A Survey of Millimeter Wave (mmWave) Communications for 5G: Opportunities and Challenges

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Abstract—With the explosive growth of mobile data demand, the fifth generation (5G) mobile network would exploit the enormous amount of spectrum in the millimeter wave (mmWave) bands to greatly increase communication capacity. There are fundamental differences between mmWave communications and existing other communication systems, in terms of high propagation loss, directivity, and sensitivity to blockage. These characteristics of mmWave communications pose several challenges to fully exploit the potential of mmWave communications, including integrated circuits and system design, interference management, spatial reuse, anti-blockage, and dynamics control. To address these challenges, we carry out a survey of existing solutions and standards, and propose design guidelines in architectures and protocols for mmWave communications. We also discuss the potential applications of mmWave communications in the 5G network, including the small cell access, the cellular access, and the wireless backhaul. Finally, we discuss relevant open research issues including the new physical layer technology, software-defined network architecture, measurements of network state information, efficient control mechanisms, and heterogeneous networking, which should be further investigated to facilitate the deployment of mmWave communication systems in the future 5G networks.

Index Terms—millimeter wave communications 5G survey directivity blockage heterogeneous networks millimeter wave communications 5G survey directivity blockage heterogeneous networks

I. INTRODUCTION

With the explosive growth of mobile traffic demand, the contradiction between capacity requirements and spectrum shortage becomes increasingly prominent. The bottleneck of wireless bandwidth becomes a key problem of the fifth generation (5G) wireless networks. On the other hand, with huge bandwidth in the millimeter wave (mmWave) band from 30 GHz to 300 GHz, millimeter wave (mmWave) communications have been proposed to be an important part of the 5G mobile network to provide multi-gigabit communication services such as high definition television (HDTV) and ultra-high definition video (UHDV) [1], [2]. Most of the current research is focused on the 28 GHz band, the 38 GHz band, the 60 GHz band, and the E-band (71–76 GHz and 81–86 GHz). Rapid progress in complementary metal-oxide-semiconductor (CMOS) radio frequency (RF) integrated circuits paves the way for electronic products in the mmWave band [3], [4], [5]. There are already several standards defined for indoor wireless personal area networks (WPAN) or wireless local area networks (WLAN), for example, ECMA-387 [6], [7], IEEE 802.15.3c [8], and IEEE 802.11ad [9], which stimulates growing interests in cellular systems or outdoor mesh networks in the mmWave band [10], [11], [12], [13], [14].

However, due to the fundamental differences between mmWave communications and existing other communication systems operating in the microwaves band (e.g., 2.4 GHz and 5 GHz), there are many challenges in physical (PHY), medium access control (MAC), and routing layers for mmWave communications to make a big impact in the 5G wireless networks. The high propagation loss, directivity, sensitivity to blockage, and dynamics due to mobility of mmWave communications require new thoughts and insights in architectures and protocols to cope with these challenges.

In this paper, we carry out a survey of mmWave communications for 5G. We first summarize the characteristics of mmWave communications. Due to the high carrier frequency, mmWave communications suffer from huge propagation loss, and beamforming (BF) has been adopted as an essential technique, which indicates that mmWave communications are inherently directional. Besides, due to weak diffraction ability, mmWave communications are sensitive to blockage by obstacles such as humans and furniture. Then we introduce two standards for mmWave communications in the 60 GHz band, IEEE 802.15.3c and IEEE 802.11ad. We also identify the challenges posed by mmWave communications, and carry out a survey of existing solutions. The challenges in the integrated circuits and system design include the nonlinear distortion of power amplifiers, phase noise, IQ imbalance, highly directional antenna design, etc. Due to the directivity of transmission, coordination mechanism becomes the key to the MAC design, and concurrent transmission (spatial reuse) should be exploited fully to improve network capacity. To overcome blockage, multiple approaches from the physical layer to the network layer have been proposed. However, every approach has its advantages and shortcomings, and these approaches should be combined in an intelligent way to achieve robust and efficient network performance. Due to human mobility and small coverage areas of mmWave communications, dynamics in terms of channel quality and load should be dealt with elab-
orately by handovers and channel state adaption mechanisms. The potential applications of mmWave communications in the 5G network include the small cell access, the cellular access, and the wireless backhaul. We then discuss some open research issues and propose design guidelines in architectures and protocols for mmWave communications. New physical layer technologies at mmWave frequencies including the multiple-input and multiple-output (MIMO) technique and the full-duplex technique are introduced and discussed in terms of advantages and open problems. Borrowing the idea of software defined networks [15], we propose the software defined architecture for mmWave networks, and discuss the open problems therein, such as the interface between the control plane and the data plane, centralized control mechanisms, and network state information measurements. In the further networks, mmWave networks have to coexist with other networks, such as LTE and WiFi. In such a heterogeneous network (HetNets), interaction and cooperation between different kinds of networks become the key to explore the potential of heterogeneous networking.

The rest of the paper is structured as follows. Section II summarizes the characteristics of mmWave communications. Section III introduces two typical standards for mmWave communications, IEEE 802.15.3c and IEEE 802.11ad. Section IV discusses the challenges including the integrated circuits and system design, the interference management and spatial reuse, anti-blockage, and dynamics due to user mobility. Existing solutions for the challenges are also discussed in section IV. The potential applications of mmWave communications in 5G are discussed in section V. In section VI we discuss open research issues to be further investigated. Finally, section VII concludes this paper.

II. CHARACTERISTICS OF MMWAVE COMMUNICATIONS

The peculiar characteristics of mmWave communications should be considered in the design of network architectures and protocols to fully exploit its potential. We summarize and present the characteristics in the following subsections.

A. Wireless Channel Measurement

Millimeter wave communications suffer from huge propagation loss compared with other communication systems using lower carrier frequencies. The rain attenuation and atmospheric and molecular absorption characteristics of mmWave propagation limit the range of mmWave communications [16], [17], [18], which is shown in Fig. 1 and Fig. 2. However, with smaller cell sizes applied to improve spectral efficiency today, the rain attenuation and atmospheric absorption do not create significant additional path loss for cell sizes on the order of 200 m [19]. Therefore, mmWave communications are mainly used for indoor environments, and small cell access and backhaul with cell sizes on the order of 200 m.

There have been considerable work on mmWave propagation at the 60 GHz band [5], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]. The free space propagation loss is proportional to the square of the carrier frequency. With a wavelength of about 5 mm, the free space propagation loss at 60 GHz is 28 decibels (dB) more than at 2.4 GHz [14].

Besides, the Oxygen absorption in the 60 GHz band has a peak, ranging from 15 to 30 dB/km [30]. The channel characterization in [31] shows that the non-line-of-sight (NLOS) channel suffers from higher attenuation than the line-of-sight (LOS) channel. The large scale fading $F(d)$ can be modeled as follows.

$$F(d) = \frac{1}{\log_{10} d_0} - S_\sigma,$$

where $PL(d_0)$ is the path loss at reference distance $d_0$, $n$ is the path loss exponent, and $S_\sigma$ is the showing loss. $\sigma$ is the standard deviation of $S_\sigma$. In Table I we list the statistical parameters of the path loss model obtained in a corridor, a LOS hall, and a NLOS hall [31]. We can observe that the path loss exponent in the LOS hall is 2.17, while the path loss exponent in the NLOS hall is 3.01. To combat severe propagation loss, directional antennas are employed at both transmitter and receiver to achieve a high antenna gain.

For the small-scale propagation effects in the 60 GHz band, it is found that the multipath effect is not obvious with directional antennas. By using circular polarization and receiving antennas of narrow beam width, multipath reflection
can be suppressed \cite{32,33}. In the LOS channel model in the conference room environment proposed in IEEE 802.11ad \cite{9}, the direct path contains almost all the energy, and nearly no other multipath components exist. In this case, the channel can be regarded as the Additive White Gaussian Noise (AWGN) channel. In the NLOS channel, there is no direct path, and the number of paths with significant energy is small. To achieve high data rate and maximize the power efficiency \cite{34}, mmWave communications mainly rely on the LOS transmission.

There are also channel measurements for mmWave cellular in other bands, such as the 28 GHz band, the 38 GHz band, and the 73 GHz band \cite{35,36}. Rappaport \textit{et al.} \cite{19} conducted the 28 GHz urban propagation campaign in New York City, where the distance between the transmitter (TX) and the receiver (RX) ranged from 75 m to 125 m. The results show that the LOS path loss exponent is 2.55 resulting from all the measurements acquired in New York City. The average path loss exponent in the NLOS case is 5.76. They also conducted an outage study in Manhattan, New York \cite{37}. It was found that signal acquired by the RX for all cases was within 200 meters, and 57% of locations were outage due to obstruction with most of the outages beyond 200 meters from the TX. The maximum coverage distance was shown to increase with increasing antenna gains and a decrease of the path loss exponent. The maximum coverage distance achieves 200 m in a highly obstructed environment when the combined TX-RX antenna gain is 49 dBi. Zhao \textit{et al.} \cite{38} conducted penetration and reflection measurements at 28 GHz in New York City, and it was found that tinted glass and brick pillars have high penetration losses of 40.1 dB and 28.3 dB, respectively. For indoor materials such as clear non-tinted glass and drywall, the losses are relatively low, 3.6 dB and 6.8 dB, respectively. For the reflection measurement, the outdoor materials have larger reflection coefficients, and the indoor materials have lower reflection coefficients. Samimi \textit{et al.} \cite{39} conducted the angle of arrival and angle of departure measurement in outdoor urban environments in New York City. It was found that New York City has rich multipath when using highly directional steerable horn antennas, and at any receiver location, there is an average of 2.5 signal lobes.

Akdeniz \textit{et al.} \cite{40} derived detailed spatial statistical models of channels at 28 and 73 GHz in New York, NY, USA, and the channel parameters include the path loss, number of spatial clusters, angular dispersion, and outage. It was found that even in highly NLOS environments, strong signals can be detected 100–200 m from potential cell sites, and spatial multiplexing and diversity can be supported at many locations with multiple path clusters received. Nguyen \textit{et al.} \cite{41} conducted a wideband propagation measurement campaign using rotating directional antennas at 73 GHz at the New York University (NYU) campus, and based on these results, they presented an empirical ray-tracing model to predict the propagation characteristics at 73 GHz E-Band. Based on the measurement results, Thomas \textit{et al.} \cite{42,43} developed a preliminary 3GPP-style 3D mmWave channel model by using the ray tracer to determine elevation model parameters. Rappaport \textit{et al.} \cite{44,45,46} conducted the 38 GHz cellular propagations measurements in Austin, Texas at the University of Texas main campus. The LOS path loss exponent for the 25 dBi horn antennas was measured to be 2.30, while the NLOS path loss exponent was 3.86. The root mean squared (RMS) delay was shown to be higher with a lower antenna gain. Based on an outage study, it was found that base stations of lower heights have better close-in coverage, and most of the outages occur at locations beyond 200 m from the base stations. The results also show that AOAs occur mostly when the RX azimuth angle is between $-20^\circ$ and $+20^\circ$ about the boresight of the TX azimuth angle \cite{44}.

In Table\ref{tab:table1} we summarize the propagation characteristics of mmWave communications in different bands in terms of the path loss exponent (PLE) under LOS and NLOS channels, the rain attenuation at 200 m, and the oxygen absorption at 200 m. We can observe that at the range of 200 m, the 28 GHz and 38 GHz bands suffer from low rain attenuation and oxygen absorption, while the rain attenuation and oxygen absorption in the 60 GHz and 73 GHz bands are significant. We can also observe that the NLOS transmission has additional propagation loss compared with the LOS transmission in the four bands.

### B. Directivity

MmWave links are inherently directional. With a small wavelength, electronically steerable antenna arrays can be realized as patterns of metal on circuit board \cite{4,47,48}. Then by controlling the phase of the signal transmitted by each antenna element, the antenna array steers its beam towards any direction electronically and to achieve a high gain at this direction, while offering a very low gain in all other directions. To make the transmitter and receiver direct their beams towards each other, the procedure of beam training is needed, and several beam training algorithms have been proposed to reduce the required beam training time \cite{49,50,51}.

### C. Sensitivity to Blockage

Electromagnetic waves have weak ability to diffract around obstacles with a size significantly larger than the wavelength. With a small wavelength, links in the 60 GHz band are sensitive to blockage by obstacles (e.g., humans and furniture). For example, blockage by a human penalizes the link budget by 20-30 dB \cite{34}. Collonge \textit{et al.} \cite{52} conducted propagation measurements in a realistic indoor environment in the presence of human activity, and the results show that the channel is blocked for about 1% or 2% of the time for one to five persons. Taking human mobility into consideration, mmWave links are intermittent. Therefore, maintaining a reliable connection for

| Corridor | 68 | 1.64 | 2.53 |
| Corridor | 68 | 2.17 | 0.88 |
| NLOS hall | 68 | 3.01 | 1.55 |

### TABLE I

\textbf{The Statistical Parameters in the Path Loss Model.}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Channel} & \textbf{PL($d_0$) [dB]} & \textbf{n} & \textbf{\sigma [dB]} \\
\hline
Corridor & 68 & 1.64 & 2.53 \\
Corridor & 68 & 2.17 & 0.88 \\
NLOS hall & 68 & 3.01 & 1.55 \\
\hline
\end{tabular}
\end{table}
TABLE II
THE PROPAGATION CHARACTERISTICS OF MMWAVE COMMUNICATIONS IN DIFFERENT BANDS.

| Frequency Band | PLE | Rain Attenuation@200 m | Oxygen Absorption@200 m |
|----------------|-----|------------------------|--------------------------|
|                | LOS | NLOS | 5 mm/h | 25 mm/h | @200 m |
| 28 GHz         | 1.8~1.9 | 4.5~4.6 | 0.18 dB | 0.9 dB | 0.04 dB |
| 38 GHz         | 1.9~2.0 | 2.7~3.8 | 0.26 dB | 1.4 dB | 0.03 dB |
| 60 GHz         | 2.23 | 4.19 | 0.44 dB | 2 dB | 3.2 dB |
| 73 GHz         | 2 | 2.45~2.69 | 0.6 dB | 2.4 dB | 0.09 dB |

delay-sensitive applications such as HDTV is a big challenge for mmWave communications.

III. STANDARDIZATION
Due to the great potential of mmWave communications, multiple international organizations have emerged for the standardization, including ECMA [6], IEEE 802.15.3 Task Group 3c (TG3c) [8], IEEE 802.11ad standardization task group [9], the WirelessHD consortium [53], and the Wireless Gigabit Alliance (WiGig) [54]. We review two standards in this section, IEEE 802.11ad and IEEE 802.15.3c, and further discuss the challenges in the next section.

A. IEEE 802.11ad
IEEE 802.11ad specifies the physical layer and MAC layer in 60GHz band to support multi-gigabit wireless applications including instant wireless sync, wireless display of high definition (HD) streams, cordless computing, and internet access [9]. In the physical layer, two operating modes are defined, the orthogonal frequency division multiplexing (OFDM) mode for high performance applications (e.g. high data rate), and the single carrier (SC) mode for low power and low complexity implementation.

In IEEE 802.11ad, a basic service set (BSS) consists of a designated device, called AP, and N non-AP devices (DEVs). AP provides the basic timing for the BSS, and coordinates medium access in the BSS to accommodate traffic requests from the DEVs. The channel access time is divided into a sequence of beacon intervals (BIs), and each BI consists of four portions including beacon transmission interval (BTI), association BF training (A-BFT), announcement transmission interval (ATI), and data transfer interval (DTI). In BTI, AP transmits one or more mmWave beacon frames in a transmit sector sweep manner. Then initial BF training between AP and non-AP DEVs, and association are performed in A-BFT. Contention-based access periods (CBAPs) and service periods (SPs) are allocated within each DTI by AP during ATI. During DTI, peer-to-peer communications between any pair of DEVs including the AP and the non-AP DEVs are supported after completing the beamforming (BF) training. In IEEE 802.11ad, a hybrid multiple access of carrier sensing multiple access/collision avoidance (CSMA/CA) and time division multiple access (TDMA) is adopted for transmissions among devices. CSMA/CA is more suitable for bursty traffic such as web browsing to reduce latency, while TDMA is more suitable for traffic such as video transmission to support better quality of service (QoS).

B. IEEE 802.15.3c
IEEE 802.15.3c specifies the physical layer and MAC layer for indoor WPANs (also referred to as the piconet) composed of several wireless nodes (WNs) and a single piconet controller (PNC). The PNC provides network synchronization and coordinates the transmission in the piconet. In IEEE 802.15.3c, network time is divided into a sequence of superframes, each of which consists of three portions: the beacon period (BP), the contention access period (CAP), and the channel time allocation period (CTAP). During BP, network synchronization and control messages are broadcasted from the PNC. CAP is for devices to send transmission requests to the PNC by the CSMA/CA access method, and CTAP is for data transmissions among devices. During CTAP, TDMA is applied, and each time slot is scheduled to a specific flow.

IV. CHALLENGES AND EXISTING SOLUTIONS
Despite the potential of mmWave communications, there are a number of key challenges to exploit the benefits of mmWave communications. Now, we discuss the challenges and present related existing solutions.

A. Integrated Circuits and System Design
With high carrier frequency and wide bandwidth, there are several technical challenges in the design of circuit components and antennas for mmWave communications [5]. In the 60 GHz band, high transmit power, i.e., equivalent isotropic radiated power (EIRP), and huge bandwidth cause severe nonlinear distortion of power amplifiers (PA) [55]. Besides, phase noise and IQ imbalance are also challenging problems faced by radio frequency (RF) integrated circuits [55], [56].

Research progress on integrated circuits for mmWave communications in the 60 GHz band has been summarized and discussed in [5], including on-chip and in-package antennas, radiofrequency (RF) power amplifiers (PAs), low-noise amplifiers (LNAs), voltage-controlled oscillators (VCOs), mixers, and analog-to-digital converters (ADCs). Hong et al. [57] deduced a novel and practical phased array antenna solution operating at 28 GHz with near spherical coverage. They also designed cellular phone prototype equipped with mmWave 5G antenna arrays consisting of a total of 32 low-profile antenna elements. Hu et al. [58] presented a cavity-backed slot (CBS) antenna for millimeter-wave applications. The cavity of the antenna is fully filled by polymer material, which reduces the cavity size by 76.8 %. Liao et al. [59] presented a novel planar aperture antenna with differential feeding, which maintains a high gain and wide bandwidth compared with conventional
high gain aperture antennas. The proposed aperture antenna element has low cost, low profile, compact size, and is also good in gain and bandwidth. Zwick et al. [60] presented a new planar superstrate antenna suitable for integration with mmWave transceiver integrated circuits, which is printed on the bottom of a dielectric superstrate with a ground plane below. Two designs for the 60 GHz band achieve over 10% bandwidth while maintaining better than 80% efficiency.

B. Interference Management and Spatial Reuse

The directivity of transmission enables less interference between links. In the outdoor mesh network in the 60 GHz band, the highly directional links are modeled as pseudowired, and the interference between nonadjacent links is negligible [61]. The details of antenna patterns can also be ignored in the design of MAC protocols for mmWave mesh networks. Due to directional transmission, the third party nodes cannot perform carrier sense as in WiFi, which is referred to as the deafness problem [62]. In this case, the coordination mechanism becomes the key to the MAC design, and concurrent transmission should be exploited fully to greatly enhance the network capacity [14].

In the indoor environments, however, due to the limited range, the assumption of pseudowired is not reasonable [63]. On the other hand, owing to the explosive growth of mobile data demands as well as to overcome the limited range of mmWave communications, in a practical mmWave communication system, the number of deployed APs over both public and private areas increases tremendously. For example, a large number of APs must be deployed in scenarios such as enterprise cubicles and conference rooms to provide seamless coverage. In this case, the interference in the network can be divided into two portions: interference within each BSS, and interference among different BSSs [65]. As shown in Fig. 3 when the two links in BSS1 and BSS2 are communicating in the same slot, since AP1 directs its beam towards the laptop, AP1 will have interference to the laptop. If the distance between them is short, the service of the laptop will be degraded significantly.

Thus, interference management mechanisms such as power control and transmission coordination should be applied to avoid significant degradation of network performance due to interference. With the interference efficiently managed, concurrent transmission (spatial reuse) on the other hand should be supported among different BSSs as well as within each BSS [62], [63], [66].

In order to address these problems, there has been some related work on directional MAC protocols for mmWave communications. Since TDMA is adopted in ECMA-387 [6], IEEE 802.15.3c [8], and IEEE 802.11ad [9], many protocols are based on TDMA [67], [68]. Cai et al. [69] introduced the concept of exclusive region (ER) to enable concurrent transmissions, and derived the ER conditions that concurrent transmissions always outperform TDMA for both omni-antenna and directional-antenna models. By the REX scheduling scheme (REX), significant spatial reuse gain is achieved. However, the interference level and the received signal power are calculated by the free space path loss model, which is inappropriate for indoor WPANs, where reflection will also cause interference. Besides, it only considers the two-dimensional space in the transmission scheduling problem, and the power control is not considered to manage interference. In two protocols based on IEEE 802.15.3c, multiple links are scheduled to communicate in the same slot if the multi-user interference (MUI) is below a specific threshold [64], [70]. However, they do not capture the characteristics of the directional antennas, and the aggregation effect of interference from multiple links is also not considered. Qiao et al. [63] proposed a concurrent transmission scheduling algorithm for an indoor IEEE 802.15.3c WPAN, and non-interfering and interfering links are scheduled to transmit concurrently to maximize the number of flows with the quality of service requirement of each flow satisfied. It can support more number of users, and significantly improves the resource utilization efficiency in mmWave WPANs. However, it does not consider the NLOS transmissions, which is important for indoor WPANs, and the interference model does not take the realistic antenna model into account. Furthermore, a multi-hop concurrent transmission scheme (MHCT) is proposed to address the link outage problem (blockage) and combat huge path loss to improve flow throughput [71]. It assumes an ideal “flat-top” model for directional antenna, and analyzes the spatial reuse and time division multiplexing gain of MHCT in the two-dimensional space. Based on IEEE 802.15.3c, the piconet controller selects appropriate relay hops for a traffic flow according to a hop selection metric, and spatial reuse is also exploited by the multi-hop concurrent transmission scheme (MHCT). For protocols based on IEEE 802.15.3c, the piconet controller is operating in the omni-directional mode during the random access period to avoid the deafness problem, which may not be feasible for mmWave systems that operate in the multi-gigabit domain with highly directional transmission, and will lead to the asymmetry-in-gain problem [72]. For TDMA based protocols, the medium time for bursty data traffic is often highly unpredictable, which will cause some flows to have too much medium time while not enough medium time for others. Besides, the control overhead for on-the-fly medium reservation may be high for TDMA based protocols. Based on IEEE 802.11 ad, Chen et al. [66] proposed a spatial reuse strategy to schedule two different SPs to overlap...
with each other, and also analyzed the performance of the strategy with the difference between idealistic and realistic directional antennas considered. It does not fully exploit the spatial reuse since only two links are considered for concurrent transmissions.

On the other hand, some protocols are based on the centralized coordination by the AP or PNC. Gong et al. [73] proposed a directive CSMA/CA protocol, which exploits the virtual carrier sensing to solve the deafness problem completely. The network allocation vector (NAV) information is distributed by the PNC. Spatial reuse, however, is not fully exploited to improve network capacity in the protocol. Son et al. [62] proposed a frame based directive MAC protocol (FDMAC). The high efficiency of FDMAC is achieved by amortizing the scheduling overhead over multiple concurrent transmissions in a row. The core of FDMAC is the Greedy Coloring algorithm, which fully exploits spatial reuse and greatly improves the network throughput compared with MRDMAC [34] and memory-guided directional MAC (MDMAC) [74]. FDMAC also has a good fairness performance and low complexity. FDMAC, however, assumes the pseudowired interference model for WPANs, which is not reasonable due to the limited range. Chen et al. [75] proposed a directional cooperative MAC protocol (D-CoopMAC) to coordinate the uplink channel access among stations in an IEEE 802.11ad WLAN. In D-CoopMAC, a two-hop path of high channel quality from the source station (STA) to the destination station (STA) is established to replace the direct path of poor channel quality. By the two-hop relaying, D-CoopMAC significantly improves the system throughput. However, spatial reuse is also not considered in D-CoopMAC since most transmissions go through the AP. Park et al. [76] proposed an incremental multicast grouping (IMG) scheme to maximize the sum rate of devices, where adaptive beamwidths are generated depending on the locations of multicast devices. Simulation based on the IEEE 802.11ad demonstrate that the IMG scheme can improve the overall throughput by 28 % to 79 % compared with the conventional multicast schemes. Scott-Hayward et al. [77] proposed to use the particle swarm optimization (PSO) for the channel-time allocation of a mixed set of multimedia applications in IEEE 802.11ad. Channel-time allocation PSO (CTA-PSO) is demonstrated to allocate resource successfully even when blockage occurs.

For outdoor mesh networks in the 60 GHz band, Singh et al. [24] proposed a distributed MAC protocol, the memory-guided directional MAC (MDMAC), based on the pseudowired link abstractions. A Markov state transition diagram is incorporated into the protocol to alleviate the deafness problem. MDMAC employs memory to achieve approximate time division multiplexed (TDM) schedules, and does not fully exploit the potential of spatial reuse. Another distributed MAC protocol for directional mmWave networks is directional-to-directional MAC (DtDMAC), where both senders and receivers operate in a directional-only mode [72], which solves the asymmetry-in-gain problem. DtDMAC adopts an exponential backoff procedure for asynchronous operation, and the deafness problem is also alleviated by a Markov state transition diagram. DtDMAC is fully distributed, and does not require synchronization. However, it does not capture the characteristics of wireless channel in mmWave bands, and only gives the analytical network throughput of DtDMAC for the mmWave technology.

C. Anti-blockage

Sato and Manabe [78] estimated the propagation-path visibility between APs and terminals in office environments where blockage by human bodies happens. To avoid shadowing by human bodies perfectly without multi-AP diversity, a lot of APs are needed. However, diversity switching between only two APs provides 98% propagation path visibility. Dong et al. [79] analyzed the link blockage probability in typical indoor environments under random human activities. The AP is mounted on the ceiling, and this work mainly focuses on the links between the AP and the user devices. The results show that as the user devices move towards the edge of the service area, the blockage probability of links increases almost linearly. With communications between user devices enabled, the blockage probability of links between user devices should also be considered.

To ensure robust network connectivity, different approaches from the physical layer to the network layer have been proposed. Genc et al. [80] exploited reflections from walls and other surfaces to steer around the obstacles. Yiu et al. [81] used static reflectors to maintain the coverage in the entire room when blockage occurs. Using reflections will cause additional power loss and reduce power efficiency. Besides, the node placement and environment will have a big impact on the efficacy of reflection to overcome blockage. An et al. [82] resolved link blockage by switching the beam path from a LOS link to a NLOS link. NLOS transmissions suffer from significant attenuation and cannot support high data rate [31], [34], [71]. Park and Pan [83] proposed a spatial diversity technique, called equal-gain (EG) diversity scheme, where multiple beams along the N strongest propagation paths are formed simultaneously during a beamforming process. When the strongest path is blocked by obstacles, the remaining paths can be used to maintain reliable network connectivity. This approach adds the complexity and overhead of the beamforming process, which will degrade the system performance eventually. Xiao [84] proposed a suboptimal spatial diversity scheme called maximal selection (MS) by tracing the shadowing process, which outperforms EG in terms of link margin and saves computation complexity. Another approach is to use relays to maintain the connectivity [34], [85]. The multihop relay directional MAC (MRDMAC) overcomes the deafness problem by PNC’s weighted round robin scheduling. In MRDMAC [34], if a wireless terminal (WT) is lost due to blockage, the access point (AP) will choose a WT among the live WTs as a relay to the lost node. By the multi-hop MAC architecture, MRDMAC is able to provide robust connectivity in typical office settings. Since most transmissions go through the PNC, concurrent transmission is also not considered in MRDMAC. Based on IEEE 802.15.3, Lan et al. [50] exploited the two-hop relaying to provide alternative communication links under such harsh environments. The transmission from relay to destination of one links is scheduled to coexist with the transmission from source to relay of another link to improve
throughput and delay performance. However, only two links are scheduled for concurrent transmissions in this scheme, and the spatial reuse is not fully exploited. Lan et al. [87] also proposed a deflection routing scheme to improve the effective throughput by sharing time slots for direct path with relay path. It includes a routing algorithm, the best fit deflection routing (BFDR), to find the relay path with the least interference that maximizes the system throughput. They also developed the sub-optimal random fit deflection routing (RFDR), which achieves almost the same order of throughput improvement with much lower complexity. With multiple APs deployed, handovers can be performed between APs to address the blockage problem. Zhang et al. [88] took advantage of multi-AP diversity to overcome blockage. There is an access controller (AC) in the multi-AP architecture, and when one of wireless links is blocked, another AP can be selected to complete remaining transmissions. To ensure the efficacy of this approach, multiple APs need to be deployed, and their locations will have a significant impact on the robustness and efficiency of this approach. Recently, Niu et al. [89] proposed a blockage robust and efficient directional MAC protocol (BRDMAC), which overcomes the blockage problem by two-hop relaying. In BRDMAC, relay selection and spatial reuse are optimized jointly to achieve near-optimal network performance in terms of delay and throughput. However, only two-hop relaying is considered in BRDMAC, and under serious blockage conditions, there is probably no two-hop relay path between the sender and the receiver, which cannot guarantee robust network connectivity. In the network layer, Wang et al. [90] exploited multipath routing to enhance reliability of high quality video in the 60GHz radio indoor networks. It mainly focuses on the video traffic, and other traffic patterns are not considered.

D. Dynamics due to User Mobility

User mobility poses several challenges in the mmWave communication system. First, user mobility will incur significant changes of the channel state. When users move, the distance between the transmitter (TX) and the receiver (RX) varies, and the channel state also varies accordingly. In Table II, we list the channel capacities under difference distances between TX and RX, adopting the PHY parameters in [91]. We assume LOS transmission between TX and RX, and thus calculate the capacities according to Shannon’s channel capacity. We can observe that the channel capacity varies with the distance significantly. Therefore, the selection of modulation and coding schemes (MCS) should be performed according to the channel states to fully exploit the potential of mmWave communications [92].

Second, due to the small coverage areas of BSSs, especially in indoor environments, user mobility will cause significant and rapid load fluctuations in each BSS [93]. Thus, user association and handovers between APs should be carried out intelligently to achieve an optimized load balance. Current standards for mmWave communications, such as IEEE 802.11ad and IEEE 802.15.3c, adopt the received signal strength indicator (RSSI) for user association, which may lead to inefficient use of resources [94], [95], [96]. With load, channel quality, and the characteristics of 60 GHz wireless channels taken into consideration, Athanasiou et al. [97] designed a distributed association algorithm (DAA), based on Langragian duality theory and subgradient methods. DAA is shown to be asymptotically optimal, and outperforms the user association policy based on RSSI in terms of fast convergence, scalability, time efficiency, and fair execution.

Besides, user mobility will also incur frequent handovers between APs. Handover mechanisms have a big impact on quality of service (QoS) guarantee, load balance, and network capacity, etc. For example, smooth handovers are needed to reduce dropped connections and ping-pong (multiple handovers between the same pair of APs). However, there is little work on the handover mechanisms for mmWave communications in the 60 GHz band. Quang et al. [98] discussed the handover issues in radio over fiber network at 60 GHz, and the handover performance can be improved using more information such as velocity and mobility direction of users. Tsagkaris et al. [99] proposed a novel handover scheme based on Moving Extended Cells (MEC) [100] to achieve seamless broadband wireless communication.

V. APPLICATIONS OF MMWAVE COMMUNICATIONS

A. Small Cell Access

To keep up with the explosive growth of mobile traffic demand, massive densification of small cells has been proposed to achieve the 10 000 fold increase in network capacity by 2030 [101], [102], [103]. Small cells deployed underlaying the macrocells as WLANs or WPANs are a promising solution for the capacity enhancement in the 5G cellular networks. With huge bandwidth, mmWave small cells are able to provide the multi-gigabit rates, and wideband multimedia applications such as high-speed data transfer between devices, such as cameras, pads, and personal computers, real-time streaming of both compressed and uncompressed high definition television (HDTV), wireless gigabit ethernet, and wireless gaming can be supported.

Ghosh et al. [101] made a case for using mmWave bands, in particular the 28, 38, 71–76 and 81–86 GHz bands for the 5G enhanced local area (eLA) access. With huge bandwidth, the eLA system is able to achieve peak data rates in excess of 10 Gbps and edge data rates of more than 100 Mbps. Singh et al. [104] presented an mmWave system for supporting uncompressed high-definition (HD) video up to 3 Gb/s. Wu et al. [105] defined and evaluated important metrics to characterize multimedia QoS, and designed a QoS-aware multimedia scheduling scheme to achieve the trade-off between performance and complexity.

B. Cellular Access

The large bandwidth in the mmWave bands promotes the usage of mmWave communications in the 5G cellular access [13], [19], [105]. In [107], [108], it is shown that mmWave cellular networks have the potential for high coverage and capacity as long as the infrastructure is densely deployed. Based on the extensive propagation measurement campaigns...
TABLE III
THE CHANNEL CAPACITIES UNDER DIFFERENT DISTANCES

| Distance (m) | 1   | 2   | 4   | 6   | 8   | 10  |
|-------------|-----|-----|-----|-----|-----|-----|
| Capacity (Gbps) | 16.02 | 12.51 | 9.05 | 7.08 | 5.74 | 4.75 |

at mmWave frequencies [19], the feasibility and efficiency of applying mmWave communications in the cellular access have been demonstrated at 28 GHz and 38 GHz with the cell sizes at the order of 200 m. It is shown in [109] that the capacity gains based on arbitrary pointing angles of directional antennas be 20 times greater than the 4G LTE networks, and can be further improved when directional antennas are pointed in the strongest transmit and receive directions. Since device-to-device (D2D) communications in close proximity save power and improve the spectral efficiency, D2D communications should be enabled in the mmWave cellular systems to support the context-aware applications that involve discovering and communicating with nearby devices. In Fig. 4, we plot the mmWave 5G cellular network architecture with D2D communications enabled.

Fig. 4. MmWave 5G cellular network architecture with D2D communications enabled.

Fig. 5. E-band backhaul for small cells densely deployed.

C. Wireless Backhaul

With small cells densely deployed in the next generation of cellular systems (5G), it is costly to connect 5G base stations (BSs) to the other 5G BSs and to the network by fiber based backhaul [110]. In contrast, high speed wireless backhaul is more cost-effective, flexible, and easier to deploy. With huge bandwidth available, wireless backhaul in mmWave bands, such as the 60 GHz band and E-band (71–76 GHz and 81–86 GHz), provides several-Gbps data rates and can be a promising backhaul solution for small cells. As shown in Fig. 5, the E-band backhaul provides the high speed transmission between the small cell base stations (BSs) or between BSs and the gateway.

Taori et al. [110] proposed to use the in-band wireless backhaul to obtain a cost-effective and scalable wireless backhaul solution, where the backhaul and access are multiplexed on the same frequency band. They also proposed a time-division multiplexing (TDM)-based scheduling scheme to support point-to-multipoint, non-line-of-sight, mmWave backhaul. In the in-band backhaul scenario, the joint design of the access and backhaul networks will optimize the resource allocation further [111]. Recently, Niu et al. [112] proposed a joint transmission scheduling scheme for the radio access and backhaul of small cells in 60 GHz band, termed D2DMAC, where a path selection criterion is designed to enable D2D transmissions for performance improvement.

In Table IV, we list the typical works according to the frequency band, the scenario, and the main application. We can observe that there are many works on the indoor WPAN/WLAN applications in the 60 GHz band, and the system design for the 5G cellular and HetNets in other bands should be investigated further.
TABLE IV
APPLYING SOLUTIONS OF MMWAVE COMMUNICATION.

| Publication   | Frequency Band (GHz) | Scenario            | Application                      |
|---------------|----------------------|---------------------|----------------------------------|
| Singh et al.  | 60                   | indoor office       | Internet access                  |
| Son et al.    | 60                   | WPAN                | transmission between devices     |
| Qiao et al.   | 60                   | WPAN                | flows with QoS requirements      |
| Chen et al.   | 75                   | WLAN                | uplink channel access            |
| Ghosh et al.  | 28, 38, 71–76, 81–86 | urban street        | access and backhaul              |
| Singh et al.  | 60                   | WPAN                | HD video                         |
| Wu et al.     | 60, 70               | indoor              | multimedia                       |
| Taori et al.  | 28                   | outdoor cellular    | in-band backhaul                 |
| Niu et al.    | 60                   | small cells in HetNets | access, backhaul, D2D          |
| Qiao et al.   | not specified        | outdoor cellular    | access, backhaul, D2D            |

VI. OPEN RESEARCH ISSUES

In this section, we discuss the open research issues that need to be investigated, and new research directions for mmWave communications to make significant impact on the next generation wireless networks.

A. New Physical Layer Technology

1) MIMO at mmWave Frequencies: Since the MIMO techniques provide the trade-off between the diversity gain and the diversity gain, there is increasing interest in applying MIMO techniques in mmWave communications [113], [114], [115]. However, the baseband precoding structure in the sub 3 GHz system cannot be applied directly into the mmWave system [116]. On one hand, the baseband precoding requires a complete dedicated RF chain for each antenna element at the transmitter or the receiver, which is expensive and adds the system complexity significantly. On the other hand, with highly directional beams, there is a shortage of multipath in the mmWave bands, and the diversity gain is low for the baseband precoding. To obtain the benefits of MIMO and also provide high beamforming gain to overcome high propagation loss in mmWave bands, the hybrid beamforming structure has been proposed as an enabling technology for 5G cellular communications [117].

The hybrid beamforming structure for the mmWave transmitter is illustrated in Fig. 6. In the structure, $N_S$ data streams are first through the baseband digital precoding, and then the output is through the $N_{RF}$ RF chains. After the RF analog beamforming, the RF signals are outputted to the $N_T$ antennas. With $N_T \geq N_{RF}$, the number of RF chains can be reduced for practical implementation [116].

Based on the hybrid beamforming structure, there has been some work on the design of the digital precoder and the analog beamformer. Ayach et al. [118] exploited the spatial structure of mmWave channels to formulate the transmit precoding and receiver combining problem as a sparse reconstruction problem. They also developed algorithms to accurately approximate optimal unconstrained precoders and combiners, which can be implemented in low-cost RF hardware. Alkhateeb et al. [119] developed an adaptive algorithm to estimate the mmWave channel parameters, which exploits the poor scattering nature of the channel. They also proposed a new hybrid analog/digital precoding algorithm to overcome the hardware constraints on the analog-only beamforming, which approaches the performance of digital solutions. In [113], it is shown by measurements and realistic channel models that spatial multiplexing (SM) and beamforming (BF) could work in tandem. The LOS channels are often of low rank, and only a couple of SM streams can be supported. NLOS channels offer more rank, but they have higher path loss, which indicates both SM and BF should be exploited for capacity gain. Singh et al. [120] developed reduced complexity algorithms for optimizing the choice of beamforming directions of multiple antenna arrays at the transmitter or the receiver in a codebook-based beamforming system, exploiting the sparse multipath structure of the mmWave channel. The cardinality of the joint beamforming search space is reduced by focusing on a small set of dominant candidate directions. Han et al. [121] investigated the optimal designs of hybrid beamforming structures, focusing on an N (the number of transceivers) by M (the number of active antennas per transceiver) hybrid beamforming structure. The energy efficiency and spectrum efficiency of the beamforming structure are also discussed, which provides guidelines to achieve optimal energy/spectrum efficiency trade-off. Alkhateeb et al. [114] reviewed two potential mmWave MIMO architectures, the hybrid analog/digital precoding/combining, and combining with low-resolution analog-to-digital converters. The advantages and disadvantages of combining with low-resolution analog-to-
digital converters are discussed and analyzed. Most of the current work is focused on the single-user mmWave MIMO systems, and multi-user mmWave MIMO systems should be investigated for the mmWave cellular systems.

In Table 1, we summarize the work according to the transceiver structure and application scenario. We can observe that the analog beamforming structure is mainly used in the short-range communication scenario for overcoming the path loss, while the hybrid beamforming structure is proposed in the 5G cellular networks to achieve the trade-off between performance and complexity.

2) Full-duplex: Wireless systems today are generally half-duplex, i.e., they can transmit or receive, but not both simultaneously. Full-duplex systems, however, are able to transmit and receive simultaneously. The challenge to design full-duplex systems is to reduce self-interference, which is due to signal received from a local transmitting antenna is usually much stronger than signal received from other nodes. The main methods to reduce self-interference include analog cancelation techniques, digital cancelation, and antenna placement. The analog cancelation techniques treat self-interference as noise, and use noise canceling chips to reduce self-interference. The digital cancelation subtracts self-interference in the digital domain after ADC, and the antenna placement techniques place another TX antenna such that two transmit signals interfere destructively at RX antenna. Jain et al. use the balanced/unbalanced (balun) transformer to support wideband and high power systems. With the half-duplex constraint removed, the medium access control (MAC) needs to be redesigned to fully exploit the benefits of full-duplex. There are two transmission modes for the full-duplex systems, the bidirectional full-duplexing and the relay full-duplexing. It is shown in that there is trade-off between spatial reuse and the full-duplex gain for traditional CSMA-style MAC, and the full-duplex gain is well below 2 in common cases from the network-level capacity gain view.

However, the current research on the full-duplex systems mainly focuses on the omnidirectional communications in the low frequency bands. There are several challenges to design full-duplex systems in the mmWave bands. First, the current full-duplex systems have the bandwidth at the order of 40MHz, and the practical implementation of the full-duplex systems for the mmWave communications with a bandwidth of several GHz should be investigated and demonstrated. Second, since mmWave communications are inherently directional, the directional full-duplex systems with directional transmission and reception need to be developed. Miura et al. proposed a full-duplex node architecture with directional transmission and omnidirectional reception based on the full-duplex architecture in . With directional antennas used for both transmission and reception in the mmWave bands, the node architecture should be redesigned to take the characteristics of mmWave communications into account. The intuitive approach is to exploit the beamforming of transmission antennas and reception antennas to reduce self-interference. With the directions of transmit and receive antennas not directed towards each other, the self-interference can be reduced by beamforming. As shown in Fig. 7 with the beams of transmit and receive antennas of each AP directed in the inverse directions, the relay full-duplex transmission can be realized by beamforming in the line-type backhaul network since any transmitter is outside the receive range of the other receiver, where we assume AP A receives negligible interference from AP C. Third, in the directional transmission scenario, the relationship between the spatial reuse and the full-duplex gain should be further investigated for the design of mmWave full-duplex networks in 5G cellular networks.

B. Software Defined Architecture

To overcome the challenges posed by mmWave communications, different approaches from the physical layer to the network layer can be exploited. However, every approach has its advantages and shortcomings, and is efficient only in certain circumstances. We should combine them intelligently to optimize the network performance. On the other hand, with multiple APs deployed, coordination among APs must be explicitly considered to achieve goals such as efficient interference management and spatial reuse, robust network connectivity, optimized load balance, and flexible QoS guarantee.

Distributed network control does not scale well, and the latency will increase significantly as more APs are deployed. Distributed control usually also has high control overhead. Moreover, it is difficult to achieve intelligent control mechanisms required for the complicate operational environments that involve dynamic behaviors of accessing users and temporal variations of the communication links in a distributed way. Therefore, we need centralized and cross-layer control mechanisms to fully exploit the potential of mmWave communications. Borrowing the idea of Software-Defined Network (SDN), which advocates separating the control plane and data plane, and abstracting the control functions of the network into a logically centralized controller to expose the functions deeply hidden inside the network stack to higher layers, the software defined network will be a promising architecture for mmWave communication systems to achieve flexible and intelligent network control. To deploy the software defined mmWave communication system, the interface between the control plane and data plane (e.g., OpenFlow) should be designed elaborately to facilitate the efficient and centralized control of the control plane. Besides, efficient and centralized control mechanisms of the control plane, and network state information measurements, on which control
mechanisms are based, are also open problems which warrant further investigations.

C. Control Mechanisms

To achieve high network performance, effective and efficient mechanisms on interference management, transmission scheduling, mobility management and handover, beamforming (BF), and anti-blockage need to be further investigated.

In table V we compare several typical MAC protocols for mmWave networks in terms of some key aspects. From the table, we can observe that every protocol has its advantages and shortcomings, and more efficient and robust protocols need to be developed to exploit the potential of spatial reuse and also overcome blockage. To achieve better network performance, centralized protocols are preferred. On the other hand, most work focuses on the scenario of one BSS [63] and does not consider the interference among different BSSs.

As regards anti-blockage, we classify the works for anti-blockage according to the strategies adopted, and the layers where the strategies are performed in table VII. Although there are several approaches such as beam switching from a LOS path to a NLOS path [82], relaying [33], performing handovers between APs [83], and exploiting spatial diversity [83], multipath routing [90], each of them has limitations, and it is efficient only under certain conditions. For example, performing handovers between APs is effective only when there is a direct path between the user device and another neighboring AP. Beam switching to a NLOS path is usually a good choice [82]. In some cases, however, the NLOS path is difficult to find, or for a high-rate flow such as HDTV, the transmission rate supported by the NLOS path cannot meet the throughput requirement. In this case, relaying may be a good choice if the links in the relay path have high channel quality. Exploiting spatial diversity increases complexity and cannot guarantee the quality of service (QoS). Therefore, how to combine these approaches and apply them appropriately in order to ensure robust network connectivity and improve network performance remains an open problem which warrants further investigations.

On the other hand, due to the diverse applications as well as the complexity and variability of the indoor environment, mmWave communication systems should be able to adapt to different traffic patterns and time-varying channel states. Even though a variety of approaches or protocols have been proposed, each optimized for a specific application or channel state, it is essential to be able to switch among them appropriately and intelligently, or to combine them efficiently, according to the actual network state. Open problems on dynamical adaption include how to combine TDMA and CSMA/CA intelligently to adapt to a variety of applications, how to select the MCSs according to the time-varying channel states, and how to manage user mobility to improve the network performance.

D. Network State Measurement

Efficient and intelligent network control are based on accurate and comprehensive network state information obtained by efficient measurement mechanisms. There already exist some work on the measurement of network state information. Ning et al. [130] considered the process of neighbor discovery in 60 GHz indoor wireless networks, and examine direct discovery and gossip-based discovery, from which the up-to-date network topology or node location information can be obtained. Kim et al. [131] analyzed the directional neighbor discovery process based on the IEEE 802.15.3c standard. Park et al. [132] proposed a multi-band directional neighbor discovery scheme, where management procedures are carried out in the 2.4 GHz band with the omni-directional antennas while data transmissions are performed in the 60 GHz band with directional antennas, to reduce the neighbor discovery time and energy consumption. Chen et al. [66] proposed a beamforming (BF) information table that records all the beam-
| Protocol                        | TDMA-based | Spatial Reuse | Anti-Blockage | Centralized/Distributed |
|--------------------------------|------------|---------------|---------------|-------------------------|
| Directional CSMA/CA [73]       | No         | No            | Not specified | Centralized             |
| MRDMAC [34]                   | No         | No            | Not specified | Centralized             |
| MDMAC [74]                    | No, time division multiplexing (TDM) | No            | Approximate TDM schedules | Distributed |
| FDMAC [62]                    | No, frame-based | No            | Greedy coloring (GC) algorithm | Centralized |
| D-CoopMAC [74]                | No, based on IEEE 802.11ad | No            | Not specified | Centralized             |
| REX [69]                      | Yes, based on IEEE 802.15.3 | Supported, by a randomized ER based scheduling scheme | Not specified | Centralized             |
| Spatial sharing [66]          | No, based on IEEE 802.11ad | Not specified | Supported, by the BF information | Centralized |
| MHCT [71]                     | Yes, based on IEEE 802.15.3c | Supported, by the MHCT scheme | Not specified | Centralized |
| STDMA based scheduling [63]   | Yes, based on IEEE 802.15.3c | Supported, by concurrent transmission scheduling algorithm | Not specified | Centralized |
| VTSA [64]                     | Yes, based on IEEE 802.15.3c | Supported | Not specified | Centralized |
| Spatial reuse TDMA [67]       | Yes, based on IEEE 802.15.3c | Supported | Not specified | Centralized |
| DtDMAC [72]                   | No, an exponential backoff procedure for asynchronous operation | Supported | Not specified | Distributed |
| BRDMAC [89]                   | No, frame-based | Not specified | Supported, by the SINR based concurrent transmission scheduling | Centralized |
| CTA-PSO [77]                  | No, based on IEEE 802.11ad | Not specified | Supported, by the link switch relay method | Centralized |
TABLE VII
THE ANTI-BLOCKAGE WORKS CLASSIFICATION

| Anti-blockage Strategies          | References | Layer     |
|-----------------------------------|------------|-----------|
| Reflection or NLOS transmission   | [80], [81], [82], [83], [84] | PHY/MAC   |
| Relaying                          | [84], [85], [86], [87], [89] | MAC       |
| Multi-AP diversity               | [83]       | MAC       |
| multipath routing                 | [90]       | Routing   |

Fig. 8. Heterogeneous networks consisting of macrocells, microcells, WLANs, and picocells in the 60 GHz band

forming training results among clients that can be established at the AP.

However, most of the current work focuses on the network state information measurement within one BSS. For user devices in the overlapped region of two BSSs, the link quality information and BF information between the devices and the neighbouring APs are also required to perform handover and interference management. To maximize concurrent transmissions among different BSSs, the interference between different BSSs must be estimated as accurate as possible. On the other hand, to ensure the real-time network control, all the network state measurements should be completed within the shortest possible time. Thus, efficient measurement mechanisms are open problems, which need to be extensively investigated to facilitate the deployment of mmWave communication systems in the future.

E. Heterogeneous Networking

Due to the limited coverage area of mmWave communications, mmWave communication systems need to coexist with other systems of other bands, such as LTE and WiFi. Therefore, mmWave networks will be inherently heterogeneous [13], [133]. As shown in Fig. 8 short-range picocells in the 60 GHz band will coexist with macrocells and microcells in other bands [134]. We can observe that cells in the microwave bands have larger coverage areas, while smaller cells such as BSSs in the 60 GHz band have higher capacity.

Heterogeneous networking has gained considerable attention from academia and industry [135], [136], [137], [138]. Mehrpouyan et al. [139] introduced a novel millimeter-wave HetNet paradigm, termed hybrid HetNet, which exploits the vast bandwidth and propagation characteristics in the 60 GHz and 70–80 GHz bands to reduce the impact of interference in HetNets. In heterogeneous networks, interaction and cooperation between different kinds of networks become the key to explore the potential of heterogeneous networking to solve the problems of mobility management, vertical handover, mobile data offloading from macrocells to microcells [140], inter-cell interference management, etc. Qiao et al. [141] introduced an mmWave+4G system architecture with TDMA-based MAC structure as a candidate for 5G cellular networks, where the control functions are performed in the 4G system. The high capacity of mmWave communications can offload traffic from the macrocells and provide better services for traffic with high throughput requirements. On the other hand, handovers between base stations (BS) of macrocells and APs in the mmWave band are able to address problems such as blockage, mobility management, load balancing, etc. For mmWave networks, there are also studies advocating distributing the control messages for channel access and coordination both on mmWave and microwave bands [142]. Thus, a part of important control signals such as synchronization or channel access requests can be transmitted in the microwave band omni-directionally. Thus, network coupling, the level of integration between different networks, has an important impact on the system performance [143]. Tight coupling is beneficial to achieve better performance, while loose coupling has low complexity. Therefore, there is a tradeoff between complexity and performance in heterogeneous networking. Meanwhile, software defined architecture with flexible programmability, such as OpenRadio [144], is a promising candidate to achieve tight coupling between networks.

VII. Conclusions

With the potential to offer orders of magnitude greater capacity over current communication systems, mmWave communications become a promising candidate for the 5G mobile networks. In this paper, we carry out a survey of mmWave communications for 5G. The characteristics of mmWave communications promote the redesign of architectures and protocols to address the challenges, including integrated circuits and system design, interference management and spatial reuse, anti-blockage, and dynamics due to mobility. The current solutions have been overviewed and compared in terms of effectiveness, efficiency, and complexity. The potential applications of mmWave communications in 5G are also discussed. Open
researches, related to the new physical technology, the software defined architecture, the measurements of network state information, the efficient control mechanisms, and the heterogeneous networking, have been discussed to promote the development of mmWave communications in 5G.

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