KEY ELEMENTS TO ENABLE MILLIMETER WAVE COMMUNICATIONS FOR 5G WIRELESS SYSTEMS

LILI WEI, ROSE QINGYANG HU, YI QIAN, AND GENG WU

ABSTRACT

Current cellular spectrum at below 3 GHz bands is experiencing severe shortage and cannot keep up with the dramatic proliferation of mobile traffic in the near future, requiring the search for innovative solutions to enable the 5G era. mmWave communications, with a possible gigabit-per-second data rate, have attracted great attention as a candidate for 5G broadband cellular communication networks. However, a complete characterization of mmWave links for 5G wireless networks still remains elusive and there are many challenges and research areas that need to be addressed. In this work we discuss several key elements to enable mmWave communications in 5G:

- Channel characteristics regarding mmWave signal attenuation due to free space propagation, atmospheric gaseous and rain are explained.
- The hybrid (digital plus analog) beamforming architecture in mmWave system is discussed.
- The blockage effect in mmWave communications due to penetration loss and possible approaches are presented.
- The application of mmWave transmission with narrow beams in non-orthogonal device-to-device communication is proposed.
- mmWave transmission in the booster cell of heterogeneous anchor-booster networks.
- mmWave transmission for small cell backhaul is further discussed.

INTRODUCTION

Mobile communication has achieved tremendous technology innovations and commercial success over several generations of evolution. First generation cellular networks refer to the basic analog systems for voice only with "brick phones" or "bag phones." Revolutionary fully digital 2G networks led to the explosive increase in mobile phone usage. Voice quality was much improved and short message service (SMS) was provided. Simple data applications such as email and web browsing could be provided with speeds of 9.6kb/s–19.2kb/s. Typical 2G standards include GSM (Global system for mobile communications) based on TDMA (time division multiple access) and IS-95 (Interim Standard 95) based on CDMA (code division multiple access). As the use of 2G phones became more widespread, the demand for data (e.g. access to the Internet) was growing. Moving from 2G to 3G introduced another revolutionary change, the introduction of packet switching rather than circuit switching for data transmission. 3G technologies have enabled faster data transmission speeds (144kb/s for high mobility, 384kb/s for pedestrian and 2Mb/s for indoor), greater network capacity, and more advanced network services such as video and audio streaming. Representative 3G systems include UMTS (Universal Mobile Telecommunications System) and CDMA2000. The Long Term Evolution (LTE) standard belongs to the fourth generation of mobile communication systems. With Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), capacity-approaching codes, pure packet-switched core network, and other technologies, 4G networks aim to offer data rates from 100Mb/s to 1Gb/s, providing robust performance for the most bandwidth intensive applications, such as high-quality video streaming. To meet IMT-Advanced (International Mobile Telecommunications) requirements, LTE-A (LTE-Advanced), as in 3GPP (Third Generation Partnership Project) Release 10, is an enhancement of the LTE standard and further improves capacity and coverage, higher data rates through carrier aggregation, and ensures user fairness. LTE-A supports heterogeneous networks with co-existing macrocells, picocells, femtocells, and relay nodes, and brings the network closer to the end users by adding these low power nodes.

According to the International Telecommunication Union (ITU), as of February 2013 there were 6.8 billion mobile subscriptions worldwide. That is equivalent to 96 percent of the world population and is a huge increase from 6.0 billion mobile subscribers in 2011 and 5.4 billion in 2010 [1]. With so many mobile users, there has been a significant growth in cellular traffic over the past few years with the invention of smart phones, tablet devices, and other mobile devices supporting a wide range of applications and services including video streaming. As the demand for capacity in mobile broadband communications increases dramatically every year, wireless

Lili Wei and Geng Wu are with Intel Corporation.

Rose Qingyan Hu is with Utah State University.

Yi Qian is with the University of Nebraska-Lincoln.

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carriers must be prepared to support up to a thousand-fold increase in total mobile traffic by 2020, requiring the search for innovative solutions to enable the 5G era [1–3]. Millimeter wave (mmWave) communications, with possible gigabit-per-second data rates, have attracted great attention as a candidate technology for 5G wireless systems.

The mmWave band often refers to the frequency range from 30 GHz to 300 GHz, also called extremely high frequency (EHF), which is the highest electromagnetic radiation radio frequency band. The 3–30 GHz spectrum is generally referred to as the super high frequency (SHF) band. Since radio waves in the SHF and EHF bands share similar propagation characteristics, 3–300 GHz spectrum is collectively referred as mmWave bands with wavelengths ranging from 1 to 100mm [4]. There are several motivations/advantages to utilize mmWave frequencies in future 5G networks [5]. First, there is an enormous amount of spectrum at mmWave frequencies, including the local multipoint distribution service at 28–30 GHz, the license-free band at 60 GHz, and the E-band at 71–76 GHz, 81-86 GHz, and 92–95 GHz [6], while the current cellular system below 3 GHz already has a very crowded and scarce spectrum. Second, at mmWave communications, due to high attenuation in free space and penetration, the same frequency can be reused at short distances. Third, the physical size of antennas at mmWave frequencies is so small that it becomes practical to build complex antenna arrays and/or further integrate them on chips or PCBs (printed circuit board). Fourth, the inherent security and privacy of mmWave transmission is better because of the limited transmission range and the relatively narrow beam widths that can be achieved.

MmWave communications have already been standardized as a physical layer (PHY) alternative for wireless personal area networks (WPAN) in IEEE 802.15 Task Group 3c (TG3c) at 57–64 GHz band, and IEEE802.11ad (WiGig) at 60 GHz mmWave for short range applications such as wireless docking and display. To enable mmWave communications in future 5G cellular networks, there are still many challenges and research areas that need to be addressed. In this article we discuss six key elements to enable mmWave communications in 5G. The first three elements are related to mmWave transmission characteristics: mmWave channel characteristics; beamforming technologies due to mmWave path loss; and block effect due to short wavelength of mmWave signals. The last three elements are concerns arising from applying mmWave communications into typical 5G network scenarios: mmWave in D2D communications; mmWave in heterogenous networks; and mmWave for small cell backhaul.

MmWave Channel Characteristics

Although the mmWave band has gained great interest for 5G cellular systems, there are many concerns about the transmission characteristics at such high frequencies, especially signal attenuation due to free space propagation, atmospheric gaseous, and rain. We will focus on these three areas to discuss mmWave channel characteristics.

Traditionally, the Friis transmission law gives us the following equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2, \tag{1}$$

where P_r and P_t are received power and transmit power, respectively; G_t and G_r are the antenna gains of the transmit and receive antennas, respectively; λ is the wavelength; and R is the distance in meters between the transmitter and receiver. A direct result of the Friis transmission law is that the free-space path gain scales at λ^2, that is, the path loss grows with the square of the carrier frequency with isotropic transmit and receive antennas ($G_t = G_r = 1$). Hence, for mmWave bands, due to the high carrier frequency, mmWave communications will suffer from high path loss. However, this statement is actually based on the assumption that the effective antenna aperture area increases with wavelength (decreases with carrier frequencies), which may not be fair for the comparison of different frequencies. It is also pointed out in [4, 7] that for a fixed physical aperture size, the antenna gain is proportional to the square of the frequency since with short wavelengths, more antennas can be packed into the same effective area. The transmit and receive antennas at higher frequencies can send and receive more energy through narrow directed beams. An example is given in [7] for transmissions at 3 GHz and 30 GHz, where a 3 GHz system with a patch receive antenna and a 30 GHz system with an array antenna of the same physical size are compared. The propagation loss is in fact the same for these two transmissions regardless of the carrier frequencies. When array antennas are used at both transmit and receive ends at 30 GHz transmission, the receive power is actually 20 dB higher than that of the 3 GHz patch antenna case.

Regarding atmospheric gaseous losses of mmWave transmission due to oxygen molecule (O_2) and water vapor (H_2O) absorption, actually only at some mmWave frequencies, absorption results in high attenuation of the radio signal. The 57–64 GHz band is an oxygen absorption peak (about 15 dB/km attenuation), and the 164–200 GHz band is a water vapor absorption peak (about 20–30 dB/km attenuation) [4, 8]. For those oxygen or water vapor absorption frequencies, high attenuation of radio signals will result in short propagation distance. Nevertheless, beyond those absorption peaks, the spectral regions of mmWave are not heavily affected by gaseous losses. For example, atmospheric loss at 28 GHz is negligible since O_2 absorption is about 0.02 dB/km and H_2O absorption is about 0.09 dB/km at this frequency [8].

Rain is another concern regarding mmWave propagation, since raindrops are roughly the same size as the radio wavelengths, and therefore cause scattering of the radio signals. Rain can be divided into categories according to the rate of precipitation: light rain describes rainfall at a rate of 0.25mm–1mm per hour; moderate rain describes rainfall of 1mm–4mm per hour; heavy rain describes rainfall of 4–16mm per

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hour; and very heavy rain describes rainfall of 16mm–50mm per hour. Figure 1 from [8] (pp. 59, Figure 10) shows the rain attenuation in dB/km at various rainfall rates. We can see that at a very heavy rainfall of 25mm/hr, the rain attenuation is about 7 dB/km at 28 GHz and about 10 dB/km at 73 GHz. Considering today's cell sizes in urban environments are on the order of 200m [3], the rain attenuations reduce to only 1.4 dB at 28 GHz and 2 dB at 73 GHz if cell coverage regions are 200m in radius even in a very heavy rainfall. Hence, rain attenuation will present a minimal impact on mmWave propagation for a small cell structure.

Beamforming Technologies in MmWave Communications

As discussed in the previous section, the path loss of mmWave transmission can be comparable to those of typical cellular frequency bands when the transmit and receive antennas are used to produce beamforming gain. Highly directional antenna arrays are expected in mmWave communication systems, and thanks to the very small wavelength of mmWave signals, large beamforming gain is possible through large antenna arrays packed into small dimensions. For a given effective area, the directivity of antenna scales with the inverse of the frequency square.

In traditional cellular communication systems, both beamforming and precoding (beamforming with multiple data streams to improve spectral efficiency) are implemented at the baseband. In mmWave systems, however, while additional antenna elements are usually inexpensive and the additional digital signal processing becomes even cheaper, the radio frequency (RF) elements are expensive and are more challenging to follow Moore's law [9]. In digital beamforming, for each antenna element at the transmitter or the receiver, a complete dedicated RF chain is required, including low-noise amplifiers, down-converters, and analog-to-digital converters, and so on. Furthermore, due to highly directive antennas, multipath is rather sparse at the mmWave band, leading to a possibly low diversity gain from digital beamforming and precoding. Thus, the high cost of mixed analog/digital signals and RF chains, and low multipath diversity gain, make operation in the passband and analog domains attractive for mmWave transmissions [10].

Correspondingly, in mmWave communication systems, a hybrid beamforming architecture with a hybrid combination of analog beamforming and digital precoding may be one favorable possibility. Hybrid beamforming offers a good compromise between all digital and all analog beamforming structures. Analog beamforming applies complex coefficients to manipulate the RF signals by means of controlling phase shifters and/or variable gain amplifiers and aims to compensate for the large pass loss at mmWave bands, while digital beamforming is done in the form of digital precoding that multiplies a particular coefficient to the modulated baseband signal per RF chain to optimize capacity using various MIMO techniques [7]. Although multipath is sparse in mmWave due to the high directivity of antennas, multiple sets of antennas can be spaced several wavelengths apart in a small effective area to enable MIMO techniques, even in a LOS environment. In general, digital beamforming is more flexible and has a better performance. But as each output needs to have a dedicated RF chain, it will have an increased complexity and cost. On the other hand, analog beamforming is a simple yet effective method to generate high beamforming gain with a large number of antennas allowed in mmWave bands. Therefore, it is a trade-off between flexibility/ cost, simplicity, and performance that drives the need for hybrid beamforming architectures.

In Fig. 2 we illustrate the different beamforming diagrams in a traditional sub 3 GHz cellular system and a mmWave system. In a traditional cellular system, beamforming is performed in the baseband with the number of RF chains equal to the number of transmit antennas. In mmWave transmission, with the very small wavelength size, we have a large number of transmit antennas N_T but with limited dedicated RF chains N_{RF} ($N_T \geq N_{RF}$), hence the hybrid beamforming architecture can be one possible solution. There can be other possibilities, such as modular antenna array. In this structure, many smaller antenna arrays are put together, where each of them steers beams on their own. On top of that there is a general control to steer the overall beams together.

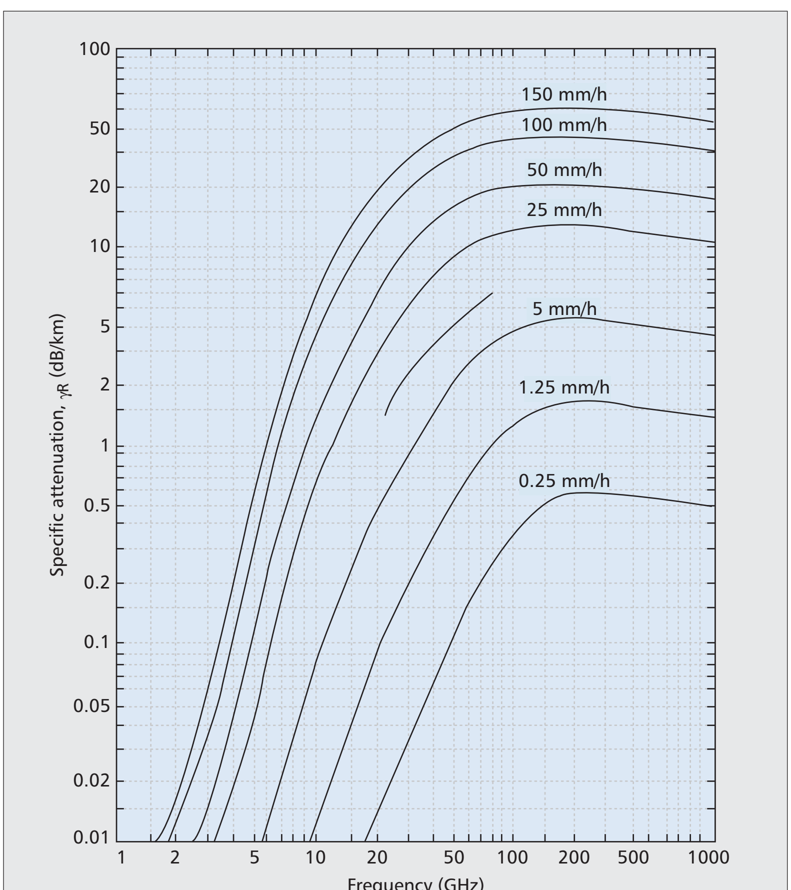

Figure 1. Rain attenuation in dB/km at various rainfall rates (figure from [8]).

Blockage Effect in mmWave Communications

While signals at lower frequencies can penetrate more easily through buildings, mmWave signals do not penetrate most solid materials very well [4]. Due to the short wavelength of mmWave signals, a distinct characteristic of mmWave communications is that mmWave links are susceptible to blockages, such as walls, wood, glass, trees, or even the human body and other devices. For example, the attenuation of a signal at 40 GHz through concrete materials with 10 cm thickness is 175 dB, while the attenuation of a wireless signal at less than 3 GHz is 17.7 dB [4]. Hence, for a user equipment (UE) being serviced with a mmWave line-of-sight (LOS) direct link, when the UE moves or a moving obstacle appears, the blockage effect may cause the loss of the mmWave LOS link. This link breakage problem needs to be handled through some anti-blocking schemes to transmit mmWave signals around the obstacles to the destination, which is crucial for mmWave communications to maintain seamless network connectivity and the achievable system throughput.

One possible approach to solve the blockage effect is through a collection of non-line-of-sight (NLOS) communications. Although reflection and diffraction reduce the range of mmWave LOS transmissions, it also facilitates NLOS link communications. When a LOS link breakage happens, the transmitter needs to quickly search through different beam directions to bypass the obstacles such that the receiver can collect some NLOS link signals to maintain the acceptable channel quality. In other words, an adaptive beamforming prototype needs to be designed to support the transformation from LOS links to NLOS links due to blockage effect. However, the path loss of a NLOS link is much more severe than that of a LOS link. We can look at an example of the Urban Micro (UMi) scenario [11] defined in the IMT-Advanced radio interface, where the height of both the antennas at the base station (BS) and those at the user devices are assumed to be well below the tops of surrounding buildings, and all these antennas are assumed to be outdoors in an area where streets are laid out in a Manhattan-like grid. The path loss model for this UMi scenario is

$$\begin{cases} PL_{LOS} = 22\log_{10}(d) + 28 + 20\log_{10}(f_c) \\ PL_{NLOS} = 36.7\log_{10}(d) + 22.7 + 26\log_{10}(f_c), \end{cases} \quad (2)$$

where d is the distance in meters and f_c is the carrier frequency in GHz. The best NLOS links can still be tens of dBs weaker than LOS signals.

Another possible approach to solving the blockage effect is through a higher density infrastructure and/or relays [6]. The BSs and relays are densely deployed in an outdoor urban area for mmWave communications, such that whenever a LOS beam blockage occurs and the collection of NLOS links does not give satisfactory channel quality, the transmitter may steer the beam direction to a target at a nearby BS or a relay which can have a LOS link with the destination. Hence, the adaptive beamforming prototype needs to be designed to support the transformation from LOS links to NLOS links, and to establish multihop LOS links to the destination. The two possible approaches are illustrated in Fig. 3. Other possible approaches may include separation between control and data planes so that a higher quality stringent control plan can be put into a reliable lower frequency band, while a more bandwidth demanding data plane can be put into the mmWave bands [12], and so on.

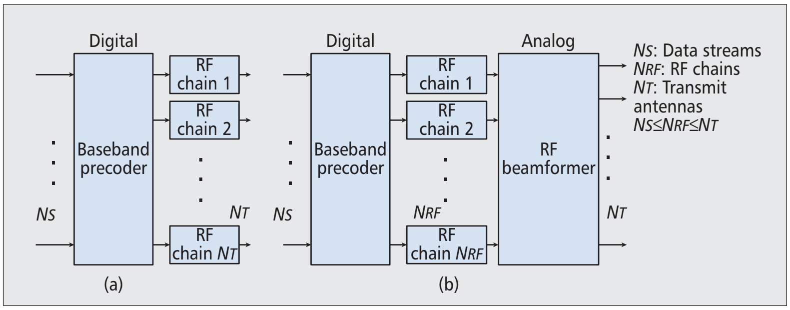

Figure 2. Beamforming diagrams: a) sub 3 GHz system; b) mmWave system.

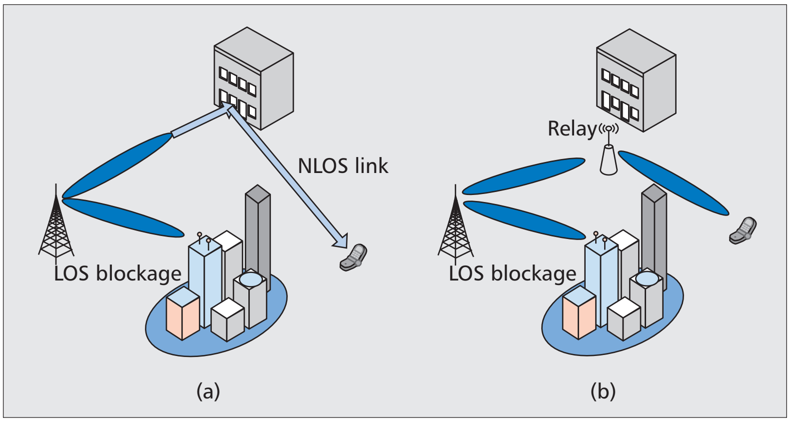

Figure 3. Two possible approaches for blockage effect.

It should be noted that the blockage issues in typical commercial deployment environments still need extensive channel measurements and modeling at the targeted frequency bands. This is an important area that requires further study. In addition, depending on the severeness and the time varying nature of the channel blockage behavior, new multiple access schemes and beamforming techniques may be required.

mmWave Transmission in D2D Communications

The usage of directional antennas in mmWave transmission brings narrow directive beams a new feature to mmWave systems, which can reduce fading, multi-path and interference. Adaptive arrays with narrow beams lessen the impact of interference, meaning that mmWave systems could more often operate in noise-limited rather than interference-limited conditions [6]. We can exploit this mmWave characteristic into device-to-device (D2D) communications [13], which allow a UE to communicate with another UE in proximity directly over a D2D link, with-

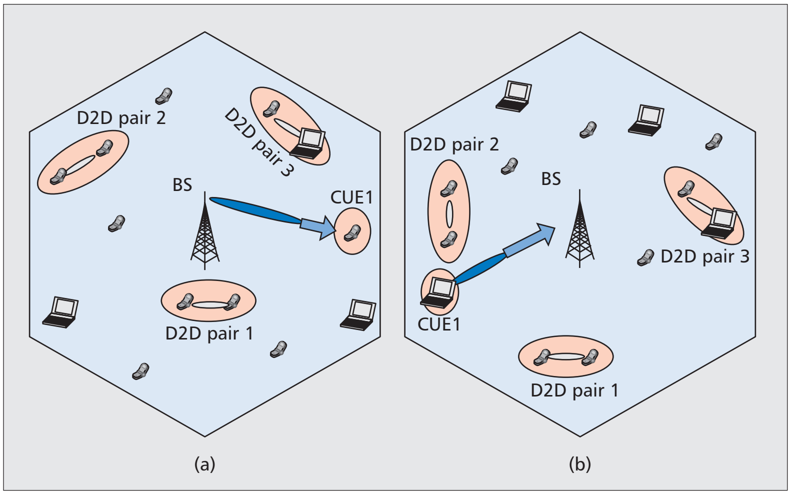

Figure 4. MmWave transmission in non-orthogonal D2D communications.

out extra hops through the central BS. As D2D communications are considered as underlaying cellular networks and may not have dedicated channel resources, chances are good that D2D pairs will share the same resources with some existing cellular UEs (CUEs).

Multiple D2D pairs in the same cell will be allowed to share the same resources with a CUE in order to maximize the spectrum efficiency. Consequently, in such a non-orthogonal co-channel sharing mode, interference management will be critical for D2D communications underlaying cellular networks. For example, when D2D pairs share downlink cellular resources, interference from high-power BS to D2D transmission can be overwhelming. Also, when D2D pairs share uplink cellular resources, if D2D pairs stay too close to a CUE, the CUE uplink transmission will be disturbed. In the meantime, a D2D pair may also be subject to strong interference from other co-channel D2D pairs.

When mmWave transmission is applied in the D2D communication architecture, D2D communications may change from non-orthogonal co-channel sharing mode to orthogonal dedicated channel mode since there can be abundant channel resources available in mmWave bands. Even if D2D communications share the same radio resources with CUEs, mmWave transmission with narrow beams can alleviate the co-channel interference issue and significantly increase the spatial reuse gain. As shown in Fig. 4, when D2D communications are implemented with mmWave transmission, highly directional beamforming will diminish the interference to other co-channel transmission links nearby. In the downlink mmWave transmission of Fig. 4a, D2D pair 1, which locates closely to the central BS, can still survive as long as it avoids the main lobe of the BS transmission beam. In the uplink mmWave transmission of Fig. 4b, CUE 1 can still fulfill its conveyance even if a co-channel D2D pair 2 is in communication, given that the D2D pair transmission is not steering at CUE 1. Hence, with the application of directional mmWave transmission in short-range D2D communications, the overall system spatial and spectrum reuse performance will be greatly improved. D2D is fundamentally a different way of communication than traditional cellular networks. The cell-less nature of D2D communication requires a new set of design consideration and engineering rules, in particular when such network clusters operate as a moving underlay network in a traditional cellular network environment.

MmWave Transmission in Heterogeneous Networks

Unlike homogeneous deployment, in heterogeneous networks (HetNet) [14] there are a diverse set of BSs, such as traditional macro BSs, and low power and low cost micro BSs such as picos, femtos, and relays to enhance network capacity, coverage, and energy efficiency. Those low power and low cost nodes can be scattered in wireless networks on coverage holes or capacity-demanding hotspots to supplement conventional single-tier cellular networks. Heterogeneity is expected to be a key feature in LTE-Advanced networks. However, single-frequency operation for macro cells and densely deployed small cells can cause strong cross-tier co-channel interference. In addition, small cells can experience frequent handovers and cell changes in high mobility areas.

A possible solution is macro-assisted small cell, called the *phantom cell* [12], or the booster cell in an anchor-booster architecture [15], which establishes a new form of multicell cross-tier cooperation between macro cells and small cells required for further network densification and spectrum extension into higher frequency bands. This new radio access network architecture is also referred to as the anchor-booster architecture. It is a key enabling technology for efficient utilization of high frequency bands through carrier aggregation techniques. In such a system, lower frequency bands such as existing sub 3 GHz cellular bands are used in wide areas for macro cells to provide blanket coverage and mobility, while higher frequency bands such as mmWave bands are employed in the small areas for small cells to provide high capacity. The control plane (C-plane) and user data plane (U-plane) of phantom cells are separated: the control information is sent by high-power nodes at lower frequencies, whereas the payload data is conveyed by low-power nodes at mmWave frequencies [6]. The phantom cell solution is illustrated in Fig. 5. For this phantom cell approach with a C-plane/U-plane split, there are no issues related to macro-to-small cell cross-tier interference. In the meantime, the control signaling due to frequent handover between small cells and macro cells, or among small cells, can be significantly reduced.

In the above frequency-separated architecture, efficient and effective small cell discovery in mmWave bands is important yet challenging. For cell discovery and association in LTE systems, the base station will omnidirectionally broadcast a common reference signal (CRS) for UEs to calculate the reference signal received power (RSRP). The discovery area of the base station is defined as the area within which the RSRP is above a certain threshold [15]. Since highly directional antenna arrays will be utilized for data transmission in mmWave bands, the difference between the discoverable area and the actual supportable area in mmWave small cells is not marginal.

There are several ways to tackle the mismatch problem. One possible way is to let the macro BS get the central control over mmWave small cell discovery, while another possible way is to implement small cell discovery at sub 3 GHz low frequency bands [15]. For the macro BS controlled approach, macro BS should know the supportable area of the mmWave small cells and track the motion of all UEs. Whenever a UE enters the coverage of a mmWave small cell, it will notify the small cell BS and the UE for further connection. The discovery using a low frequency band approach needs to choose a proper RSRP threshold to match the discovery area by the low frequency band with the actual supportable area in the mmWave band.

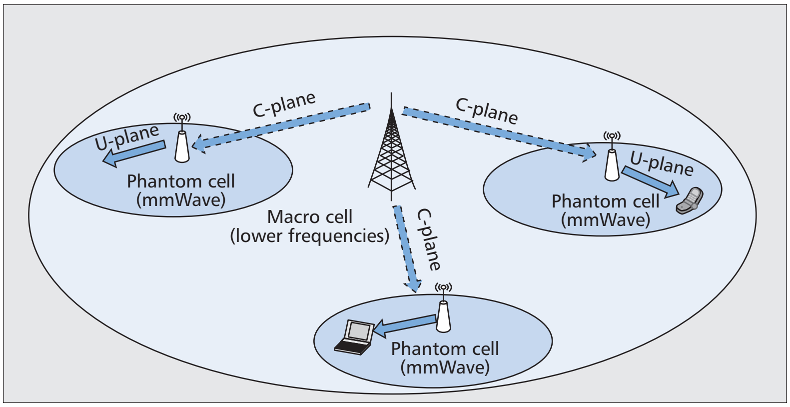

Figure 5. MmWave small cells with C-plane/U-plane split.

MmWave Transmission for Small Cell Backhaul

As mentioned in the introduction, the proliferation of mobile data applications and traffic is demanding revolutionary approaches for the realization of future 5G systems. Based on [1], compared with today's 4G wireless networks, 5G systems will need to further support the following:

- 1000 times higher mobile data volume per area.
- 10 to 100 times higher number of connected devices.
- 10 to 100 times higher user data rate.
- 10 times longer battery life for low power massive machine communications.
- Five times reduced end-to-end delay.

As a viable approach to delivering the above ambitious objectives, small cells have emerged as one of the most promising technologies for the future 5G requirements. While small cells can greatly increase the network capacity/coverage, extend the mobile device battery life, and achieve wireless network energy efficiency, there are still many challenges to overcome. One of the most significant challenges is how to provide scalable, affordable, and flexible mobile backhaul to connect high capacity small cells back into the network.

Of course, fiber is one of the preferred solutions for small cell network backhaul, as it has been a proven technology that offers abundant capacity and high scalability. However, the cost and challenge of implementing fiber to each small cell site make the solution impractical, particularly in the unplanned small cell sites or in dense urban areas where streets and sidewalks may not easily be trenched. On the other hand, if wireless backhaul is considered, some other factors need to be considered, including spectrum availability, propagation environment, LOS availability, and capacity requirements. Licensed spectrum in sub-6 GHz would be a favorable option due to its higher spectral efficiency and higher tolerance to NLOS propagation. However, the sub-6 GHz band does not have sufficient bandwidth to support the backhaul links needed for the high capacity 5G small cells. Similarly, traditional licensed LOS microwave point-to-point links between 6 GHz to 42 GHz have played important roles in backhaul for 3G and 4G, but the demands of 5G will quickly deplete its capacity. The fast escalation of 5G capacity requirements will push the backhaul spectrum toward higher frequency bands, for example, beyond 42 GHz mmWave bands. The popular mmWave candidate bands include the unlicensed 60 GHz band and the lightly licensed 70-80 GHz band, where there are abundant spectrums available and the LOS wireless communications can help control interference and thus offer a larger spectrum reuse again. Furthermore, even though mmWave normally would need LOS, it can still work in an NLOS environment by using relays or relying on diffractions/ reflections to compensate for NLOS, provided quality-of-service (QoS) can still be achieved. We compare small cell backhaul candidates in Table 1.

Although mmWave has huge potential to deliver high-capacity links, reliability issues due to rain-fade and beam-alignment will remain as the major technical hurdle for the mmWave based mobile network backhaul. It relies on tightly-focused antenna beamwidths and a big chunk of spectrum allocation to approach the target 5G capacities. Self-configurable electronic beam-steering/switching with high directional accuracy is thus desirable to help for beam alignment due to wind or other causes. mmWave link attenuation increases quickly as rainfall increases, and in fact the biggest attenuation in the entire 1–100 GHz frequency range occurs around the popular 60/80 GHz range, as shown in Fig. 1. As pointed earlier, a heavy rain level (25mm/h) causes 10 dB/km loss, and a tropical rain level (100mm/h) causes 30 dB/km loss. Nevertheless, as mentioned previously, most of the small cells are targeted to work in the range of 100-200m inter-site distance (ISD), rendering the rainfall loss to fall into an acceptable range.

Conclusions

Millimeter wave communications are promising candidates for future wireless networks to meet the requirement of the mobile traffic explosion. In this work we discuss six key elements to enable mmWave communications in future 5G broadband cellular communication networks and

Small cell backhaul candidates	Cost	Reliability	Capacity	Deployment
New fibers (not existing ones)	Medium	Very high	Very high	Difficult
Licensed sub 6 GHz	Low	High	Low	Easy
Unlicensed sub 6 GHz	Low	High	Low	Easy
Unlicensed 6–42 GHz	Low	Medium	Medium	Easy
Beyond 42 GHz mmWave	Low	Medium	High	Easy

Table 1. Small cell backhaul candidates comparison.

try to address those mmWave challenges with possible approaches.

- For mmWave channel characteristics, we explained that with the same physical sized array antenna, the propagation loss of mmWave transmission can be comparable to those of typical cellular frequency bands. We also showed that beyond some absorption peaks, the spectral regions of mmWave are not heavily affected by gaseous losses. Then we showed that rain attenuation will present a minimal impact on mmWave propagation for small cell structure.
- We described a hybrid beamforming architecture as a possible solution for mmWave beamforming.
- To deal with the blockage effect, we can collect NLOS communications or through a higher density infrastructure and/or relays.
- With mmWave in non-orthogonal D2D communications, we discussed the advantages of overall system spatial and spectrum reuse performance improvement.
- For mmWave transmission in heterogenous networks, we described the possible solution of a macro-assisted small cell architecture, with booster cells performing in the mmWave band and macro cells performing in the lower cellular band.
- With mmWave transmission for small cell backhaul, we compared the small cell backhaul candidates with different frequency bands.

Research areas with more specific solutions and analysis for those six elements will be open issues for further investigation. Overall, it is believed that millimeter wave communications will be a main feature in the 5G era.

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Biographies

LILI WEI [S'05, M'11] (liliwei@ieee.org) received the B.S. and M.S. degrees from Shanghai Jiao Tong University, China, and the Ph.D. degree from the State University of New York at Buffalo, respectively. From 2000 to 2001 she worked as an R&D engineer at the Wuhan Research Institute of Posts and Telecommunications, China. Then she was with the Chinese Academy of Telecommunication Technology, Beijing, China and worked on the development of 3G TD-SCDMA wireless communication systems until August 2003. After pursuing the Ph.D. degree, she worked as a Postdoc Research Fellow at the State University of New York at Buffalo, Shanghai Jiao Tong University, and Utah State University. She is a senior research scientist in the Mobile and Communications Group, Intel Corporation. Her research interests are in communication theory and signal processing, including wireless cooperative networks, spread-spectrum theory and applications, and practical communication systems. Dr. Wei is a member of IEEE Communications Society.

ROSE QINGYANG HU [S'95, M'98, SM'06] (rosehu@ieee.org) received a B.S. degree in electrical engineering from the University of Science and Technology of China, an M.S. degree in mechanical engineering from the Polytechnic Institute of New York University, and a Ph.D. degree in electrical engineering from the University of Kansas. From January 2002 to June 2004 she was an assistant professor with the Department of Electrical and Computer Engineering at Mississippi State University. She also has more than 10 years of R&D experience with Nortel, Blackberry, and Intel as a technical manager, a senior wireless system architect, and a senior research scientist. She was Nortel 4G wireless system level simulation and performance evaluation prime. Currently she is an associate professor with the Department of Electrical and Computer Engineering at Utah State University. Her current research interests include next-generation wireless communications, wireless network design and optimization, green radios, multimedia QoS/QoE, communication and information security, wireless system modeling, and performance analysis. She has published extensively and holds numerous patents in her research areas. She is currently serving on the editorial boards for *IEEE Wireless Communications Magazine*, *IEEE Internet of Things Journal*, and *IEEE Communications Surveys and Tutorials*. She has also been a six-time guest editor for *IEEE Communications Magazine*, *IEEE Wireless Communications Magazine*, and *IEEE Network Magazine*. Prof. Hu received the IEEE Globecom 2012 Best Paper Award. She is a senior member of IEEE and a member of the Phi Kappa Phi and Epsilon Pi Epsilon Honor Societies.

YI QIAN [M'95, SM'07] (yqian@ieee.org) is an associate professor in the Department of Computer and Electronics Engineering, University of Nebraska-Lincoln (UNL). Prior to joining UNL he worked in the telecommunications industry, academia, and the government. Some of his previous professional positions include serving as a senior member of scientific staff and a technical advisor at Nortel Networks, a senior systems engineer and technical advisor at several startup companies, an assistant professor at the University of Puerto Rico at Mayaguez, and a senior researcher at the National Institute of Standards and Technology. His research interests include information assurance and network security, network design, network modeling, simulation and performance analysis for next generation wireless networks, wireless ad hoc and sensor networks, vehicular networks, broadband satellite networks, optical networks, high-speed networks, and the Internet. He has a successful track record in leading research teams and publishing research results in leading scientific journals and conferences. Several of his recent journal articles on wireless network design and wireless network security are among the most accessed articles in the IEEE Digital Library. He is a member of ACM.

GENG WU [SM'04] (geng.wu@intel.com) received the B.Sc. degree in electrical engineering from Tianjin University, Tianjin, China, and the Ph.D. degree in telecommunications from Université Laval, Quebec City, Canada. He is currently chief scientist and director of standards and advanced technology with the Mobile and Communications Group, Intel Corporation. Prior to joining Intel he was director of wireless architecture and standards with Nortel Networks, where he was responsible for wireless technology and standards development. He has over 20 years of research and development experience in the wireless telecommunication industry, extensively contributed to Second-, Third-, and Fourth-Generation air interface technologies and network architecture development. He is the holder of 28 U.S. patents. His current research interests include mobile computing and communication platforms, heterogeneous networks and cloud-based radio access networks, next-generation air interface technologies, and advanced mobile services and applications.