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Research Article

Optimization of Cell Size in Ultra-Dense Networks with Multiattribute User Types and Different Frequency Bands

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Ultra-dense cellular networks (UDNs) represent the trend for 5G networks in dense urban environments. With the aim of exploring the optimal extent of network densification under different performance requirements and the trade-off between the network capacity and deployment cost in UDNs, a multiple-objective optimization model is proposed. This novel optimization design consists of a multiattribute user type in which users are grouped based on their propagation conditions and an infinitesimal dividing modeling method termed the ring method for network capacity dimensioning. The optimal cell size is estimated to maximize the total network capacity and minimize the deployment cost under different levels of user capacity demand. Additionally, the corresponding total network capacity and the required number of base stations are presented. Furthermore, two conventional frequency bands, 800 MHz and 1.8 GHz, and two new bands, 3.5 GHz and mmWave 28 GHz, are considered to investigate their feasibility and the potential of higher frequency bands in the 5G network.

1. Introduction

Existing cellular networks are being challenged by the explosive growth of traffic demand from a variety of mobile and internet services such as high definition live video streaming and mobile online gaming. This challenge will become more severe with emerging new services such as 3D multimedia, augmented reality, and virtual reality. Because these new services will progressively be delivered over wireless communication, the mobile and wireless traffic volume has been predicted to increase 1000-fold in the near future [1]. More specifically, the area throughput in some densely populated areas may reach tens of Tb/s/km^2 and the data rate experienced by users might exceed 1 Gbps [2]. To improve system capacity and meet the expected demand, better wireless modulation and additional spectrum bandwidth can be employed. However, the potential gain seems to be limited. Therefore, the most efficient way to increase cell density is by reducing coverage [3].

Motivated by the above, the ultra-dense cellular network (UDN) is emerging as a promising technology with new characteristics for fifth-generation (5G) networks [3–5]. The network evolved from the traditional macro-cell-only Homogenous Network (HomNet) to a multiband Heterogeneous Network (HetNet) where macro cells operating at low frequency bands underlie small cells operating at high frequencies. The UDN can be seen as another evolution from HetNet with further densification of small cells [5]. The basic idea of this new paradigm is to shorten the distance between the access node and end user as much as possible and thus densely deploy small cells in crowded districts or hotspots where enormous data traffic is generated. The average intersite distance (ISD) for UDNs is reduced to around or less than 100 m in contrast to the 400 m distance in the traditional 4th-generation (4G) deployment [6]. The UDN can be defined as small cell deployment in dense urban scenarios where the active user density is high, with about 600 active users per km^2 [5–7]. Together with higher frequency bands where much wider bandwidth is available, UDNs are expected to fulfill very high demands on system capacity and achievable end-user data rates [8]. Currently, cellular systems mainly operate at frequency bands below 3 GHz. However, higher frequencies up to millimeter-wave (mmWave) are considered candidates for 5G deployment [9].

The strategy of operating UDNs on new and higher frequency bands brings new and multiple challenges for network operators in network planning and actual deployment, including network architecture, resource management, difficult handover control, and interference management [3]. Other specific challenges this paper focuses on are as follows.

(i) One challenge is to find the fundamental limits in network densification, i.e., to what extent the cell size can be reduced. Network densification cannot be continued since too close a distance between cells will generate high interference [5]. As discussed in [4], this is considered a key question for future network designs

(ii) Another is to minimize the cost of the network design. There is always an inherent trade-off between the cost and other objectives such as capacity and quality of service (QoS) [10]. This is more significant in network densification since the cost will increase greatly as more cells are needed

(iii) There are various propagation conditions for massive numbers of users in the urban environment. Line-of-sight (LOS) components become more probable when users are closer to the base station (BS). Therefore, both LOS and non-line-of-sight (NLOS) should be considered in the study of dense networks [5]. The target for UDNs is usually dense urban areas where users are often located in buildings and above the ground. It is important to emphasize indoor usage because up to 80% of data traffic is generated in indoor environments [11]. Therefore, it is necessary but difficult to take all these factors into consideration in UDN network research

(iv) Another challenge is to further study the feasibility of high frequency bands in dense urban scenarios. As argued in [12], the value and feasibility of higher frequency bands need to be further considered. This is because, at lower and higher frequency bands, each spectrum has its own pros and cons in urban environments. At lower frequencies, the signal has less path and penetration loss. Meanwhile, the interference from adjacent cells is higher. On the other hand, at higher frequencies, the available system bandwidth is increased, and the interference is decreased. However, more signal loss occurs

With the aims of exploring the proper extent of cell densification and investigating the trade-off between capacity and deployment cost for UDNs, this work proposes an innovative optimization model to determine the cell size in UDNs with multiple objectives including maximizing network capacity, minimizing the deployment cost, and guaranteeing each user's capacity demand. Multiple factors are taken into consideration in the system model such as various user propagation conditions, 3D urban environments, and two urban network deployment scenarios. Furthermore, four frequency bands are employed for the carrier frequency to investigate their pros and cons in UDN deployment. The paper is organized as follows: In Section 2, we review the related literature. The system model is introduced in Section 3 and the optimization formulation is described in Section 4. Based on the simulation, numerical results are presented in Section 4. Finally, our findings and further works are described in Section 5 along with the conclusion.

2. Related Works

Since it evolved from multiband HetNet, 5G UDN jointly consists of small cells and macro cells. However, the macro cells will probably be configured only to transmit control data to solve user handover problems in the small cells while the small cells will be in charge of high speed user data transmission [4]. Many advanced handover technologies have been proposed for UDNs. A software defined network-enabled authentication handover system was proposed in [13] that involves user-specific context information sharing and privacy protection using multiple network paths to transmit data. These two solutions have been proven to simplify the handover by reducing latency and enhancing privacy protection in 5G networks. In [14], measurement-based mmWave dynamic channel models were innovatively employed to study the handover in mmWave systems. With extensive simulation, the proposed dual connectivity framework, which allows fast switching between LTE and mmWave radio access as well as secondary cell handover across mmWave eNodeBs (eNBs), was demonstrated to improve the latency and throughput stability of mmWave systems.

On the other hand, many studies place emphasis on the user throughput and network capacity of UDNs since this is the motivation for network densification. Aiming at bringing detailed analysis of user throughput and network capacity of UDN, a network model with various configurations including different ISDs, user equipment (UE) densities, and frequency bands was used in [15] to reveal the gain of network densification. The simulation results showed that dense cell deployment with an ISD of 35 m can increase the average UE throughput by more than 7.56 times and that using a 10 GHz band with a bandwidth of 500 MHz can further increase the network capacity up to 5-fold.

However, finding the optimal site position or configuration for the purpose of planning objectives like coverage, capacity, and deployment cost requires further research such as network planning or cell optimization. Since these objectives are always interdependent and interrelated [10], joint optimization of multiple objectives is an important research topic in UDN deployment for further investigation [5]. A novel Cognitive Radio Network- (CRN-) applied 5G UDN architecture was designed in [16] and a graph-based algorithm and genetic-based algorithm were used to maximize the user throughput and minimize communication interference. The results showed that the proposed optimization algorithms can effectively improve network performance in terms of throughput and signal-to-interference-plus-noise ratio (SINR). A novel optimization design for UDNs that involves dividing massive numbers of users into groups based on moving speed and selecting suitable subnets was proposed in [17]. Optimization is then performed to coordinate suitable UDN subnets for each group to meet huge service demands with the minimum quantity of resources. The numerical results showed that the proposed approach can make the best use of bandwidth resources to provide services that meet user demands. With the purpose of balancing the trade-off between energy efficiency (EE) and spectrum efficiency (SE), an improved version of the nondominated sorting genetic algorithm-II (NSGA-II) [18] intelligent approach was proposed in [19] to optimize the performance of EE and SE by jointly allocating transmission power and resource blocks to users in UDNs. This was the first time NSGA-II was applied in a UDN for such optimization and the novel improved version has several advantages including fast nondominated sorting and less complexity. All the aforementioned literature details optimization cell planning for 5G UDN but the objective and methods are distinctive. The distinctive contributions and innovations of the proposed system model in this paper are summarized as follows.

(i) Instead of optimizing either the network capacity or deployment cost, this work is aimed at balancing the trade-off between both parameters for dense small cells

(ii) The optimal solutions, i.e., optimal ISDs within the constraint of different user capacity demands, provide insights to determine the ideal extent of network densification

(iii) A novel method involving multiattribute user types is utilized in the proposed system model. Instead of grouping a large number of users based on single user attributes, like user mobility in [17], this method is designed to cover all possible propagation conditions for users including LOS or NLOS, outdoor or indoor, and UE heights. Other works [15–17, 19] consider only individual or limited combinations of these possible propagation conditions in real urban environments. This method is described in more detail in Section 3

(iv) An innovative infinitesimal dividing modeling method termed the ring method is proposed in this work for network capacity dimensioning and optimization. Compared to the summation of the capacity of all users in the network in [15, 16, 19], the ring method is specially designed to properly derive the number of users in each group since the LOS probability is assumed to be a function of the distance between the user and the BSs. Detailed analysis of the proposed ring method is presented in Section 4

(v) Compared to other works, several frequency bands, specifically two conventional frequency bands (800 MHz and 1800 MHz) and two 5G frequency bands (3.5 GHz and 28 GHz), are investigated in both urban macro (UMa) and urban micro- (UMi-) street canyon deployment scenarios. Although multiple frequency bands can be deployed in the two 5G frequency bands, small cells using high frequency bands will be in charge of high speed user data transmission and macro cells at low frequency bands will probably be configured only to transmit control data regarding handovers [4]. Therefore, the two 5G frequency bands are the main targets and the two conventional bands are also investigated for comparison and to demonstrate they may be not competent in the task of transmitting user data in UDNs

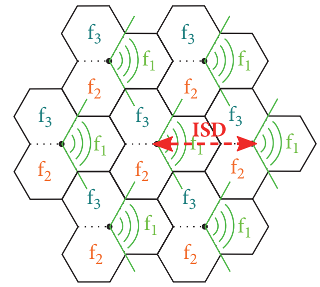


FIGURE 1: Cell layout of network.

3. System Model

We consider the deployment of a UDN cellular network in a dense urban area of 1 km^2. The goal is to maximize the total network throughput and minimize the deployment cost under certain user capacity constraints. The system model is as follows.

3.1. Cell Layout. Figure 1 details the cell layout in this work. The hexagonal grid three-sector site described in [20] is used. A frequency reuse number of three is assumed where the frequencies used in three sectors of each cell are different. Due to the above, the user only receives interference signals from three BSs when the interference is only considered on the first tier. Generally, there are two kinds of small cell BSs, namely, fully functioning BSs (picocells and femtocells) and macro-extension access points [5]. Here, picocells installed outdoors are considered the BSs in the network.

3.2. User Distribution and Multiattribute User Types. The users are assumed to be uniformly distributed in the target area, which means that the number of active users equals the product of active user density and area. In reality, users in urban areas are always in different propagation conditions such as LOS or NLOS and outdoor or indoor. As shown in Table 1, the users are classified into four types by using different propagation conditions as multiple attributes. The detailed conditions for each user type are presented in Figure 2. The specific number of users of each type is calculated according to the indoor user ratio and LOS probability in [20].

3.3. Carrier Frequency and System Bandwidth. This work investigates four carrier frequencies, namely, 800 MHz, 1800 MHz, 3.5 GHz, and 28 GHz. 800 MHz was popular for cellular network deployment before the 3G. Frequency bands below 3 GHz such as 1.8 GHz were introduced in order to employ 3G and 4G mobile communication services. For the 5G, higher frequency bands up to mmWave bands are expected

Table 1: *Multiattribute user types* in urban scenario.

User type	User condition
Type 1	LOS + outdoor
Type 2	LOS + indoor
Type 3	NLOS + outdoor
Type 4	NLOS + indoor

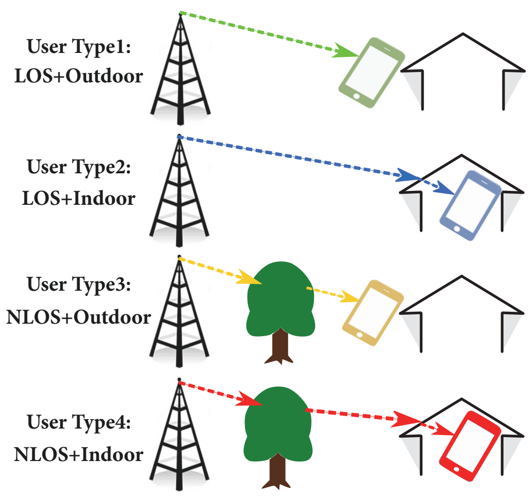


Figure 2: Diagram for four user types.

to provide more bandwidth resources to fulfill the anticipated capacity demand. Among them, 3.5 GHz and 28 GHz are two important candidate bands because a large portion of spectrum resources is available at 3.5 GHz below 6 GHz and at 28 GHz above 6 GHz [9]. Regarding the system bandwidth, 5% of the carrier frequency is assumed. It is reasonable and necessary to consider different bandwidths for different carrier frequencies, since much larger available bandwidth is the main motivation for the consideration of high frequency bands in 5G.

3.4. Radio Propagation Model. Empirical propagation models are broadly used to predict the path loss in feasibility studies and initial deployment in cellular network planning. Conventional propagation models like the Hata and Stanford University Interim (SUI) models used in another of our research works [21] are only applicable to low frequency bands and lack the parameters to simulate an urban environment. Therefore, the 3D propagation model from 3GPP [20] is used. This model supports frequencies ranging from 500 MHz to 100 GHz in urban scenarios and provides diverse parameters such as 3D propagation distance, environment height, standard shadow fading, LOS probability, indoor user rationing, and outdoor-to-indoor penetration loss. These parameters are critical for simulation of the proposed model with multiattribute user types based on user propagation conditions. The urban scenario is further divided into two subscenarios in [20]: UMa and UMi-street canyon. In the UMa urban scenario, the BS antennas are mounted above the rooftop level of surrounding buildings. In contrast, the antennas are below the building rooftops in the UMi-street canyon scenarios. Another difference is that the ISD for UMa is larger than that for the UMi-street canyon. These two scenarios are, respectively, investigated in this work.

4. Problem Formulation and Optimization

4.1. Problem Formulation Using the Ring Method. For UDN deployment, the key challenge is to provide top quality services while minimizing network cost. Focusing on this issue, the goal of this work is to maximize the total network capacity while keeping the deployment cost as low as possible. The total cost is roughly proportional to the number of deployed small cells in the network. Therefore, the total cost of the network is measured as the number of BSs that need to be deployed in the network. The constraint is to guarantee that every user is satisfied with a specific capacity demand, which means the capacity of every user should be higher than or equal to the demand bound constraint. Therefore, it becomes a multiple-objective optimization problem which can be formulated as

$$\begin{gathered} \text{Maximize}\ \{C_{network}\}, \\ \text{Minimize}\ \{\mathrm{N}_{\mathrm{BS}}\}, \end{gathered} \tag{1}$$

within the constraints

$$C_{user} \geq C_0, \tag{2}$$

where $C_{network}$ is the total capacity of the network, C_0 is the capacity demand bound constraint, and N_{BS} is the number of required BSs:

$$N_{BS} = \frac{1000^2}{S_{cell}} = \frac{1000^2}{3 * \left(2.6 * (ISD/3)^2\right)}, \tag{3}$$

where S_{cell} is the area of one cell and is determined by the ISD (m).

Now the main challenge is how to quantify the total network capacity $C_{network}$. An infinitesimal dividing modeling method termed the ring method is proposed in this work. As Figure 3 shows, one cell is divided into many small parts and the width of each part is 1 m. d_i is the distance between the inflection point (marked as a dot in Figure 3) and the BS. Because 1 m is quite small compared to the cell coverage, each part can be seen as a circular arc, which is referred to as a ring here. All users in any single ring $Ring_i$ can be assumed to have the same distance d_i to the BS. Four types of users are distributed in $Ring_i$, according to the LOS probability and indoor user ratio.

Figure 4 is the flowchart for the method used to derive the total network capacity $C_{network}$. The detailed process is explained as follows. As defined in [22], the minimal distance between the UE and picocell BS is 2 m. Therefore, the area of $Ring_i$ can be expressed as

$$S_i = \begin{cases} \sqrt{3} d_i + \dfrac{\sqrt{3}}{2}, & 2 \leq d_i \leq \dfrac{ISD}{3} - 1 \\ \dfrac{\sqrt{3}}{3} ISD, & \dfrac{ISD}{3} - 1 < d_i \leq \dfrac{2}{3} ISD - 1. \end{cases} \tag{4}$$

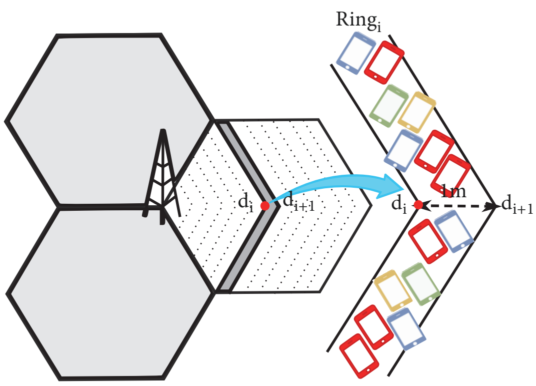


Figure 3: An illustrative diagram of the ring method.

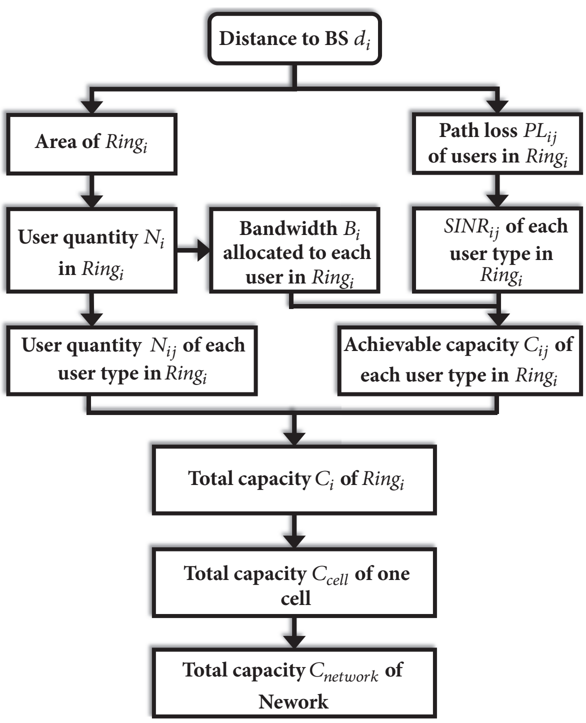


Figure 4: Flowchart for the derivation of total network capacity.

Since the users are uniformly distributed in the cell, the number of active users N_i in $Ring_i$ equals the product of active user density ρ_{user} and ring area S_i:

$$N_i = \rho_{user} * \mathrm{S_i}. \tag{5}$$

It is assumed that bandwidth is uniformly allocated to every user in the cell so the bandwidth B_i allocated to each user equals

$$B_i = \frac{0.05 * f_C}{N_{reuse} * N_{cell}} = \frac{0.05 * f_C}{N_{reuse} * (\rho_{user} * S_{cell})}, \tag{6}$$

where f_C is the carrier frequency, N_{reuse} is the frequency reuse number which equals three here, and N_{cell} is the number of users in one cell. Ignoring feeder loss, the received power P_{ij} of UE type j in $Ring_i$ can be expressed as

$$P_{ij} = \begin{cases} P_T + G_T + G_R - PL_{ij}(d_i) - SF, & \text{outdoor UE} \\ P_T + G_T + G_R - PL(d_i) - L_{O2I}(f_c) - SF, & \text{indoor UE,} \end{cases} \tag{7}$$

where P_T is the transmitter power of the base station antenna, G_T is the transmitter antenna gain, G_R is the receiver antenna gain, and SF is shadow fading. The path loss, PL_{ij}, and the outdoor-to-indoor penetration loss, L_{O2I}, are calculated using the 3D path loss model and the low-loss out to indoor penetration model in Technical Report 38.901 by 3GPP, respectively [20]. Note that the indoor user is assumed to be standing by the wall or window where there is no inside loss after signal penetration through the wall or window. In Figure 2, the interference I_{ij} of UE type j in $Ring_i$ is the sum of the power of three received interference signals transmitted by the adjacent three BSs:

$$I_{ij} = \begin{cases} \sum_{k=1}^{3} \{P_T + G_T + G_R - PL_{ijn} - SF\}, & \text{outdoor UE} \\ \sum_{1}^{3} \{P_T + G_T + G_R - PL_{ijn} - SF - L_{O2I}(f_C)\}, & \text{indoor UE,} \end{cases} \tag{8}$$

where PL_{ijn} is the path loss of the interference signal transmitted by interference BS n and is also calculated with the 3D path loss model. After deriving the received signal power P_{ij} and the interference I_{ij} power, the $SINR_{ij}$ of UE type j in $Ring_i$ can be achieved by

$$SINR_{ij} = \frac{P_{ij}}{Noise + I_{ij}}. \tag{9}$$

Then C_{ij}, the user maximum achievable capacity of UE type j in $Ring_i$, can be calculated using the Shannon capacity:

$$C_{ij} = B_i * \log_2 (1 + SINR). \tag{10}$$

As defined in [20], the indoor user ratio is 80% in urban areas and the LOS probability is a function of the distance d_i. Then, N_{ij}, the user quantity of UE type j in $Ring_i$, can be calculated as

$$N_{ij} = \begin{cases} 0.2N_i * P_{LOS}(d_i), & j = 1 \\ 0.8N_i * P_{LOS}(d_i), & j = 2 \\ 0.2N_i * (1 - P_{LOS}(d_i)), & j = 3 \\ 0.8N_i * (1 - P_{LOS}(d_i)), & j = 4. \end{cases} \tag{11}$$

Note that when N_{ij} is smaller than 1, it represents the probability that the user is in $Ringi$ and under type j. Combining (10) and (11), the total capacity of $Ring_i$ equals the sum of the capacities for all users:

$$C_i = \sum_{j=1}^{4} C_{ij} * N_{ij}. \tag{12}$$

The sum of the total capacity of all rings is the total capacity of one cell C_{cell}:

$$C_{cell} = \sum_{i=1}^{(2/3)ISD-2} C_i. \tag{13}$$

Finally, the total capacity of the network is

$$C_{network} = C_{cell} * N_{cell}, \tag{14}$$

where the number of cells in the network N_{cell} is determined by the optimization ISD result. At this point, optimization objective equation (1) and constraint equation (2) are ready for the following optimization procedure.

4.2. Optimization Procedure. The goal of this work is to maximize the total network capacity while keeping the deployment cost as low as possible within the constraint that every user is satisfied with a specific capacity demand. In this optimization problem, ISD is the only variable and the two objectives are maximizing the total network capacity and minimizing the number of deployed small cells. It is difficult to handle small cell planning for UDNs by considering multiple-objective functions at the same time and within the constraints. The genetic optimization algorithm is introduced to solve this multiple-objective optimization problem and derive the optimal ISD. The genetic algorithm is a type of optimization algorithm that imitates the biological processes of reproduction and natural selection to solve for the target function solutions [23]. It is widely used in wireless communication [16, 19], and results in [16] indicate that the genetic algorithm outperforms other network planning algorithms like graph theory. The NSGA-II [18] is exoteric non-domination-based and is arguably the most famous genetic algorithm for optimizing multiobjectives. With the aim of a less bug-prone and convenient implementation, we use the *gamultiobj* function in the MATLAB global optimization toolbox. It uses a controlled, elitist genetic algorithm, which is a variant of the NSGA-II. The *gamultiobj* function can be expressed as

$$X = gamultiobj\left(f_{\text{fitness}}, n_{\text{VARS}}, LB, UB, f_{\text{constraint}}\right), \tag{15}$$

where X is a set of optimization results, i.e., optimal ISDs. Here, the fitness function $f_{fitness}$ is represented by (1) and the constraint function $f_{constraint}$ by (2), n_{VAS} is the dimension of the optimization problem (equal to one here since ISD is the only variable), and LB and UB are the lower and upper bounds of the variable ISD, respectively.

During the optimization procedure, *gamultiobj* first randomly creates the initial population, which is a set of individuals (variable ISDs), with respect to the bounds. Then *gamultiobj* evaluates the objective function $f_{fitness}$ and constraint $f_{constraint}$ for the population and uses those values to create scores for the population. Next, the individuals with the best scores are selected as parent individuals to create children individuals of the next generation by mutation and crossover. This iteration starts over until a termination criterion applies, such as when the average relative change in the best fitness function value is less than or equal to a predefined *FunctionTolerance* or when the generation number exceeds the given *MaxGenerations*. At this point, *gamultiobj* will output the optimized ISD.

Table 2: Simulation parameters [15, 20, 22, 24, 25].

Parameters	UMa	UMi-street canyon
Carrier frequency f_C	800 MHz 1.8 GHz 3.5 GHz 28 GHz	
System bandwidth	$5\% * f_C$	
TX antenna height (m)	25	10
Outdoor user RX antenna height (m)	1.5	1.5
Indoor user RX antenna height (m)	9	9
TX antenna gain, G_T (dBi)	5	5
RX antenna gain, G_R (dBi)	2	2
BS TX power, P_T (dBm)	30	30
Thermal noise density (dBm/Hz)	-174	-174
Effective environment height (m)	1	1
Active user density d_{user} (users/km2)	600	600
Indoor user ratio	0.8	0.8
Minimum distance between UE and BS (m)	2	2
Shadow fading in LOS (dB)	4	4
Shadow fading in NLOS (dB)	6	7.82

5. Simulation Results

Four carrier frequency bands are investigated and the available system bandwidth is set to 5% of the carrier frequency. For each carrier frequency, the maximum achievable capacity guaranteed for every user will be limited. In the simulation, the optimization algorithms cannot provide the right result when the capacity demand bound constraint C_0 reaches its limit. Due to this, the optimal ISD is derived against C_0 varying from 1 Mbps to the maximum value. The initial population in MATLAB *gamultiobj* is randomly created so the optimization result for each run can be slightly different. The results presented in this section are the average values from 10 runs. The simulation parameters including the picocell BS antennas and 3D propagation model are summarized in Table 2. Table 3 lists the *gamultiobj* parameters which are tuned for proper functioning and relative stable output results. The other *gamultiobj* parameters all use the provided default values.

The results for the optimal ISD against the capacity demand bound constraint are presented in Figure 5. The corresponding total network capacity and the number of BSs needed are shown in Figures 6 and 7, respectively. In Figure 5, the optimal ISD decreases as the user capacity

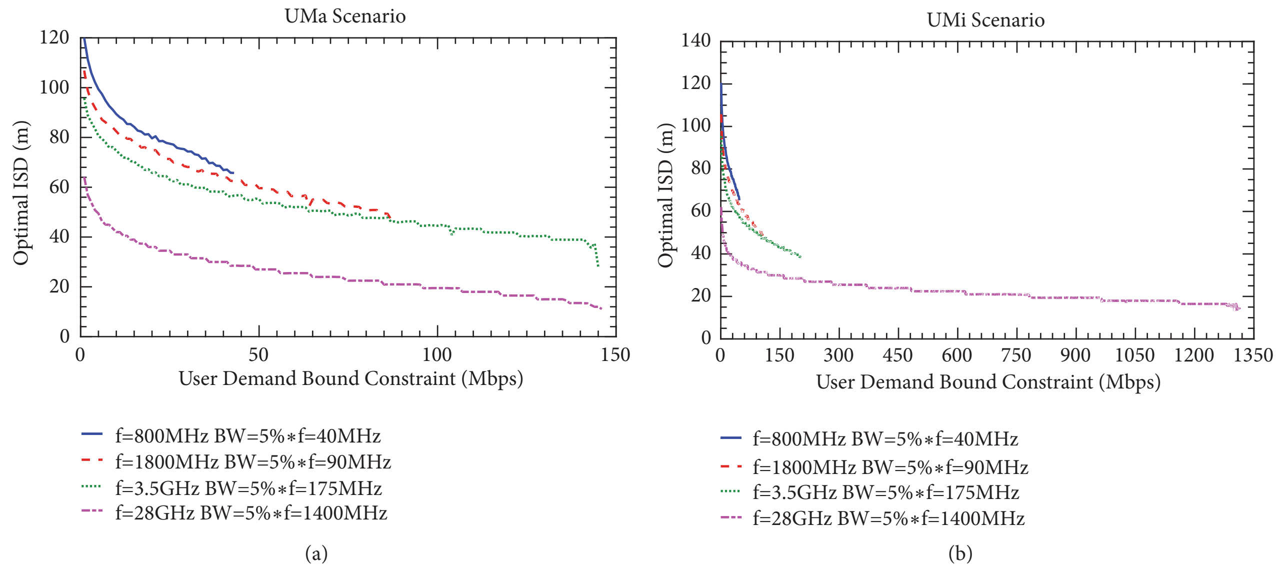


Figure 5: Optimal ISD vs. user demand bound constraint. (a) UMa scenario; (b) UMi-street canyon scenario.

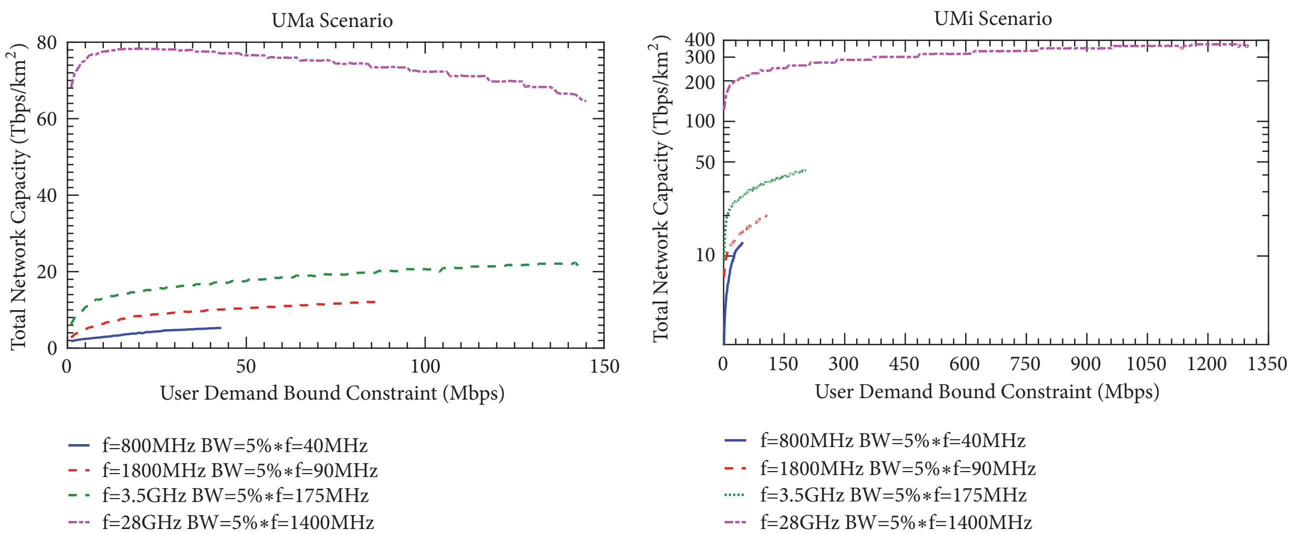
Table 3: Parameters used in MATLAB *gamultiobj* function.

Parameters	**Value**
LB	5 (m)
UB	500 (m)
FunctionTolerance	1e-6
MaxGenerations	300
PopulationSize	100
ParetoFraction	0.3

demand increases. In smaller cells, the path losses for users are smaller and the bandwidth allocated to each user becomes larger since fewer users exist in the cell. For the same user demand bound, the higher the frequency is, the smaller the optimal cell size becomes. Because higher frequencies suffer severe path and penetration loss, the cell size needs to be reduced to provide sufficient SINR to the cell edge and indoor users. In the UMa scenario, the maximum capacity which every user can be satisfied with is 43 Mbps for a frequency of 800 MHz and ISD of 65 m and 87 Mbps for a frequency of 1.8 GHz and ISD of 47 m. For 3.5 GHz, up to 145 Mbps can be guaranteed when the ISD is reduced to 30 m.

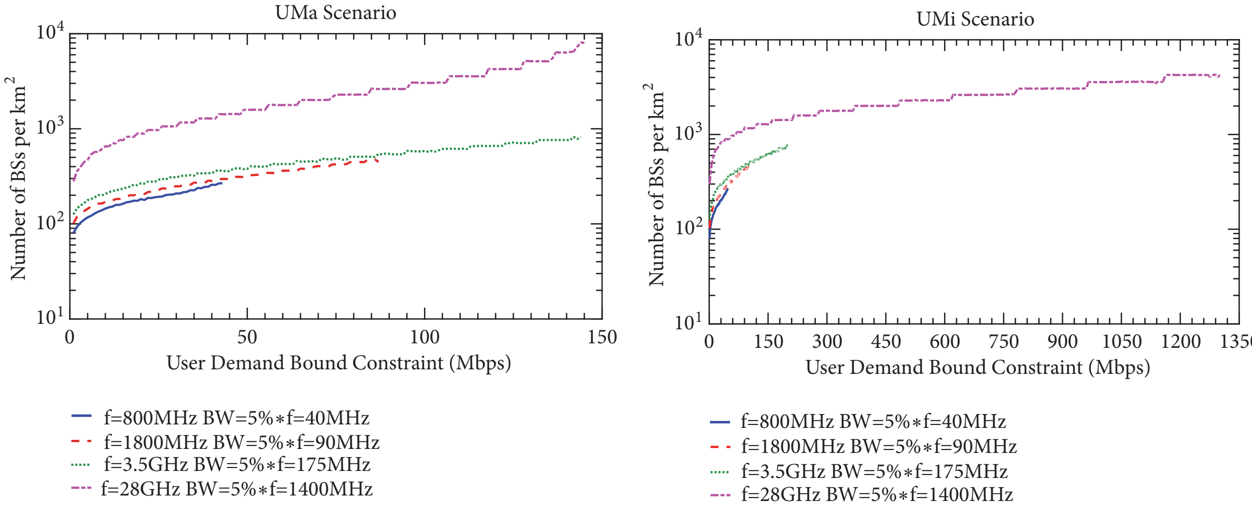
There are two reasons why higher frequencies can support higher user demand. One is that higher frequencies may bring about lower intercell interference. Another reason is that the achievable capacity is determined by bandwidth as well as SINR. For the same SINR, a smaller bandwidth of 800 MHz and 1.8 GHz limits the maximum achievable capacity. Meanwhile, 3.5 GHz can provide much wider bandwidth, which can support much higher user demand. However, note that 28 GHz can guarantee almost the same maximum achievable capacity as 3.5 GHz despite the enormous bandwidth. This is because the propagation loss for 28 GHz is so high in the UMa scenario that even the huge bandwidth cannot compensate for it. On the other hand, the bandwidth of 28 GHz is shown to be advantageous in the UMi-street canyon scenario as every user can be guaranteed up to 1.3 Gbps when ISD is decreased to 10 m. Additionally, 3.5 GHz yields 50 Mbps higher guaranteed user capacity in the UMi-street canyon scenario. The difference between the two scenarios results from the 15 m higher BS antenna height in the UMa scenario compared to the UMi-street canyon scenario. In the 3D propagation model, the propagation distance has three dimensions, which means a higher antenna can provide longer propagation distance for the same horizontal distance between BS and UE. That is, the BS antenna is much closer to users in the UMi-street canyon scenario. The primary disadvantage of high frequency bands, i.e., severe propagation loss, has a lighter effect on user achievable capacity. Therefore, the achievable capacity can be increased with the wider bandwidth of higher frequency bands.

Figure 6 shows the total network capacity versus user demand bound constraints. Generally, the network capacity keeps growing but reaches a limit as the guaranteed user demand increases. In Figure 6(a), the total network capacity for 28 GHz reaches the peak rapidly and then starts to decrease. The network needs to be densely positioned to provide higher capacity to users at the cell edges or indoors. However, the total network capacity cannot increase without limit because the number of active users in the network is limited. Therefore, some cells may not include active users when cells are extremely dense. In addition, when network densification surpasses a certain threshold, some users may receive more severe interference from the interfering BSs. When conventional bands such as 800 MHz and 1.8 GHz are employed, the maximum network capacity is limited below 12 Tbps/km^2 in UMa and 20 Tbps/km^2 in the UMi scenario. New bands at higher frequencies have larger total network capacity. For 3.5 GHz, the total network capacity can reach up to 50 Tbps/km^2 in the UMi scenario. For 28 GHz, the



(a) (b)

Figure 6: Total network capacity vs. user demand bound constraint. (a) UMa scenario; (b) UMi-street canyon scenario.



(a) (b)

Figure 7: Number of needed BSs vs. user demand bound constraint. (a) UMa scenario; (b) UMi-street canyon scenario.

capacity may be about 80 Tbps/km^2 in the UMa scenario and hundreds of Tbps/km^2 in the UMi scenario. Similar to Figure 5, UMi is advantageous compared to UMa since the BS antennas are closer to users in the UMi-street canyon scenario. UDNs are expected to cover urban areas with small cells, providing a higher data rate than 100 Mbps to every user [6]. Several services in 5G may require a user achievable data rate of at least 1 Gbps and an area capacity of tens of Tbps/km^2 [26]. Figures 5 and 6 show that it is difficult to meet these requirements if UDNs are deployed with conventional bands such as 800 MHz and 1.8 GHz. The new 28 GHz band has been proven to have the potential to meet the requirements for 5G. Furthermore, it is more advantageous in the UMi scenario, i.e., lower antenna heights.

There is a cost when high frequency bands are employed. Figure 7 shows the number of BSs per km^2 when every user is guaranteed a certain capacity. The cost of network deployment is generally proportional to the number of BSs in the area. In both UMa and UMi scenarios, the higher the carrier frequency is, the more the BSs needed for the same user demand bound constraint are. In particular, the number of BSs required for 28 GHz is almost five times that required for 800 MHz or 1.8 GHz. To provide at least 1 Gbps for every user, operators have to deploy around 3500 BSs per km^2. Therefore, the deployment cost with high frequency bands is much higher than that with conventional bands. To meet lower user demand, the conventional lower frequency band can be a more economical choice for the deployment of UDNs since the number of BSs is lower. However, even though the network capacity for 3.5 GHz is twice that for 1.8 GHz, the number of BSs is slightly different. Therefore, 3.5 GHz may be the more economic choice. If the target area is a hotspot that requires an extremely high user data rate and area capacity, higher frequencies such as 28 GHz, at the expense of great deployment cost, may be the only choice for operators.

6. Conclusions

In this paper, a multiple-objective optimization model for UDNs was proposed for both UMa and UMi-street canyon scenarios. The novel optimization design includes multi-attribute user types in which users are grouped based on their propagation conditions and an infinitesimal dividing modeling method termed the ring method for network capacity dimensioning. The optimal ISD was evaluated to maximize the total network capacity while minimizing the deployment cost under certain user capacity demand bound constraints. Four frequency bands, 800 MHz, 1.8 GHz, 3.5 GHz, and 28 GHz, were investigated for the carrier frequency. The numerical results showed that it would be difficult for conventional bands to meet the requirements of UDN deployment for 5G services. Meanwhile, new higher frequency bands demonstrated the potential to provide 100 Mbps or up to 1 Gbps for every user in the network and tens or even hundreds of Tbps/km^2 in terms of total network capacity. Considering the trade-off between the capacity and deployment cost, 3.5 GHz can be a more economical choice for operators with user demands lower than 200 Mbps. For hotspots with extremely high user-experienced data rates and dense data traffic, 28 GHz in the UMi-street canyon scenario can be employed but the ISD needs to be less than 20 m. This may result in huge deployment costs such as thousands of BSs per km^2.

Data Availability

The simulation data to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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