network layer, Niu *et al.* [176] introduce a centralized controller through abstracting the control functions from the network layer to the physical layer. Thus, a logically programmable control center is built for task management in both the network and physical layers. Fine-grained control and flexible programmability can be realized in this system, facilitating interference management, spatial reuse, anti-blockage, QoS guarantee, and load balancing. Quantitative simulation results demonstrate its superior performance in terms of network throughput.

C. Cross Layer Optimization Between Transport Layer and Physical Layer

Although mmWave communications can provide huge bandwidth, how to fully exploit these resources at higher layers remains an open problem. The uncertainty of mmWave links has an enormous impact on the design of congestion control mechanisms at the transportation layer. Yet existing TCP strategies cannot effectively mitigate this effect. In result, Azzino *et al.* [177] develop a cross-layer strategy for adjusting the congestion window of uplink flows in mmWave cellular networks. The core of this scheme is to carry out an estimation of available data rate in physical layer, which is based on the actual resource allocation and SINR, then feed this information to the transport layer. It can shorten the transmission latency, avoid buffer overflow in the cellular stack, and recover quickly from TCP retransmission timeout.

D. Conclusion of Cross Layer Optimization

From above description, cross layer optimization implies that effective complementation between different layers in mmWave networks can provide a superior performance in terms of interference management, space utilization ratio, load balancing and so on. For cross layer optimization, the design of upper layers highly relies on the unique features and real-time state in physical layer. Meanwhile, by mapping some of the functions in upper layers to physical layer, fine-grained and flexible control can be realized in mmWave networks. These mechanisms will bring appealing advantages to boost the performance of mmWave networks.

VIII. Use Cases of mmWave Communications

By virtue of the aforementioned merits of mmWave such as huge bandwidth and narrow beam, it can be employed in many applications. The classification of mmWave use-cases is depicted as follows:

- mmWave communications in wearable devices;
- mmWave communications in virtual reality;
- mmWave communications in vehicular networks;
- mmWave communications in satellite communication;
- mmWave communications in 5G communication systems;
- Object imaging and tracking with mmWave technology;
- Object detection with mmWave technology.

Obviously, the reason why mmWave technique is applied in areas such as wearable networks, virtual reality, vehicle networks, and satellite communication and 5G networks lies in its huge bandwidth. Then, due to its small wavelengths and narrow beams, it can also be utilized for building high-accuracy imaging, tracking, and detecting systems.

A. mmWave Communications in Wearable Devices

Mobile wearable devices are widely used owing to great progress in miniature electronics fabrication technology and wireless communications. These high-end wearable devices include smartwatches, smart wristbands, smart glasses, motion trackers and so on. Conventional wearable devices around the user are shown in Fig. 10. Various kinds of wearable devices produce massive data traffic, which requires huge bandwidth to deliver for low latency.

Therefore, applying mmWave communications to connect these wearable devices is a promising candidate [178], [179]. Some released standards, including WirelessHD, IEEE 802.11ad, ECMA-387, IEEE 802.15.3c, have already provided several examples for short range mmWave communications. However, none of them gives an use-case of mmWave wearable networks. The task group working for IEEE 802.11 begins to lay down a criterion for mmWave-based wearable networks in public places. In these crowded scenes, high interference caused by the simultaneous use of wearable devices may be a major issue. Coordination among wearable devices is of great concern for interference reduction among wearable devices. But cooperative operation will bring high overhead and complexity to wearable networks. Meanwhile, the volatility of wireless connectivity has a significant influence on the performance of coordination.

Construction of a dense wearable network, in which devices of different users are independent, is an pressing problem to address [180]. Venugopal and Heath [28] propose an assessment methodology to assess the performance of mmWave-based indoor single-hop wearable networks, ignoring the coordination among wearable devices. In this system,

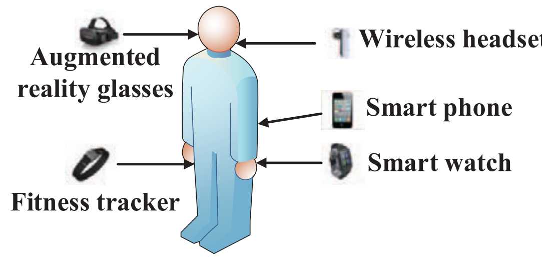

Fig. 10. Wearable devices around the user.

each device is equipped with mmWave antennas. Factors such as user density, orientation of user body relative to wearable devices, and location of users are evaluated to derive the best conditions for achieving optimal network performance. The results can shed light on understanding how these factors affect the performance of wearable networks and lay a good foundation for the design of dense wearable network.

Recent academic and industrial developments show that progress in energy density of contemporary lithium-ion batteries does not nearly comply with the Moores law. Therefore, it is time to emphasize the importance and urgency of reduction of power consumption [181]. "Green communication" has been proposed by research union such as GreenTouch. Optimization about network spectral and energy efficiencies are proposed in [182] and [183], meaning that a comprise between data rates and energy savings should be made. Galinina *et al.* [184] build a model for mmWave-based wearable networks. It highlights energy consumption under dense interference-limited scenes. In particular, energy efficiency is expressed as a simple equation for the arbitrary shape of the coverage area. Ultimately, through extensive simulations, it demonstrates that beamforming is favorable to the system efficiency primarily at high densities, and should be employed whenever collisions between data streams are detected.

B. mmWave Communications in Virtual Reality

Besides wearable devices, mmWave communications can also be served as the "bridge" between virtual reality (VR) headsets and VR server (VRS). However, nowadays' VR headsets usually should be connected to VRS by a cable, significantly limiting the user's mobility and then VR experience. The high data rate requirements from the links between VRS and VR headsets (multiple Gbps) preclude its candidates by traditional wireless technologies, such as WiFi and Bluetooth. Hence, Abari *et al.* [185] suggest to utilize mmWave technology to deliver multi Gbps data traffic between VRS and VR headsets. They develop a system framework combined with designed algorithms to overcome the frequent blockage problem in mmWave networks.

From another perspective, Kim *et al.* [186] derive a dynamic/adaptive algorithm to undertake the task of power allocation in the 60GHz mmWave transceivers, which are embedded in both VRS and VR headsets. This is because substantial data traffic delivery introduces significant power consumption in transceivers. The proposed scheme can allocate the power dynamically so as to realize time-average energy-efficiency for VR data transmission over mmWave links.

C. mmWave Communications in Vehicular Networks

Vehicles become a necessity for human beings in daily life. People don't just require vehicle quality and reliability. They expect to enjoy more vehicle services, such as collision detection, adaptive cruise control, lane change warning, and in-vehicle Internet access. It is reported that Internet-integrated vehicle applications will occupy 90% by 2020. Meanwhile, motivated by government polices, the market of connected vehicles is constantly growing. For example, U.S. Department of Transportations (DOT) National Highway Traffic Safety Administration (NHTSA) declared that it would deploy wireless communication technologies in light vehicles.

However, massive mobile data traffic produced by these services poses a great challenge to connected vehicular networks. Naturally, wireless techniques that can provide huge bandwidth are in demand. Lu *et al.* [187] present and compare conventional wireless technologies that can be applied to vehicular networks, including Bluetooth, ZigBee, Radio-Frequency Identification, Ultra-Wideband, and 60GHz mmWave. They also point out which type of communication scenarios should these wireless technologies be adapted to and potential problems about constructing vehicular networks. As shown in Fig. 11, vehicular networks mainly consist of vehicle-to-sensor on-board (V2S), vehicle-to-vehicle (V2V), vehicle-to-road infrastructure (V2R), and vehicle-to-Internet (V2I). Choi *et al.* [188] emphasize the motivations and challenges when employing mmWave communications for V2V and V2I applications. As one critical technique in mmWave communications, beamforming always brings considerable overhead. In this paper, through obtaining the information derived from the sensors or DSRC as side information for mmWave link configuration, the overhead caused by beam alignment can be substantially cut down.

For in-vehicle communications, detailed propagation measurements about mmWave channels are carried out in [189] and [190]. In particular, they have made a comparison between in-car UWB channels and 60GHz mmWave channels. In addition, large-scale and small-scale parameters of channels are evaluated in different antenna configurations, polarizations and more. Measurements are conducted in 60GHz in-car wireless communication systems with omni-directional antennas. It proves that antenna alignment does not have much significant influence on UWB and 60GHz vehicular network performance, especially for wide main lobe of antenna patterns. Meanwhile, RMS delay increases from 4nsec to 8nsec when the number of passengers increases from 1 to 4. Therefore, the number of passengers should be taken into consideration when building 60GHz and UWB in-car communication systems. Finally, the measured mmWave path loss exponent, which is equal to 2.08, is larger than that of microwave band.

For off-vehicle communications, Tassi *et al.* [29] model a mmWave vehicular network on the highway and characterize its fundamental link budget metrics. Vehicles are served by

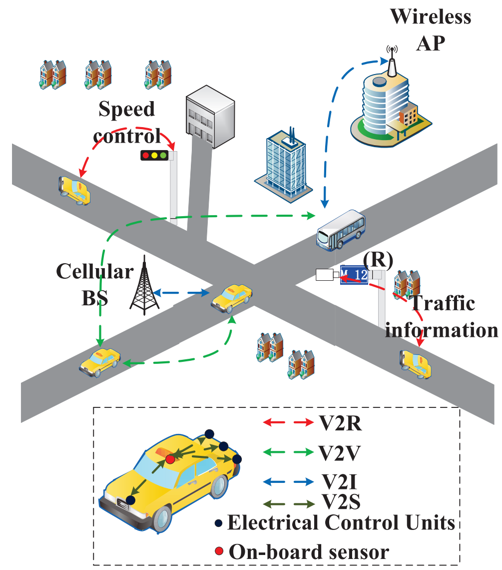

Fig. 11. Overview of connected vehicles.

mmWave base stations deployed alongside the road. They build a theoretical model to evaluate the mmWave vehicular network in a special setting, where heavy vehicles (such as buses and lorries) are in slow lanes, acting as obstacles. Based on stochastic geometry, the Signal-to-Interference-plus-Noise Ratio (SINR) outage probability and rate coverage probability can be derived. Analysis shows that smaller antenna beamwidths and BS densities have negligible influence on improving the SINR outage probability and the rate coverage probability.

D. mmWave Communications for Satellite Communications

Owing to severe attenuation induced by atmospheric absorption, frequencies around 60GHz are not the suitable candidates for high-speed transmission over satellite networks. Hence, W-band corresponding from 75GHz to 110Ghz is proposed to satisfy the high-speed and stringent quality-of-service (QoS) requirements of next-generation digital communication services, which can not be realized in currently saturated bandwidth portions (Ku and Ka bands) [191]. Detailed mmWave frequencies for terrestrial and satellite communications allocated by Federal Communication Commission can be captured in Table VI.

In [192], the data collection experiment of the scientific mission named DAVID (Data and Video Interactive Distribution) launched by Italian space agency investigate the utilization of W-band for telecommunications. Specifically, mass data collected from remote or virtually remote sites can be realized based on W-band links in a time window of several minutes. Based on these experimental results, Lucente *et al.* [193] explore the critical aspects concerning W-band satellite communication. Tradeoff should be made related to hardware components, the performance of which is restricted by involved distortions and increased noise. Specifically, phase noise caused by low-cost high-frequency oscillators will seriously impair carrier recovery if spectrally-efficient modulations without residual carrier are

TABLE VI
mmWave Frequency Allocation Based on FCC

Service	Frequency(GHz)
Fixed terrestrial communications	31.0-31.3, 36.0-40.0, 40.5-43.5, 46.9-47, 47.2-50.2, 50.4-52.6, 55.78-66, 71-75.5, 81-86, 92-95, 102-105, 116-134, 149-164, 168-182, 185-190, 200-217, 231-241, 265-300
Mobile terrestrial communications	36.0-40.0, 40.5-43.5, 45.5-47, 47.2-50.2, 50.4-52.6, 55.78-71, 71-75.5, 81-86, 92-100, 116-142, 149-151, 168-182, 185-200, 200-217, 231-241, 252-300
Fixed satellite	30.0-31.0, 37.6-41.0, 42.5-45.5, 47.2-50.2, 50.4-51.4, 71.0-75.5, 81-84, 92-95, 102-105, 149-164, 202-217, 231-241, 265-275
Mobile satellite	30.0-31.0, 39.5-40.5, 43.5-47, 50.4-51.4, 71-74, 81-84, 95-100, 134-142, 190-200, 252-265
Earth exploration satellite	31.3-31.8, 36.0-37.0, 50.2-50.4, 52.6-59.3, 59.0-59.3, 65.0-66.0, 86-92, 95-100, 100-102, 105-126, 150-151, 164-168, 174.5-176.5, 200-202, 217-231, 235-238, 250-252,
Inter-satellite	32.0-33.0, 54.25-58.2, 59.0-71.0, 116-134, 170-182
Broadcasting satellite	40.5-42.5, 84-86
Radio navigation satellite	45.5-47, 66.0-71.0, 134-142, 190-200, 252-265
Amateur satellite	47-47.2, 75.5-76.0, 77.0-81.0, 142-149, 241-250

employed for digital transmission. Thus, a modulation scheme with residual carrier are always suggested to be adopted, which should also account for Doppler estimation and compensation in satellite communication.

Furthermore, the exploitation of W-band to provide high-quality HDTV broadcast service is explored in [194]. Considering typical W-band impairments such as phase noise, rain attenuation and non-linearities, it is verified that W-band based satellite communication can support top-quality services with the increased number of channels compared to DVB-S2 standard using Ku and Ka band. Further, Mukherjee *et al.* [195] concentrate on the optimization of W-band communication links and derive the received SNR thresholds for DVB-S2 adaptive coding and modulation when applying extremely high frequency (EHF) links.

Aiming at wider carrier frequency, including Q, V, and W bands, Rossi *et al.* [196] conduct the Alphasat Aldo Paraboni communication experimental campaign hosted as piggy-back on a GEO satellite. This is the first time for satellite communication to be carried out with adaptive propagation impairments mitigation techniques, channel estimation, adaptive coding and modulation, and uplink power control and space diversity. The performance of channel estimation depends on the window length. For instance, when setting the window length to 5, the slope absolute value of SNR can exceed 0.1dB in many cases, while it is less than 0.5 if the window length is set to 25. These obtained results can be utilized to set the maximum and minimum thresholds of hysteresis control loop, thus adapting to channel variations.

E. mmWave Communications in 5G Communication Systems

The next generation cellular system (5G) is expected to deliver enormous wireless data traffic produced by various bandwidth hungry applications. Despite that 5G is still in its infancy, a great deal of pioneering research work on 5G communications has already been carried out. For instance, 3GPP NR, the first attempt to realize the commercialization of 5G visions in mmWave cellular networks, is developed by the 3GPP [129]. The fundamental technologies including numerologies, channel coding, and MIMO are redesigned in this standard. Here, we mainly introduce the deployment of high-density networks, backhaul, cognitive radio networks, and multi-hop cooperative systems.

1) High-Density Networks: Ultra-dense network (UDN) is regarded as a key technology for realizing gigabit-per-second data rate, high energy efficiency, and low latency in 5G communication systems. To implement UDN, it is essential to construct a reliable, cost-effective, gigahertz bandwidth backhaul connecting macrocell base stations (BS) and associated small-cell BSs. However, applying conventional optical fiber as backhaul is costly to deploy and maintain. Therefore, wireless backhaul, especially mmWave backhaul, is a potential candidate. Gao *et al.* [88] evaluate the feasibility and identify the challenges of mmWave massive-MIMO-based backhaul for UDN. Using large-scale mmWave antenna arrays, they implement mmWave wireless backhaul for future 5G UDN. In particular, a hybrid precoding/combining scheme and associated CS-based channel estimation algorithm are combined to ensure that macro cell BS can simultaneously support multiple small-cell BSs with multiple streams. Nevertheless, it does not consider handovers between BSs, thus extending the handover delay significantly.

Taori and Sridharan [30] propose a point-to-multipoint (PMP) architecture as a scalable approach. BSs enabling point-to-multipoint can communicate with several BSs. Hence, all BSs can exchange control information with neighboring BSs for interference coordination or handover coordination, contributing to the reduction of handover delay. An in-band method allows access links such as BS to mobile station and backhaul links such as BS-to-BS to be multiplexed on the same frequency band, facilitating the spectrum and hardware reuse. Then, cost can be further cut down.

2) Backhaul: During the past few years, research pertaining to the application of mmWave communications for 5G network backhaul has been widely investigated [197]–[199]. For instance, in 2014, a collaborative project is launched for mmWave based backhaul networks. However, compared to existing backhaul leveraging microwave frequency band, several challenges are posed when employing mmWave backhaul. Firstly, mmWave based backhaul networks cover a limited coverage range. Secondly, mmWave based backhaul networks are less reliable due to its susceptibility to blockages. Finally, owing to directional transmissions, broadcast control mechanism is not suitable for mmWave backhaul. Hence, Singh *et al.* [200] develop a stochastic geometry based mmWave cellular model, realizing resource sharing between access and directional backhaul links. Based on self-backhaul, different combinations of wired backhaul fraction and BS density can provide the same QoS.

In the meantime, in order to explore the influence of diffraction on mmWave backhaul networks, Malila *et al.* [201] design a NLOS backhaul framework for densely deployed small cells. Based on the Single Knife Edge diffraction model, the diffraction loss can be computed when encountering blockages. It is verified that fine-grained alignment between antennas based on artificial intelligence is indispensable when applying NLOS backhaul networks.

Yet, the cost of mmWave backhaul network construction has not been evaluated by above research work. Therefore, Semiari *et al.* [202] propose a multi-hop mmWave backhaul network framework, in which there exist several mobile network operators (MNOs). Base stations work in a collaborative manner to determine multi-hop mmWave links over backhaul networks belonging to different MNOs, and then allocate resources among these links. The determination process can be divided into two stages: A multi-hop network formulation stage and a resource management stage, accounting for mmWave channel features and economic factors. The proposed framework demonstrates a high performance in terms of average sum rate and backhaul sum rate with manageable complexity. In addition, it provides an insight on the tradeoff between efficiency and cost of the cooperative mmWave backhaul network for MNOs.

3) Cognitive Radio Networks: In order to enhance spectral efficiency, cognitive radio network (CRN) has been suggested to be employed in 5G mmWave systems. In CRN, an unlicensed system can utilize the same spectrum resources with the licensed primary system, either based on an interference-free mode or an interference-tolerant mode [203]. This operation can be performed according to proper spectrum monitoring using energy detection, which is referred to as spectrum sensing. However, spectrum sensing in cognitive radio networks is affected by the spatial and time characteristics of radio channel that highly depends on the local environment and frequency of operation. Hence, efficient spectrum sensing strategies are needed in mmWave bands. Owing to severe attenuation, especially rain fading, Papanikolaou *et al.* [204] build an analytical physical-mathematical model to evaluate the influence of rain attenuation on the probability of energy detection, which can be expressed as a function of log-normal distribution in linear scale. It is verified that in heavy rainy regions, the energy detection probability for the same threshold declines with the decrease of transmitting power.

In the meantime, densely deployed small cells is an effective methodology to considerably improve the spectrum resources, and then the data rate and capacity of mmWave networks. However, this mechanism will also result in spectral leakage and substantial interference. Therefore, the adaption of subcarriers can effectively avoid spectral leakage and interference among these cells [108]. It can be realized by obtaining the cognitive information from wavelet packet based spectrum sensing (WPSS) and lowering sidelobes using wavelet-based filter bank multicarrier modulation. WPSS shows a higher performance in terms of power spectral density, detection probabilities, and false alarm compared to Fourier-based spectrum sensing.

4) Multi-Hop Cooperative Systems: Multi-hop mmWave cooperative systems are essential to connect multiple piconets. Thus, fast route discovery can be effective to support multimedia applications with high data rate [205]. A scheduling scheme is presented in [206], so as to minimize the delay time caused by link scheduling in multi-hop mmWave networks. The optimization problem can be formulated as a constrained binary integer programming (BIP) problem according to the mmWave interference model and Markov chain based blockage model. The BIP problem can be addressed by the proposed scheme, where an optimal streaming path is selected for each data flow, followed by the link scheduling optimization to maximize the throughput at each time slot.

Meanwhile, as a promising candidate for 5G communication backhaul, multi-hop relay plays a significant role in backhaul data traffic delivery, especially when encountering blockages. Sahoo *et al.* [207] develop a highly flexible scheme for frame reconfiguration, which can adapt to dynamic backhaul traffic. Subsequently, a heuristic strategy based on adaptive power allocation is designed for multi-hop relay, accounting for the traffic load at each base station. The proposed scheme shows a superior performance in terms of network capacity and number of successful flows in comparison with existing optimal schemes.

F. mmWave Communications for Imaging and Tracking

Great progress has been made in radio-based object imaging and tracking based on conventional microwave band (2.4GHz or 5GHz) [208]–[211]. For example, automatic driving vehicles, UAVs, robots are gradually applied in daily life and military fields. One of the greatest challenges for these autonomous devices is the design of environmental sensing system. However, existing solutions with microwave band lack of accuracy or need substantial expenditure. It will bring multifold advantages if mmWave technology is adopted in imaging and tracking systems. Firstly, the vast majority of 60GHz mmWave beams can be reflected by objects larger than the wavelength. Secondly, miniaturized antenna arrays for mmWave communications are small enough to be integrated into contemporary smartphones and tablets. Thirdly, highly directional 60GHz links can be realized, contributing to interference reduction and a novel dimension for object imaging and tracking. The comparison between conventional microwave localization and mmWave tracking is shown in Fig. 12.

In [212], commodity 60GHz mmWave chipsets are embedded into a mobile radar imaging system, which is referred to

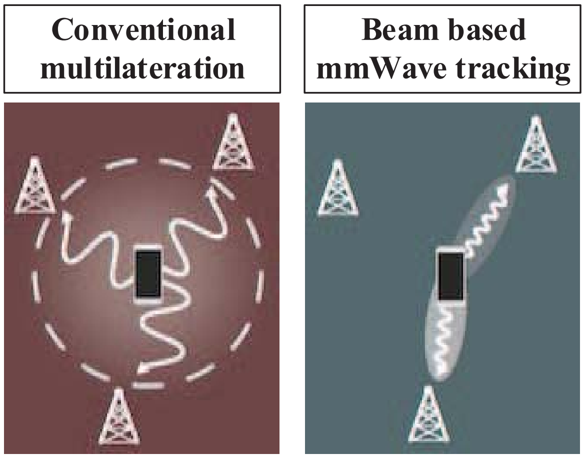

Fig. 12. Conventional wireless localization v.s. Beam based mmWave tracking.

as Nightcrawler. In this system, mobile devices are regarded as receivers and decoupled transmitters are embedded in the infrastructure or "deployed" on-demand by the user. As users move, a virtual antenna array with large aperture can be emulated. Based on the strength and phase of the received signal, high precision sensing can be achieved. Nevertheless, it employs synthetic aperture radar (SAR) to derive object position and boundary, thus ignoring the influence of noise. Consequently, poor precision will occur in Nightcrawler practically if device positioning errors are relatively large. This is because device positioning errors have an significant influence on the accuracy of phase information.

In order to overcome this shortcoming, Zhu *et al.* [213] propose a 60GHz imaging algorithm–RSS Series Analysis, which only utilizes received signal strength (RSS) measured along the device's trajectory to image an object. It introduces the mirror and lens equation to obtain information about object surface orientation and curvature. Next, an RSS model for surface reflection is built to compute the surface boundary of objects. Finally, according to a reflection loss table, which is a collection of values as a function of surface material and angle of incident [214], potential surface materials can be identified. The proposed algorithm can achieve higher precision of centimeter-level across all the objects compared to SAR scheme. In the meantime, it exhibits strong robustness against noise in device position and trajectory tracking.

For the design of tracking, Wei and Zhang [215] design mTrack, a tracking system to track a passive writing object with sub-centimeter accuracy. A transmitter sends 60GHz mmWave signals and a handheld device roams on a trackpad area. When the object moves, the reflected signal's path length undergoes changes, leading to phase changing in turn. Two directional receivers record the received signal strength (RSS) and phase information. Tx and two Rxs are placed at (2a,2b), (a,2b) and (2a,b), respectively. Both a and b are known. Based on Received Signal strength (RSS) and phase (relative to Tx), they propose two novel algorithms to realize accurate localization and tracking despite existence of background interference.

G. *mmWave for Detecting*

In most airports, security personnel need to check the conditions of runways manually several times every day, resulting in the delay of aircraft traffic and substantial overhead. In addition, visual inspection may bring detection errors in bad weather conditions. Promoted by Air France Concorde crash happening in July 2000 [216], accurate detection of Foreign Object Debris (FOD) on airport runways gains more and more attention. According to related report [217], the FOD detection system should have the ability to detect a metal cylinder of 2.54 cm height and diameter in a 60m range, requiring the detection system to perform 1000 times higher than the accuracy of automotive radar. As a promising candidate, mmWave is suggested to be applied to FOD detection system. Based on a 94GHz mmWave radar prototype, Kohmura *et al.* [218] propose a FOD detection system for airport runways. In the system, Radio over Fiber (RoF) links are utilized to overcome the attenuation problem caused by wireless transmission, meaning that links between radar front-ends and signal source are connected by optical fibers with much less transmission loss. By massive experiments, it shows that amplifiers can compensate RoF attenuation properly and thus RoF links perform well in several kilometers distance of airport applications. Instead of 94GHz mmWave, Essen *et al.* [219] propose to employ 220GHz mmWave to detect FOD. Compared to conventional radar systems, it brings advantages as follows:

- There is almost no interference between high frequency radar systems and other existing radar systems;
- Due to much shorter wavelengths, higher precision for ROD detection can be realized;
- Due to a greater relative roughness of the scattering target objects, discrimination from clutter is easier and dependency of the signature on aspect angle is negligible.

In the railway system, detection for FOD is also necessary. Furthermore, handover in the railway system occurs much more frequently than conventional 4G communication system, which results in the decline in throughput. Aiming at capacity enhancement and FOD detection, both omnidirectionally radiated licensed lower frequency bands is responsible for the delivery of critical signaling and data, while mmWave bands are utilized for transmitting large-volume communication data and performing environment detection based on beamforming [220]. Relying on the cloud radio access network (C-RAN) architecture, lower frequency band radio remote units (RRUs) and mmWave band RRUs establish the connection with a building baseband unit (BBU) pool by high-speed backhauls. Numerous results verify that the proposed integrated network can improve the network capacity and realize high resolution detection.

H. *Conclusion of mmWave Use Cases*

In this section, we have classified and discussed the application fields of mmWave.

- We have introduced the application of mmWave communications in wearable networks. Available literature mainly focuses on interference minimization and robustness enhancement. However, based on highly directional mmWave links, beam alignment and tracking schemes are crucial in the design of wearable networks due to body movement. Therefore, efficient beam tracking schemes should be developed based on the extraction of motion characteristics. In the meantime, complex wearable networks such as wearable devices located at different heights should also be investigated since it is more in line with the actual environments.

- When applying mmWave communications in virtual reality, it brings the flexibility of operation as well as uncertainty. In the indoor environments, human activities have an enormous influence on the game experience. Consequently, NLOS links induced by wall reflection can be utilized when human body blocks the LOS link between the VRS and VR headset. Besides, adaptive transmitting power allocation based on physical layer status is a promising research direction since the quantity of electricity in the headset is limited.
- For mmWave vehicular networks, existing studies can be divided into V2V, V2I, V2R, and V2S. In V2V communications, there exist several challenges, such as link maintenance in a moving state, interference, blockages, and target vehicle outside of the transmission range. When vehicles are in a moving state, the mmWave beam established between two vehicles will be prone to misalignment. Therefore, instantaneous driving information such as speed, direction should be exchanged between these two vehicles, thus constructing a robust mmWave vehicular network. Meanwhile, when building a novel mmWave link, corresponding mechanisms should be developed to minimize the interference to other established mmWave links. Then, strategies based on the combination of carrier sensing and directional links are an effective method to reduce interference. Finally, if the current link is blocked or the target vehicle is outside of the coverage range, a conventional solution is to leverage multi-hop communication. Naturally, the selection strategy of relay vehicles should be designed based on criterions like interference and delay minimization, or a center controller like cloud infrastructure is set to enable direct connection between any two vehicle pair. In V2I communications, pressing challenges also exist. A typical problem in V2I networks lies in mobility management. High speed and directional beams can easily render mmWave links between BSs and vehicles disconnected. Appropriate beam adaption algorithms can be useful to maintain the established mmWave link. Another traditional problem is frequent handover in mmWave V2I network. Existing methodologies can be divided into two kinds: Multi-connectivity and utilization of LTE or WiFi. For multi-connectivity, the number and selection of connected base stations, the maintenance of multi links, and the handover mechanism between these links need in-depth research. For combination with LTE or WiFi, the topology of mmWave BSs and LTE BSs or WiFi APs should be determined with the lowest expenditure. Detailed cooperation mechanisms between different kinds of base stations also should be designed to provide efficient communication.
- For mmWave satellite communication, problems will become more challenging compared to terrestrial communication. Available integrated circuits embedded in satellites can not provide high computing power, thus lowering the digital processing capability of satellites. In the meantime, the performance of digital devices in satellites is remarkably influenced by solar radiation and single particle effect. Therefore, the primary task of realizing mmWave satellite communication is to improve the reliability and to decrease the computing power of the digital devices. Subsequently, with the increase in frequency, the transmission power of satellite components will be reduced, resulting in the power waste and enormous heat dissipation. An effective solution to address this problem is to improve the transmitted power on the ground.
- Due to the huge bandwidth that mmWave communications can provide, it will be employed as the wireless technique in future 5G networks. In order to satisfy the requirements of 5G such as high data rate, large capacity, and short delay, there exist several main problems that need to be addressed. Firstly, the cost and energy consumption for 5G networks should be reduced since densely deployed mmWave base stations and high data rates will bring much more expenditure and energy consumption in comparison with existing LTE networks. Secondly, future 5G networks will be deeply integrated with IoT. Hence, it implies that 5G network should meet various requirements of IoT services. Thirdly, it can be foreseen that there will be an explosive growth of the number of mobile terminals. Providing friendly user experience and various applications is the key to 5G networks.
- mmWave communications have been utilized for realizing high accuracy imaging, tracking and detecting systems because of its small wavelengths and narrow beams. Nevertheless, these systems are developed in very simple scenarios, even without considering obstruction. For future work, when existing LOS links are broken, we can exploit the received signals from NLOS paths to determine object position and trace.
- In the near future we can imagine that optical wireless communication (OWC) [227] and visible light communication (VLC) [228] could be used as complementary technology to mmWave channel. The optical technology could be used in scenario that required higher capacity, higher security or for specific application such as high capacity back haul, satellite communication, in door communication, or in some case in automotive technology.

IX. AVAILABLE RESOURCES ABOUT MMWAVE COMMUNICATIONS

Coupled with the rapid development of mmWave, a great deal of research work about mmWave has been carried

TABLE VII
COMPARISON OF COMMONLY USED MMWAVE FREQUENCIES

Frequency	Feature	Application
28GHz	High available spectrum bandwidth and security, relatively small attenuation	Long distance communications
39GHz	Large communication capacity, good security and confidentiality	Long distance communications
60GHz	Rich spectrum resources, high allowable transmit power, strong anti-interference ability, high attenuation	Short distance communications
73GHz	High attenuation on rainy days, wide range of available continuous bandwidth, large communication capacity	Long distance communications
77GHz	Narrow beam, ability of strong penetration and working at all-weather situation and all-day except rainy days, large bandwidth, high measurement accuracy and resolution and small volume	Radars

out. According to these studies, we make a classification and summary of available resources, which can be divided into mmWave books, commonly used mmWave frequencies, mmWave based protocols, and experimental platforms.

A. Related Books About mmWave Communications

Nowadays, massive papers and books have been published owing to the research upsurge of mmWave communications. These literature elaborates on various aspects of mmWave technology. For example, some books mainly introduce the design and development of mmWave hardware [221]–[223], including the design of mmWave antennas and advanced silicon processing technologies. Specifically, the book of [223] introduces the components of low-power 104GHz mmWave devices and the performance evaluation of a customized 90nm device when embedded into a low-power 60GHz amplifier. The book of [221] carries out an in-depth analysis of mmWave silicon technology, including CMOS, SiGe, and architectures of active and passive mmWave devices. Furthermore, based on existing silicon-based cases, it introduces the design methodology of highly integrated mmWave transceiver. An introduction to mmWave microstrip antennas and printed circuit antennas is presented in [222], as well as design of these kinds of mmWave antennas.

The book of [224] provides an important insight into mmWave communications between vehicles. In particular, detailed channel measurements and analysis in vehicular networks are carried out, especially for physical layer and medium access control layer. Extensive simulations can identify the influence of degrees of directionality and blockages on the performance of mmWave vehicular communications.

Meanwhile, some books introduce and analyse mmWave technology from a more comprehensive view [225], [226]. As one of the most outstanding work in mmWave communications, the book of [225] is a useful tool for readers to gain a more profound and thorough understanding of mmWave. It introduces the conventional applications of mmWave, including WLANs, WPANs, cellular networks, data centers and so on. Meanwhile, it provides an in-depth analysis of digital communications and mmWave fundamentals, which can divided into design of antennas and antenna arrays, analog circuit design, and baseband circuit design. Finally, it reviews higher-layer (above the physical layer) design problems and standardization efforts for 60GHz wireless communication systems.

B. Commonly Used Frequencies in mmWave Communications

In the vast majority of research work, there exist several typical mmWave frequencies commonly used. As one of the most extensively employed frequency, 60GHz mmWave radio with unlicensed 7GHz band available is a promising candidate for mmWave communications. Directional links and narrow beams can be easily obtained in the 60GHz band, thus realizing high resolution and super anti-interference. Yet it can only be applied to short distance communications because of severe attenuation and hard penetration. 28GHz band is another commonly utilized frequency. It is usually employed under the scene of long distance communication due to relatively slight attenuation. By virtue of narrow beam, the ability of working under all weather conditions except rainy days, 77GHz mmWave is regarded as a critical component of automotive radar systems. Detailed comparison of these frequencies is shown in Table VII.

C. mmWave Based Protocols

According to [9], up to now, there exist several international standards for mmWave communications in WLANs, WPANs, and cellular networks. They are WirelessHD, ECMA-387, IEEE 802.15.3c, WiGig, IEEE 802.11ad, and 3GPP NR, respectively. Next, we will briefly elucidate these standardizations.

1) WirelessHD: As the first global wireless standard for 60GHz mmWave, WirelessHD mainly targets short range high-definition multimedia streaming applications. Backed by several major mmWave market players, such as Broadcom, Intel, LG Electonics, Samsung, Sony and so on, WirelessHD 1.0 is first released in January 2008. Then, in January 2009, its compliance specification is issued. It is a private or closed 60GHz WPAN standard, supporting up to 3.807Gbps data rate.

2) ECMA-387: ECMA-387 was proposed in December 2008 for the first time. It provides the architecture for

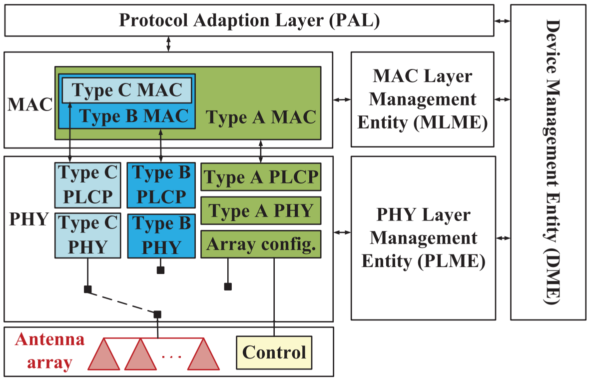

Fig. 13. Protocol structure of ECMA-387.

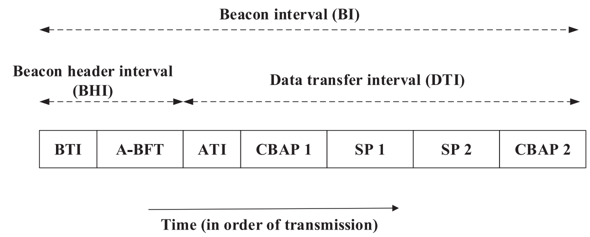

Fig. 14. Example of beacon interval format.

all potential WPAN network topologies, rather than high-definition wireless streaming video. The structure of ECMA-387 is shown in Fig. 13 [225]. It defines three distinct types of devices according to performance, complexity, and power consumption. They are Type A devices, Type B devices, and Type C devices. From this picture, we can see that each multiplexer makes a decision about which PHY to operate under. In MAC layer, Type A MAC is a subset of Type A MAC and it also contains Type C MAC. Meanwhile, it supports the strategy of channel bonding, the core of which is to multiply the throughput up to a factor of four. Based on ECMA-387, we can realize up to 6.35Gbps data transmission speed, which is much faster than that of WirelessHD.

3) IEEE 802.15.3c: As an extension of IEEE 802.15.3 WPANs, IEEE 802.15.3c is first designed for the physical layer of mmWave WPANs in September 2009. Owing to the unique features of mmWave communications, some key functionalities in MAC layer have been added to it. In MAC layer, WPAN ad hoc networks are defined by piconets, which consists of a single piconet coordinator (PNC) and several devices (DEV). Network time is divided into multiple superframes. Superframe can be further divided into the beacon period (BP), the contention access period (CAP), and the channel time allocation period (CTAP). During the beacon period, PNC completes network synchronization and data transmission transpires between two DEVs. During the contention access period, devices send transmission requests to the PNC. During CTAP, TDMA is applied to allocate time slots for scheduling flows. In the physical layer, a common mode and three different operating modes are utilized to ensure high performance. Based on the common mode, low-directional (omnidirectional) antennas can be employed and scanning beams can be used to seek weaker stations. Three operating modes, respectively as single carrier mode (SC-PHY), high-speed interface mode (HSI PHY), and audio/visual mode (AV PHY), can realize operations in a low-complexity, efficient, flexible way.

4) WiGig: WiGig is first put forward in December 2009 by a private industry consortium, including Advanced Micro Devices, Broadcom Corporation, Cisco systems, Microsoft Corporation and so on. It combines the advantages of WirelessHD with traditional WiFi Technology. As the extension of MAC layer, it can support up to 7Gbps data rate in WLAN topologies. In comparison to WirelessHD, WiGig can be fused with WiFi. Therefore, it can be downwardly compatible with 802.11n. Furthermore, WiGig can be applied to some other areas, not just home wireless HD transmission market.

5) IEEE 802.11ad: As the future of WLANs, IEEE 802.11ad defines a new physical layer for 802.11 networks in the 60GHz mmWave band. Based on multiple-antenna beamforming technique, the salient feature of IEEE 802.11ad is new directional multi-gigabit (DMG) PHY, which can support up to 7Gbps data rates. The time of DMG channel access in IEEE 802.11ad is divided into beacon intervals, which is elucidated in Fig. 14. Service set control points (PCP) or access points (AP) partition each interval into distinct access periods, respectively as Beacon Transmission Interval (BTI), Association Beamforming Training (A-BFT), Announcement Transmission Interval (ATI), and Data Transfer Interval (DTI). In particular, during BTI, a PCP or AP transmits beacons in order to establish the beacon interval and access scheduling, synchronize the network, exchange access and capability information, realize beamforming training. A-BFT is a beamforming training period reserved to train the PCPs or APs. ATI is the time period for exchange of request and response frames between the PCP/AP and other stations. As the most important period in the beacon interval, data frames exchange among all stations.

In the physical layer, four procedures are able to format 60GHz waveforms. They are control PHY (CPHY), OFDM PHY, Single-Carrier (SC) PHY, and low-power SC-PHY. Specifically, CPHY can ensure compatibility among all DMG IEEE 802.11ad devices regardless of the vendor implementation. OFDM PHY allows multiple carrier operation and consequently improves spectral efficiency. SC PHY makes a balance between spectral efficiency and implementation complexity. At last, LP SC-PHY is in charge of minimizing implementation complexity and power consumption.

6) 3GPP NR: Supported by 3GPP, 3GPP NR is the first standardization attempt to bring mmWave communications into commercialization for the next generation cellular networks. Since mmWave communications vary from conventional microwave communication, critical techniques including numerologies, channel coding, and MIMO in physical layer have been redesigned, in order to satisfy the key performance indicators like high data rates, real traffic capacity, energy efficiency, small latency, and mobility.

TABLE VIII
CLASSIFICATION OF MMWAVE EXPERIMENTAL PLATFORMS

Experimental Platform	Application scenario	Utilization
FMCW radar system	Airport runways and railways	Detection of foreign object debris
WiMi, OpenMili, OpenMili 2.0	Mobile communications	A custom-built 60GHz software radio platform
COBRA-220 radar	Airport	Delivery of position information and classification of debris
Wilocity 60GHz chipset	Indoor mobile communications	60Ghz radio production
HXI gigalink 6451 60GHz radios	Outdoor communications	60Ghz radio production
OPNET modeler	Wireless personal area network (WPAN)	Performance evaluation of WPANs
Measurement facility for RF circuity and on-chip antennas	mmWave antenna	The design of mmWave antenna
HIRATE channel sounder setup and R&S test and measurement equipment	Indoor communications	Channel characterization measurements
NI mmWave transceiver system	mmWave transceiver	High performance mmWave head
Keysight 5G testbed	5G communications	5G system evaluation
NIST over-the-air (OTA) testbed	5G communications	OTA measurements for mmWave devices

D. Experimental Platforms for mmWave

Various kinds of experimental platforms are set up to perform mmWave experiments. For example, FMCW radar system and COBRA-220 Radar can be employed to detect and classify debris in airports. Wilocity 60GHz chipset can be utilized to measure indoor communications while HXI Gigalink 6451 60GHz radios can be applied to measure outdoor communications. Based on the platform of SEMCAD X simulation model and measurement facility, we can evaluate the performance of mmWave antennas and RF circuit. Detailed classification of experimental platforms are shown in Table VIII.

X. CONCLUSION

In this paper, we have reviewed and summarized available literature about mmWave communications, mainly including research in physical layer, research in MAC layer, research in network layer, cross layer optimization, and use cases of mmWave communications. Critical problems and future work are identified for each section. In addition, we list existing resources related to mmWave technology, including mmWave books, mmWave protocols, commonly used carrier frequencies, and experimental platforms. Although extensive research on mmWave communications has been carried out, there still exist several pressing problems to be solved in the future. For hardware design in mmWave communications, antenna arrays with high gain should be proposed to enhance the network coverage. Meanwhile, cost-effective mmWave circuits such as PA are also needed to combat phase noise and nonlinear distortion. Efficient MAC protocols are necessary to reduce interference among concurrent links and thus improve capacity of mmWave WLANs. For mmWave cellular networks, novel MAC protocols are required to handle initial access, mobility management, and handover. We also should design new relay deployment strategies to enhance the coverage, as well as free from the influence of obstacles even in a highly dynamic environment. As a promising technique in connected vehicles, detecting and imaging field, it is forecasted that mmWave will be applied into more areas.

With the advent of the 5G Era, we believe that mmWave communications will gain more and more attention. We hope that this survey will serve as a useful guidelines for interested individuals to have a quick and comprehensive understanding of mmWave.

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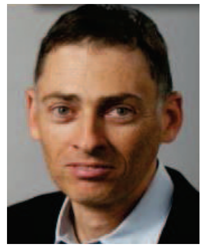

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