10 Gb/s HetSNets with Millimeter-Wave Communications: Access and Networking – Challenges and Protocols

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ABSTRACT

Heterogeneous and small cell networks (HetSNets) increase spectral efficiency and throughput via hierarchical deployments. In order to meet the increasing requirements in capacity for future 5G wireless networks, millimeter-wave (mmWave) communications with unprecedented spectral resources have been suggested for 5G HetSNets. While the mmWave physical layer is well understood, major challenges remain for its effective and efficient implementation in HetSNets from an access and networking point of view. Toward this end, we introduce a novel but 3GPP backwards-compatible frame structure, based on time-division duplex, which facilitates both high-capacity access and backhaul links. We then discuss networking issues arising from the multihop nature of the mmWave backhauling mesh. Finally, system-level simulations evaluate the performance of HetSNets with mmWave communications and corroborate the possibility of having capacities of tens of gigabits per second in emerging 5G systems.

INTRODUCTION

The traffic load of wireless communications networks with various quality of service (QoS) requirements has recently been increasing rapidly due to the widespread use of mobile Internet applications by smart terminals. This trend continues, requiring emerging wireless networks to be designed to meet these requirements. The fifth generation (5G) cellular communications system is expected to be standardized around 2020 [1]. The overarching goal of 5G is to achieve 10 to 100 times higher user data rates such that in dense urban environments the typical user data rate will range from 1 to 10 Gb/s, while supporting 10 to 100 times more connected devices. Moreover, to facilitate the vision of the tactile Internet, end-to-end latency will need to be less than 5 ms so as to provide ultra-fast application response times.

As a result, novel physical, access, and network layer technologies are required to realize such ambitious goals. Generally speaking, there are several means to improve network performance. The first one is to increase the available bandwidth (e.g., carrier aggregation or cognitive radios). The second way is to increase geographic spectrum reusability through, say, device-to-device (D2D) communication and small cell techniques [2, 3]. The third but not least is to improve spectral efficiency, such as (massive) multiple-input multiple-output (MIMO) and non-orthogonal multiple access (NOMA) techniques. However, even though some of these techniques are able to boost performance substantially, there is no clear roadmap on how to achieve the so far defined 5G performance targets. Breakthrough technologies are thus needed in the near future.

Low frequency bands have been almost used up in recent years, and it is difficult to find sufficient frequency bands in the microwave range for 5G. By contrast, there are still a large number of unused frequency bands in the millimeter-wave (mmWave) bands, which may be of potential use to mobile cellular communications given recent advances in hardware and electronic components. At present, mmWave communications have already had numerous indoor and outdoor applications. It is well suited for not only in-home applications like audio/video transmission, desktop connections, and portable devices, but also outdoor point-to-point applications. MmWave communications also play an increasingly significant role as the wireless backhaul for outdoor small cells, thanks to its low costs, quick deployment, and flexibility. Apart from these benefits, the evolved NodeB (eNB) in a small cell may provide high system throughput through mmWave communications. The propagation characteristics of mmWave communications are characterized by a high level of oxygen absorption and rain attenuation, especially in outdoor environments. This limits the range and cell coverage of mmWave radio as opposed to microwave radio.

On the other hand, mmWave communications systems facilitate integration with the increasingly popular massive MIMO technology [4]. This is because the wavelength of mmWave radio is small enough so that the physical size of

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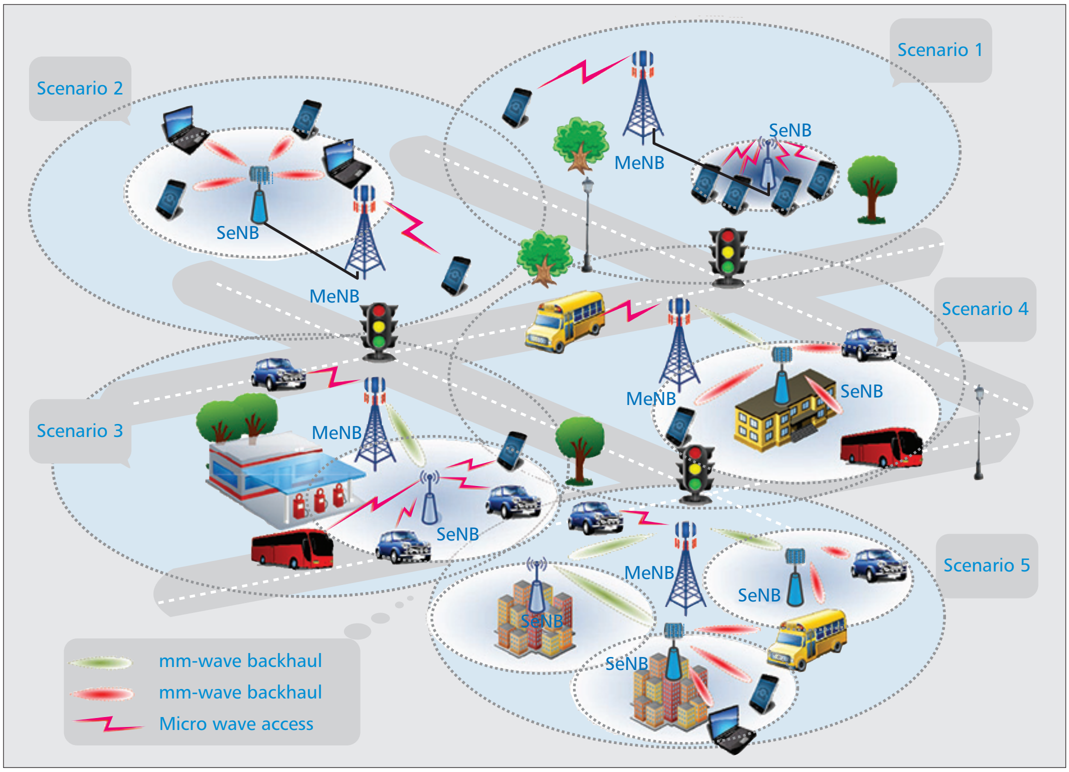

Figure 1. Illustration of typical deployment scenarios with both mmWave and microwave systems.

Heterogeneous and small cell networks (HetSNets) with mmWave communications will play a very important role in future 5G cellular networks. However, there are many problems related to the implementation of HetSNets with mmWave communications capabilities.

a massive antenna array can be greatly reduced for easy deployment at small-cell eNBs. Apart from improving spectral efficiency, massive MIMO is also an effective technique to compensate for the severe propagation loss of mmWave radio [5]. Recently, beamforming/precoding techniques with massive MIMO in mmWave have been studied widely in IEEE standards, such as IEEE 802.15.3c (TG3c) for wireless personal area networks (WPANs), IEEE 802.11ad (TGad), and the Wireless Gigabit Alliance (WiGig). Meanwhile, massive MIMO with 3D beamforming is becoming a much discussed topic in Release 12 of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) [6].

Therefore, heterogeneous and small cell networks (HetSNets) with mmWave communications will play a very important role in future 5G cellular networks. However, there are many problems related to the implementation of HetSNets with mmWave communications capabilities. While there is ample physical (PHY)-layer material available, such as [7], to the best of the authors' knowledge there have been few reported studies in the literature addressing the communications challenges from an access and networking point of view [8]. The scope of this article is thus to study the interplay of mmWave and microwave communications in HetSNets from the access and networking points of view.

Toward this end, the article is organized as follows. We briefly discuss typical deployment scenarios for HetSNets with mmWave communications. Given the scenario requirements, we then design a 3GPP-LTE-compliant time-division duplex (TDD) frame structure capable of supporting multihop transmission via a wireless backhaul. We discuss medium access and networking related challenges and solutions for HetSNets with mmWave communications. We then present and discuss performance results of previously introduced protocols. Finally, conclusions are drawn.

DEPLOYMENT OF MMWAVE COMMUNICATIONS IN HETSNETS

A HetSNet typically consists of multiple types of radio access nodes in a 3GPP LTE network, for example, a macrocell eNB (MeNB) and multiple small cell eNBs (SeNBs) such as pico, femto, and relay eNBs. In such a network, each SeNB combines its backhaul data with that received from other nodes in the network before forwarding it to the MeNB. The SeNBs are supposed to be separated by short distances (e.g., 100~200 m), which helps mitigate severe propagation losses. Coverage within the small cells (i.e., user access) may also be provided by mmWave radio, reducing the level of interference experienced on the sub-3 GHz frequency bands used for traditional cellular communications.

TYPICAL DEPLOYMENT SCENARIOS

With the introduction of mmWave communications in the HetSNet, there are several potential deployment scenarios with mmWave communications being used for backhaul and/or user access links. Some typical scenarios are illustrated in Fig. 1 and discussed in more detail below.

Scenario 1 (Baseline): Traditionally, an SeNB is connected to its donor MeNB through a wired backhaul such as an optical fiber. All user equipments (UEs) are served by either the MeNB or

Backward compatibility with 3GPP LTE systems must be considered when introducing mmWave communications into HetSNets. To facilitate the utmost efficient system design, a new frame structure has to be designed for mmWave communications coexisting with microwave communications in HetSNets.

SeNBs on the microwave band. Under this scenario, interference coordination schemes have to be carefully designed so as to avoid interference between the MeNB and SeNBs.

Scenario 2: Compared to scenario 1, the UEs communicating with the MeNB work on the microwave band, whereas the UEs served by the SeNBs use mmWave radio. The SeNBs are connected to the MeNB via a wired backhaul. No interference coordination is needed between the MeNB and SeNBs under this scenario. However, the UEs should support dual bands for smooth handover between the MeNB and SeNBs, thus increasing the costs of the UEs.

Scenario 3: In lieu of a wired backhaul, the mmWave band is employed for backhaul transmission between the MeNB and SeNBs. For the sake of implementation, only single-hop is permitted for backhaul transmission with mmWave radio. Through such a deployment, only network facilities need to be upgraded, while the UEs remain unchanged. This is helpful for quick deployment of SeNBs. Similar to scenario 1, advanced interference coordination schemes are necessary between the MeNB and SeNBs.

Scenario 4: MmWave communications are adopted for single-hop wireless backhaul for the SeNBs in scenario 4. Moreover, the SeNBs serve the UEs in a small cell via mmWave radio, which can significantly increase network capacity thanks to the tremendous bandwidth offered by the mmWave band.

Scenario 5: Increasing geographic spectrum reusability is another means to improve network capacity, resulting in dense small cell deployment. Then multihop wireless backhaul is a good way to connect dense SeNBs with the MeNB. In this scenario, the SeNBs can cooperate with one another and communicate with their donor MeNB via mmWave radio. Also, the access links between the SeNBs and their served UEs work on the mmWave band. This scenario is much more flexible and can provide high capacity, in which most key techniques for HetSNets with mmWave communications may be applicable.

Since Scenario 1 is the baseline, and Scenarios 2–4 are generally a subset of Scenario 5, we subsequently study the more general Scenario 5 from an access and networking point of view. Based on that scenario as well as the unique characteristics of mmWave communications, we subsequently design an improved 3GPP LTE backward-compatible access and backhaul frame structure.

FRAME STRUCTURE

The propagation characteristics of mmWave communication bands are fairly different from those of microwave communications, such as the Doppler frequency shift and multipath delay. Therefore, the orthogonal frequency-division multiplexing (OFDM) parameters for microwave communications in 3GPP LTE systems are *not* applicable to mmWave communications without modifications. On the other hand, much larger frequency bandwidths are available on mmWave communication bands, which means the bandwidth per subcarrier needs to be enlarged in order to keep unchanged the size and complexity of the fast Fourier transform (FFT). Moreover, backward compatibility with 3GPP LTE systems must be considered when introducing mmWave communications into HetSNets. To facilitate the utmost efficient system design, a new frame structure has to be designed for mmWave communications coexisting with microwave communications in HetSNets.

Assume that 28 GHz band with 1 GHz in bandwidth is used for mmWave communications due to its availability and popularity [9]. Measurement results show that the delay spread is not severe if the transmitter-receiver (Tx-Rx) separation is less 200 m at 28 GHz in the urban environment. In the line of sight (LOS) case, there are too few multipaths to determine the root mean squared (RMS) delay spread, while in the case of non-line-of-sight (NLOS), most measured multipath components have RMS delay spreads below 0.2 µs. Thus, OFDM-based mmWave wireless systems need to tolerate an RMS delay of 0.2 µs or less. The guard interval for mmWave communications is expected to be much larger than the RMS delay in order to alleviate intersymbol interference (ISI). Besides this, backward compatibility with microwave communications has to be taken into consideration.

Therefore, a guard period of 0.469 µs is selected, because this value is not only two times more than the measured RMS delay but also one tenth[1] of the guard period in microwave communications. A symbol period of 66.67 µs is selected in 3GPP LTE, which is 66.67/4.69 times larger than the guard period. Correspondingly, a useful symbol duration of 6.667 µs can be chosen for mmWave communications and the subcarrier spacing is computed as the inverse of the OFDM useful symbol duration (i.e., 150 kHz). Then the basic mmWave frame has 10 subframes, each of which is of 0.1 ms duration and consists of 14 OFDM symbols. The frame structure and main parameters are depicted in Fig. 2a as one possible TDD solution to HetSNets with mmWave communications.

When wireless backhaul is adopted in the HetSNet with mmWave communications, the mmWave subframe configuration is able to support multihop transmission. Each mmWave subframe can be used for single-hop transmission. Figure 2b illustrates an example configuration for multihop transmission. In the first mmWave subframe, the MeNB transmits backhaul signals to the nearby SeNB 1# in the first-hop transmission, and SeNB 2# far from the MeNB sends information to its small cell UEs (SUEs) simultaneously. Subsequently, the MeNBs remain silent in the second mmWave subframe, and SeNB 1# transmits signals to SeNB 2# and their SUEs, taking advantage of spatial multiplexing. The uplink procedure is similar to that of the downlink. Moreover, in order to reduce the Rx/Tx switch, several mmWave subframes can be grouped together to provide radio resources for a single hop.

MAC AND NETWORKING DESIGN CHALLENGES

The use of highly directional beamforming raises a number of new challenges in the network design. We focus only on the medium access

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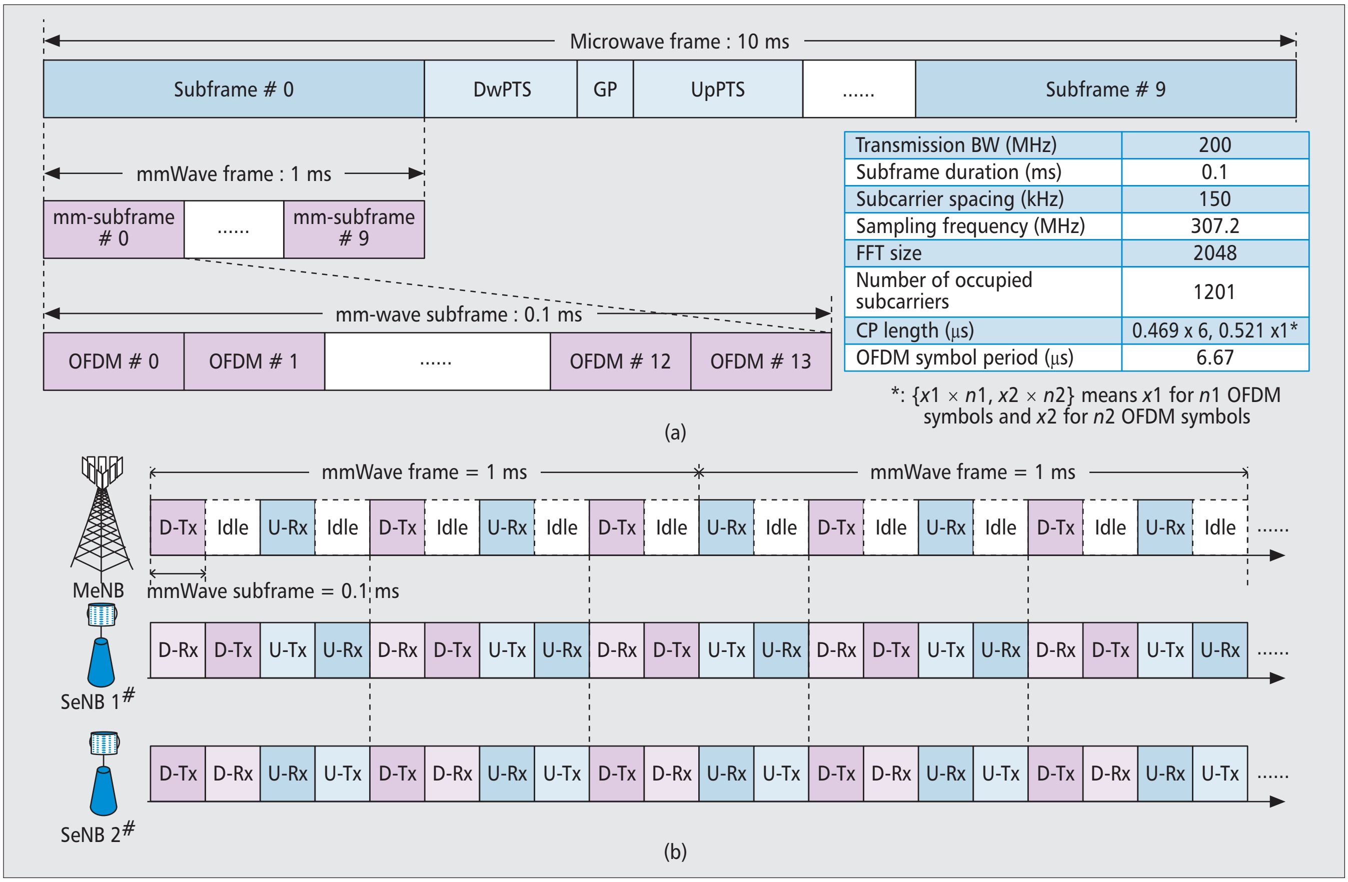
[1] Note that this approach is the inverse of a recent machine-type communications (MTC) approach, where the channel is downsampled by a factor of 10. In the future, we envisage legacy 3GPP LTE/LTE-A systems run at the sampling rate, whereas low-complexity MTC devices run on a tenth of the sampling rate, and ultra-high-capacity mmWave systems at a 10 times higher sampling rate.



Transmission BW (MHz)	200
Subframe duration (ms)	0.1
Subcarrier spacing (kHz)	150
Sampling frequency (MHz)	307.2
FFT size	2048
Number of occupied subcarriers	1201
CP length (μs)	0.469 x 6, 0.521 x1*
OFDM symbol period (μs)	6.67

*: $\{x1 \times n1, x2 \times n2\}$ means $x1$ for $n1$ OFDM symbols and $x2$ for $n2$ OFDM symbols

Figure 2. Illustration of the proposed frame structure: a) modified TDD frame structure for mmWave communications; b) mmWave subframe configuration for multihop communications.

control (MAC) and networking layers in this article. Thanks to the dense deployment of small cells using narrow beams with large gains on mmWave communication bands, multihop transmission is made possible in HetSNets. Routing schemes with a specific metric under certain delay constraints and reasonable control overheads become very important. Different from interference coordination in microwave communications, mainly in either the time or frequency domain, spatial interference coordination receives more attention in mmWave communications, and is thus discussed in this section. Moreover, due to the limited coverage of mmWave communications, control channels are implemented on microwave communication bands for connectivity and mobility management, and data channels via mmWave communication bands.

Routing in Multihop HetSNets

In dense urban areas, a large number of small cells may be deployed closely in HetSNets. There are backhaul connections among the SeNBs via mmWave radio. The backhaul between the SeNBs and their donor MeNB can be via either mmWave radio or wired links, depending on the deployment scenarios. In such a network, the nodes can cooperate with each other, providing improved reliability, enhanced coverage, and reduced equipment costs. Compared with mobile ad hoc networks, route recovery and energy efficiency are not major concerns for multihop HetSNets due to limited mobility and the existence of power supply at the eNBs. Moreover, there is almost no interference between mmWave signals due to the narrow beamform with large gains. In other words, the channels for connecting the SeNBs can be regarded as orthogonal, so no channel assignment is needed. However, each channel has its own propagation characteristics, and network topology is determined by the deployment scenario. Therefore, how to design an efficient routing protocol becomes one of the key challenges in multihop HetSNets.

When designing a routing scheme, one needs to taken into account several objectives, such as increasing system throughput, decreasing end-to-end delay, and achieving a good load balance. Thus, much attention is paid to obtaining a reliable quantitative routing metric, which can link several factors (e.g., system throughput, end-to-end delay, and connectivity) with the quality of the routing scheme. In general, we can define such a metric as a function of N influence factors I_j (i.e., $\gamma = f(I_1, I_2, \cdots, I_N)$). For example, there are two QoS factors that mainly affect the routing performance: the end-to-end delay τ and the packet loss rate η of the path. Then the routing metric can be defined as a linear weighted sum of the two influence factors, $\gamma = (1 - \beta)\tau + \beta\eta$, which determines the importance of the delay relative to the loss rate, and where β is a weighting coefficient.

Most existing routing algorithms are based on

Since the signal strength deteriorates rapidly in the mmWave band, more than one eNB can transmit simultaneously if they are not very close to each other. Thus, all the SeNBs are grouped into clusters according to the distances not only between themselves but also to their donor MeNB.

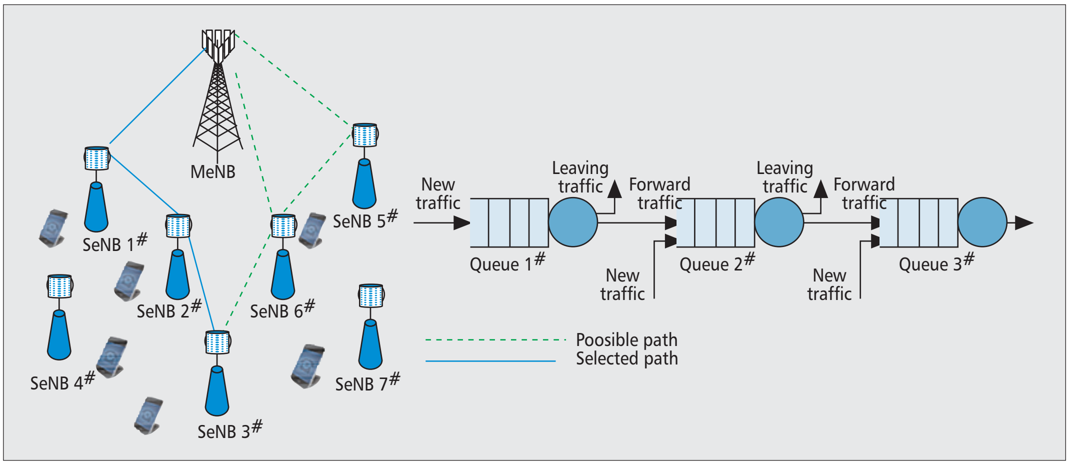


Figure 3. A routing example in multihop HetSNets.

the minimum hop count, which is of no interest for this article. Instead, through guaranteeing some end-to-end QoS requirements, QoS routing algorithms with specific routing metrics become much more promising in future broadband wireless communications networks. Queue theory is a good theoretical tool to solve QoS-related problems. In a multihop wireless network, not only the traffic arrival process but also the variation of the wireless channel can be modeled by a completed tandem queuing framework [10]. The queuing dynamics of nodes in a given path determines the end-to-end QoS metrics including the delay and loss rate, which have to be measured in a timely fashion in order to enable the routing algorithm to adapt to the changes of the network in time. The end-to-end delay is the sum of the delays that any packet experiences in all the queues and links along its routing path. Packets may be lost due to buffer overflow in one of the queues in tandem.

As shown in Fig. 2, a number of consecutive time slots form a fixed-sized time frame, where the time slots in each time frame are periodically allocated to some transmission links. Representing one hop, each link may be allocated time slots in each time frame with different spatial orthogonal channels formed by mmWave beamforming signals. Figure 3 presents an example of a possible path from an SeNB to the MeNB and its corresponding tandem queue. Data traffic entering each queue may come from different connections. Traffic from connections other than the considered connection may come and leave the tandem system in any queue. In other words, in each queue of the tandem system (except queue 1), either new or forwarding traffic arrives while the buffered traffic is leaving. There are K single queues along the route. The arrival traffic to each queue is from the previous queue of the tandem system and from other connections traversing the corresponding link (except for queue 1). Given the allocated radio resources for each link along the tandem system, we can determine the service rate. Thus, if the arrival probability for the aggregate traffic is determined, the queuing performance measures for each queue in the tandem system can be calculated.

Assume that all the end-to-end performance measures for a general tandem system of queues with an arbitrary number of hops can be found. Then the tandem queuing model can be applied to find a path of connections from a source node to its desired destination node so that the end-to-end QoS requirements for the connection can be satisfied. Given an optimization objective (e.g., minimizing the end-to-end delay), the best feasible route can be found by exhaustively searching all possible routes. However, this approach results in large signaling overhead and prohibitively high computational complexity. Therefore, investigating new routing schemes with the tandem queuing model in consideration of feasible implementation complexity becomes one of the challenges in studying the multihop HetSNet with mmWave communications.

Moreover, the route information of HetSNets can be updated periodically in the control channel to keep track of the changes in topology and traffic load of the network. To reduce the control overhead and delay, hierarchical routing schemes may be applied in HetSNets. Several neighboring SeNBs can be grouped together to form a cluster. Then routing can be performed either intra-cluster or inter-cluster, depending on service requirements.

Access Control and Interference Coordination

Thanks to the narrow beam in massive MIMO with mmWave radio, spectral resources can easily be reused spatially. The interference among various links and cells in the HetSNet with mmWave communications becomes much simpler than that with only microwave radio. However, since multihop transmission is allowed, and each eNB works in the half-duplex mode (still), the interference between the downlink and uplink has to first be avoided through interference coordination among the eNBs in the time domain. Since the signal strength deteriorates rapidly in the mmWave band, more than one eNB can transmit simultaneously if they are not very close to each other. Thus, all the SeNBs are grouped into clusters according to the distances not only between themselves but also to their donor MeNB. The eNBs in the same cluster can-

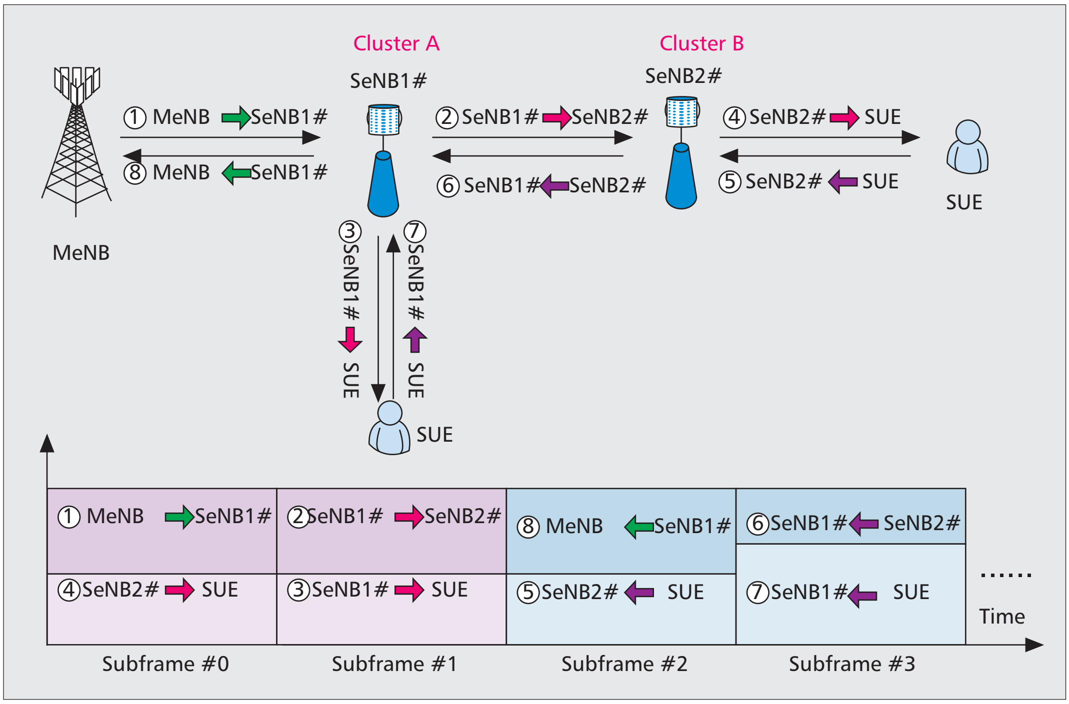


Figure 4. Illustration of radio resources allocation in multihop HetSNets.

Although dense small cells can facilitate geographic spectrum reusability, their small cell size may cause overly frequent handover. Consequently, it is imperative to introduce mechanisms for mobility management in the HetSNet with mmWave radio.

not transmit simultaneously, whereas those in different clusters can if the distance between the clusters is large enough. As illustrated in Fig. 4, the MeNB and SeNB 1# belong to Cluster A, while SeNB 2# is in Cluster B because it is a little far from the MeNB. Assuming that the configuration in Fig. 2b is adopted in the system, the MeNB establishes downlink backhaul transmission with SeNB 1# in subframe 0, while SeNB 2# also serves its SUEs in this subframe. In subframe 1, SeNB 1# transmits signals to both its SUEs and SeNB 2# distinguished by narrow beams, while the MeNB remains silent. A similar procedure is performed in subframes 2 and 3. Thus, by properly grouping all the SeNBs, interference can be avoided between the downlink and uplink in the HetSNet with mmWave communications.

Since the interference between the eNBs can be nearly eliminated through beamforming, neither intracell nor intercell coordination is necessary on the downlink. In other words, each eNB can reuse all the spectral resources. As shown in Fig. 4, due to the limitation of SUEs, distinguishing uplink signals cannot rely only on the spatial domain. In subframe 2, there is almost no interference between the access link from SUE to SeNB 2# and the backhaul link from SeNB 1# to MeNB due to spatial reuse. However, the signals from SUEs without beamforming arrive at SeNB 1# simultaneously in subframe 3, as well as the wireless backhaul signal sent from SeNB 2#. They may interfere with each other if no action is taken. A feasible way to avoid possible interference is to make the signals orthogonal in the frequency domain. Since the beamformer with large gains can still be used in the backhaul link, much less spectral resources are needed for the backhaul link of SeNB 2# to SeNB 1# than the access link from SUEs to SeNB 1#. Moreover, if there are more than one SeNB in cluster A, the uplink interference between the access links of the small cells can be coordinated by specific soft-frequency reuse schemes.

MMWAVE SOFTCELL CONCEPT

Although dense small cells can facilitate geographic spectrum reusability, their small cell size may cause overly frequent handover. Consequently, it is imperative to introduce mechanisms for mobility management in the HetSNet with mmWave radio. Motivated by the soft cell concept [6], control channels are provided by the MeNB with microwave communications, while high date rate services are supported by the SeNBs with mmWave communications in the small cells simultaneously (i.e., separated C-plane/U-plane configuration). Also, the MeNB mainly ensures wide-area coverage so as to maintain good connectivity and mobility. One of the carriers on the microwave bands is selected as the anchor carrier, in which the system and control signaling information are sent by the MeNB. When the control channels in the anchor carrier work normally, the SeNBs do not send cell-specific signals/channels, such as primary/secondary synchronization signals (PSS/SSS) and cell-specific reference signals (CRS). However, the resources for the control channels are reserved in the small cells and become active in the event of emergency, which is managed by the MeNB under the master-slave mode. Usually, the radio resource control (RRC) connection procedures such as channel establishment and release between the SUEs and SeNBs are controlled by the MeNB through the anchor carrier.

One of the most important benefits of the separation between C-plane and U-plane lies in its robustness to handover. There is no handover when a UE moves from one small cell to another within the coverage of the MeNB. Meanwhile, the requirements on the RRC messages can be relaxed because of the low handover probability between the macrocells. Also, energy efficiency can be improved by the separated C-plane/U-plane configuration in a massive deployment of small cells. For example, some SeNBs can be turned off when there are no serving SUEs. However, this requires new features of the UEs. Dual transmit channels and MAC entities in both the microwave and mmWave carriers have to be supported in the UEs. Then all the carriers can be measured and discovered rapidly.

PERFORMANCE AND DISCUSSIONS

System-level simulations for different cases of Scenario 5 have been carried out to evaluate the system performance of HetSNet with mmWave communications, where we evaluate the downlink throughput. Detailed simulation parameters, including the channel model and system assumptions, are summarized in Table 1, most of which are defined in the 3GPP specifications [11]. All the UEs are evenly distributed in circular areas around their donor eNB. For simplicity, an ideal tractable piecewise-linear array pattern is used in the simulations [12]. This pattern is a good approximation to the practical radio pattern. Assuming broadside transmission (i.e., maximum gain at the azimuth angle of 0), the normalized array gain at an azimuth angle θ is given by

$$g(\theta)=\begin{cases} 1, & \text{for } \theta<\theta_1 \\ 1-\dfrac{|\theta|-\theta_1}{2(\theta_{3dB}-\theta_1)}, & \text{for } \theta_1 <|\theta|\leq \theta_2 \\ \text{FBR}, & \text{for } \theta_2<\theta\leq \pi, \end{cases} \quad (1)$$

where FBR denotes the front-to-back ratio, and θ_{3dB} is the half-power beamwidth. The variables θ_{3dB}, θ_1, and θ_2 control the array manifold shape, half-power beamwidth, and FBR, respectively.

Parameters		Values
Carrier frequency/bandwidth (microwave)		2 GHz/ 10 MHz
Carrier frequency /bandwidth (mmWave)		28 GHz/ 200 MHz
MeNB inter-site distance (ISD)		500 m
Cellular layout		Hexagonal grid/ 19 sites/3 sectors per site
Small cell deployment		2, 4, 10 SeNBs per sector
UE density		60 UEs per site
Total MeNB Tx power		46 dBm
Total SeNB Tx power		37 dBm
MeNB antenna configuration		2
SeNB antenna configuration		Linear array
UE antenna configuration		1
Noise figure at UE		9 dB
Thermal noise density		–174 dBm/Hz
Penetration loss (mmWave)		100 dB
Shadowing standard deviation		8 dB microwave/ 12 dB mmWave
Path loss	Microwave	128.1 + 37.6log(*R*), *R* in km
	mmWave	157.4 + 32log(*R*), *R* in km [5]

Table 1. Parameters assumption in HetSNets with mmWave communication.

As shown in Fig. 5a, we consider densely populated areas where there are multiple SeNBs deployed in each sector that is at most three hops away from the MeNB. Placement of the SeNBs may significantly affect the performance of the HetSNets. Usually, the SeNBs are placed as close as possible to the cell edge, while a qualified backhaul link can be maintained by a high-gain beam. Also, enough distance between each SeNB should be maintained in order to avoid excessive interference among one another. Then, in our simulations for Cases 1 and 2 (i.e., 2 or 4 SeNBs/sector, respectively, as illustrated in Fig. 5a), the SeNBs are placed on the circles around the centers of the hexagons with a radius of 1/9 intercell distance (ISD) in consideration of cell edge priority. In Case 3 (i.e., 10 SeNBs per sector), the SeNBs are placed in two two-tier circles, with radii of 1/10 ISD and 1/5 ISD for the inner and outer circles, respectively. Each SeNB can independently schedule its connected UEs according to a certain channel-aware scheduling algorithm on the mmWave frequency band. A small number of SUEs may occupy the entire mmWave frequency band, resulting in very high data rate transmission.

Figure 5b presents the spatial characteristics of the signal-to-interference-plus-noise ratio (SINR) of the HetSNet under different cases. Different colors represent different throughput values. For example, the area marked in red has a higher SINR than that marked in green or blue. It is clear that there are more areas with the red color in Cases 2 and 3 than in Case 1. The SINR performance is thus dramatically increased by deploying more SeNBs. However, such an improvement is more obvious in Case 2 than in Case 3. When a large number of SeNBs with full frequency reuse among cells are deployed (e.g., 10), the close distance between the SeNBs may cause interference and decrease the SINR even with narrow beams on the mmWave frequency band.

The performances including the average SUE throughput and aggregate throughput (TP) of small cells in the networks under different cases are compared in Table 2. In Case 1, only 21.7 percent of all the UEs are served by the SeNBs with an average throughput per SUE of 333.5 Mb/s due to sparse deployment. With the increase of SeNBs deployed, more UEs choose to connect to the SeNBs with single or multihop

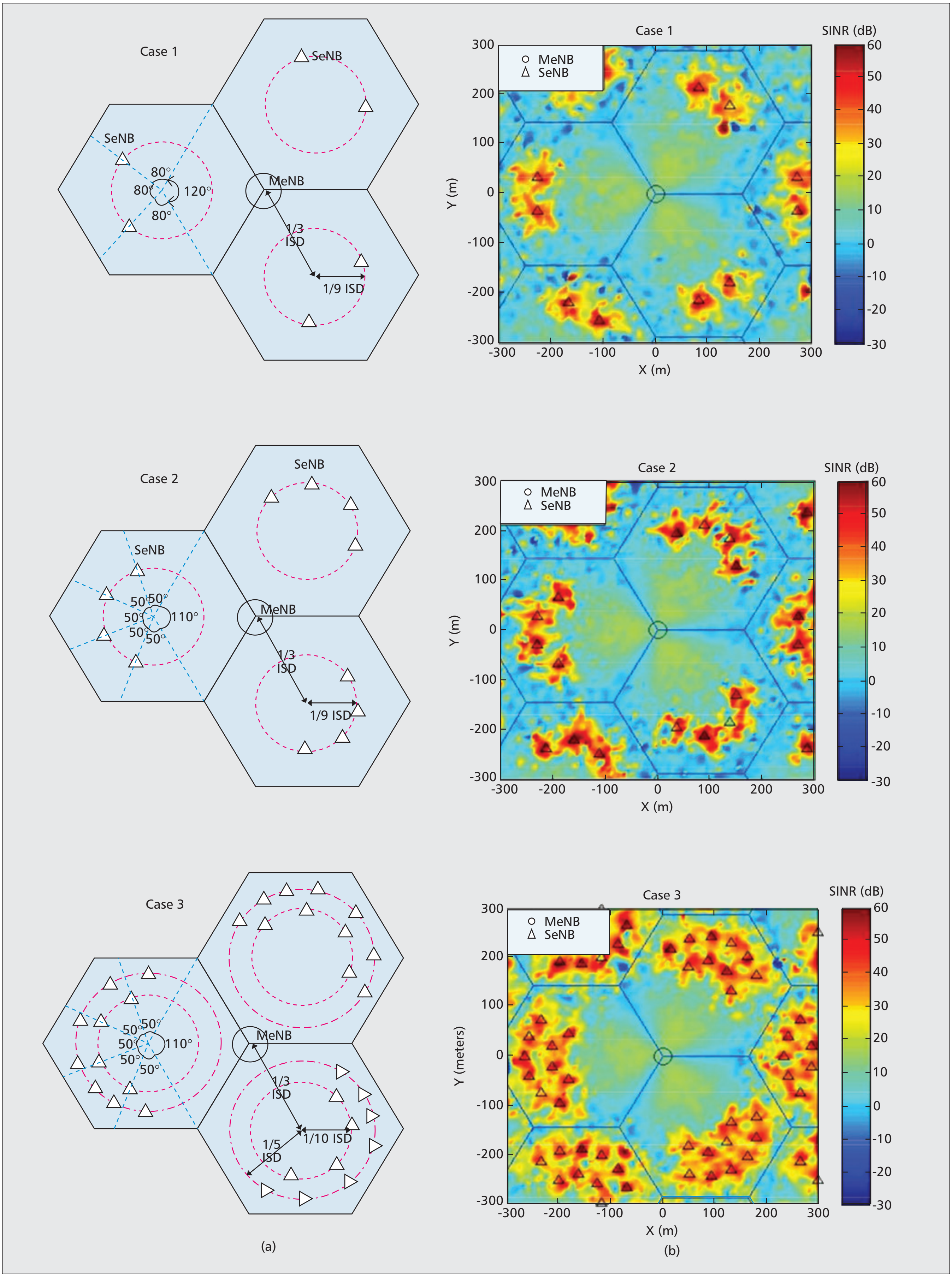


Figure 5. Illustration of deployment and SINR performances in HetSNets with mmWave communications: a) SeNB deployment; b) geometry of SINR performance.

With the development of new mmWave physical layer techniques, the fundamental knowledge on mmWave communications becomes more solid. Future research on HetSNets with mmWave communications will then be motivated by a tight coupling of the unique characteristics of mmWave communications and wireless heterogeneous networks.

	Average throughput per SUE (Mb/s)	Average number of SUEs per cell	Ratio of SUEs/all UEs	Total cell throughput (Gb/s)
Case 1	276.9	13	13/60 = 21.7%	3.64
Case 2	422.2	20	22/60 = 33.3%	8.26
Case 3	388.2	34	34/60 = 56.7%	12.98

Table 2. Performance comparisons in HetSNets under difference cases.

transmission (i.e., 33.3 and 56.7 percent of all the UEs in Cases 2 and 3, respectively), since the distance between SeNBs and UEs is shorter. Meanwhile, more small cells means that the same frequency resources can be more frequently reused with the aid of beamforming techniques. Therefore, not only the average throughput per SUE but also the total throughput rapidly increase. Moreover, in this way, more severe co-channel interference due to close distance arises when a larger frequency reuse factor is adopted. The average throughput per SUE slightly decreases in Case 3 compared to that of Case 2. However, because many more UEs may access the network through their nearby SeNBs in Case 3 than in Case 2, the total throughput performance continues to be improved when the number of SeNBs increase from 4 to 10 (i.e., 12.98 Gb/s), almost doubling that in Case 2.

CONCLUSIONS AND FUTURE WORK

HetSNets with mmWave communications are critical to meeting the requirements of future 5G wireless communications. Due to the vast spectral resources of mmWave radios, users will be able to enjoy unprecedented services with almost wire-like user experience. We investigate the feasibility of mmWave communications in HetSNets under various deployment scenarios, and propose a new 3GPP LTE-A backward-compliant frame structure. This allows us to address several important challenges facing mmWave communications, and achieve an aggregated cell throughput of nearly 13 Gb/s, an order of magnitude more than the current best 5G system design [13].

With the development of new mmWave physical layer techniques, the fundamental knowledge on mmWave communications becomes more solid. Future research on HetSNets with mmWave communications will then be motivated by a tight coupling of the unique characteristics of mmWave communications and wireless heterogeneous networks. Specifically, a more in-depth study of decoupling the control and data channels is needed, which will lead to new handover, call admission control, and radio resource management protocols. Furthermore, mmWave offloading mechanisms ought to be studied from the load and queue points of view.

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