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Capacity Performance Analysis of 73 GHz Frequency Band for 5G Technology

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ABSTRACT

Small cells, millimeter waves (mmW), and massive multiple-input multiple-output (MIMO) deployments have emerged as key technologies for mobile systems in the fifth generation (5G). However, a very few studies have been done on combining these three technologies into the cellular systems. In this paper, the authors provide an in-depth capacity analysis for the integrated small cells of mmW systems. Small cells are deployed for enhancing the capacity. It turns out that mmW signals are responsive to blockages, leading the line of sight (LOS) and non-line of sight (NLOS) conditions to have very different path loss rules. They divide power research into low signal-to-noise (SNR) and high SNR regimes based on signal-to-interference plus noise ratio. In the noise-dominated (low-SNR regime), the capacity analysis is derived by the simplest assumptions of the Shannon-Hartley theorem. The results of this study show that under NLOS and LOS scenarios, mmW frequency and distance between the user equipment and base station decrease logarithmically for system capacity.

KEYWORDS

5GNetwork, Channel Capacity, Link Budget Calculations, mmWave MIMO System, Path Loss Models With LOS and NLOS Scenarios

1. INTRODUCTION

The exponentially increasing number of mobile users and the ever-increasing demand for high data rates are big challenges for the modern cellular network operators. Despite these high demands, currently only the sub-6 GHz bands are widely used in the fifth generation (5G) mobile communication systems. These sub-6 GHz bands are already crowded due to the increasing demand for mobile data traffic and their applications in other sectors. Therefore, to enlarge the frequency bands to accommodate the emerging data traffic, new frequency bands should be considered in the 5G mobile communication systems (Kim et al., 2014; Saha & Aswakul, 2016). In order to address these serious problems of system capacity shortage due to increasing data traffic in cellular networks, standardization on heterogeneous networks (HetNets) with overlay deployment of low-power BSs in the service area of conventional networks is being carried out by the Third Generation Partnership Projects (3GPP) and some other standardization bodies (Sakaguchi, et al., 2015 & Hamadeh et al., 2017). In 5G, HetNets are practical

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realities and they exhibit a lot of diversities (Rappaport et al., 2017). Several new frequency bands have been proposed for the emerging communication technologies in Routray et al. (2019). In 5G several new applications have emerged which did not exist in the previous generations. For instance, the Internet of things (IoT) has become an integral part of mobile cellular networks which needs its own frequency bands. For the full scale 5G deployment several new bands are under study for future deployment. The newly proposed bands provide several opportunities and unknown challenges for the operators and deployment engineers. Millimeter waves (mmW) have several attractive features for high data rate communications. However, it also poses new challenges.

In addition to the above challenges, there are growing interest in cellular systems based on mmW bands ranging between 30 GHz and 300 GHz. The commonly available spectra in these frequencies are 10 to 100 times greater than today's cellular networks which use the sub-3 GHz bands (Cetinkaya, 2017). In order to use the mmW band more efficiently, it is suggested that the dense deployment of small cells with many antennas called massive multi-input multi-output (MIMO) technology should be provided with very high capacity enhancement in conjunction with short-range mmW technology (Kim et al., 2014; Zhang et al., 2017; Feng et al., 2016). The high bandwidth applications such as real time streaming (at 3 Gbps and higher) are not possible in the below 3 GHz frequency bands (Sharma et al., 2020). In addition to that there are several other difficulties with the sub-3 GHz bands such as harnessing high spectral efficiency for high data rates. From the previous mobile cellular generations also we see that every new generation uses new frequency bands and higher bandwidths (Routray & Sharmila, 2016). It is also the same for the 5G because it needs higher bandwidths in the high frequency bands. Several research findings have justified the use of mmW for 5G (Rappaport et al., 2015; Rappaport et al., 2017). Currently, these mmW are used in a very few electronic sectors such as satellite communications and some advanced radio detection and ranging applications. In 5G, the mmW can be used for high data rate communications using small cells (Rappaport et al., 2017).

In this work, we analyze the capacity related performances of mmW based 5G networks. We analyze the main issues due to the high sensitivity of blockages such as buildings and the significant path loss (PL) for non-line of sight (NLOS) cases. Millimeter wave links are tested which result in significantly different PL exponents for line of sight (LOS) and NLOS scenarios. Several studies on mmW have been reported on the multi-Gbps communication links (Cetinkaya, 2017; Zhang et al., 2017). In Zhao (2018), several applications of mmW for wireless communication systems have been presented. Salous et al. (2016) and Matalatala et al. (2017) studied the utilities of mmW for 5G communication systems. These studies found the mmW are suitable for high data rate applications in 5G. In 3GPP Release 14 several aspects of mmW have been analyzed for 5G deployments (ETSI, 2016). The studies therefore focused on the mmW linkage of the E-band (around 73GHz). This band is selected for the following reasons as shown in Table 1. It has both advantages and disadvantages for the mobile communication purpose. However, for the small cell based MIMO system it is suitable and provides a large bandwidth.

Table 1. A brief list of pros and cons of mmW systems in several frequency bands (Feng et al., 2016)

Frequency Band	Advantage (Pros)	Disadvantage (Cons)
28 GHz (Ka-band)	Suffers the least PL; Low oxygen absorption and rain Attenuation.	Lightly licensed; The bandwidth is relatively small.
38 GHz (Q- band)	Relatively less attenuate caused by oxygen absorption and rain.	Less research and applications done.
60 GHz (V- band)	Unlicensed bands; Large bandwidth to achieve multi-gigabit rate.	Peak point of oxygen absorption; Relatively large rain attenuation.
73 GHz (E- band)	Small effects of atmospheric absorption.	Large rain attenuation; Large path loss due to high frequency point.

In this paper, we analyze the performances of 73 GHz frequency band for 5G. We correlate the theoretical concepts of the 73 GHz communication systems with their practical performance related aspects of 5G. These practical implications are validated through simulations. We aim to provide a complete picture of the performance related aspects of 73 GHz mmW bands in 5G.

The remaining parts of this article are organized in five different sections. In section 2, we present the related works which have analyzed the 5G performances in different frequency bands. In section 3, we present a typical system model and its associated link budget for a 5G system. In section 4, we analyze the effect of SINR on the 5G network capacity. In section 5, we analyze the results and discussed their overall effects in different scenarios. In the last section, we conclude the paper with the main points.

2. RELATED WORK

Capacity performance analysis is associated with several estimations of communication networks (Bestfat et al., 2020). Very often estimations of the key parameters for the entire network are required for a clear picture for planning and deployment. Such complete network estimations are well known as dimensioning. In the deployment of new networks such as the 5G and other advanced technology based networks dimensioning is essential (Martín-Pérez et al., 2022). Dimensioning of networks is also an essential task for the cost estimation at the very beginning of network design and network planning stages (Routray et al., 2013). It provides the all the basic requirements of a network and its associated costs. Without proper dimensioning it is not possible to estimate the accurate costs to deploy a network (Shreesha & Routray, 2016). On the other hand, properly estimated dimensioning provides a clear picture of the budget and different network requirements. Several network parameters can be estimated from the basic entities such as the area of the network and the main processing nodes (Routray et al., 2014). Some advanced parameters such as the short path lengths and the network requirements for transparency can also be estimated from the network statistical models (Routray et al., 2015). Traditionally used below 3 GHz bands are not sufficient to provide the increased number of services in the cellular networks. New bands have been proposed to handle the changing trends (Routray et al., 2019). The global communication scenarios have been changed through new services and their associated economic activities. In Mohanty and Routray (2016), a global picture of ICT driven consumer electronics and their impact on the world economy have been analyzed. It showed that new spectrum is essential for emerging communication services. Network evolution has created new demands for spectrum and it emerged from quick evolutions of different generations of mobile communications (Adibi et al., 2009). Despite the use of new frequency bands, 5G will not be the ultimate cellular system to exploit the wireless advances. In 6G even higher frequencies are expected to be used (Routray & Mohanty, 2021). For beyond 5G networks several new frequency bands have been proposed. They include the mmW and upper range microwave frequencies which were never proposed for electronic communication before. Even some researchers are optimistic about the terahertz and sub-terahertz frequencies for beyond 5G networks (Xing & Rappaport, 2021). Based on different frequency bands network capacity dimensioning methods have been developed to scale the potentials of the cellular networks. Marcano and Christiansen (2018) studied the network capacity dimensioning for 5G HetNets using different multiple access schemes. In this work they showed that the non-orthogonal multiple access schemes are very effective for 5G HetNets in improving the cellular capacities. Capacity and coverage of 5G HetNets are very closely related. 5G new radio capacity and coverage have been analyzed for Indonesian urban environment by Rahmawati et al. (2021). In this research, the authors analyzed the performances of 3.5 GHz band for capacity and coverage of 5G HetNets in the urban areas. Iradier et al. (2022), analyzed the throughput, capacity and latency in 5G networks using non-orthogonal multiple access schemes. It was found in this work that appropriate models provide better accuracy about the network performances. Sousa et al. (2021) used direct test measurements from beamforming antennas to predict the 5G capacity and other performance parameters. They showed that direct measurements provide better accuracies than the predictions based on theoretical models.

There are several advanced features of the 5G communication networks. High data rates, ultra low latency and massive machine type communications are the three main focus areas of 5G (Saha & Aswakul, 2016). However, in addition to the above three focus areas there are many new provisions in 5G in both the core and the access parts (Routray et al., 2019). The core parts are mostly high speed optical networks and these optical networks extend till the base stations just before the last mile (Sharma et al., 2020a). The last mile wireless links in the access area use massive MIMO technologies for high data rates and higher spectral efficiency. Core and access parts in 5G are complex hybrid networks of optical and wireless elements (Routray & Mohammed, 2019). Energy consumption in 5G will be reduced using advanced waveforms. In Routray et al. (2018) several 5G waveforms have been analyzed from the energy consumption view points. Due to the exemplary energy efficiency, 5G can be considered as an energy efficient cellular communication technology. Several green initiatives have been introduced in 5G and the energy efficiency of 5G is estimated to be much better than 4G (Routray & Sharmila, 2016). The number of services in 5G will be much higher than its previous legacy systems. These services will be managed though software defined networking (SDN) technique. Network slicing will be widely used to segregate different types of services from each other. All these functions will be executed through the SDN frameworks (Routray & Sharmila, 2017) of 5G. Dimensioning of 5G parameters based on the average performance metrics have been done in Besfat et al. (2021). It estimates the key parameters such as the bandwidth required per base station and other units in the hierarchy. It also estimates several other essential parameters of 5G networks based on the ITU specifications.

The PL models play critical roles in the network capacity and coverage planning in the cellular networks. Kamboh et al. (2021) studied the 60 GHz mmW for 5G using different setups. They used different 3D ray tracing algorithms to estimate the effects of path losses in 5G. Cheng et al. (2021) studied the mmW PL models using deep learning models with dilated convolution and attention. They found that deep learning based models provide improved accuracies for 5G scenarios. Elmezughi and Afullo (2021) studied different PL models for indoor environments and analyzed their overall effects for better accuracies. They analyzed 14 GHz, 18 GHz and 22 GHz bands in the indoor setups and developed the PL prediction models. They compared the real data with their prediction model outputs. Their outcomes were comparatively more accurate than the other available models for the indoor scenarios.

3. SYSTEM MODEL AND LINK BUDGET FOR CAPACITY ANALYSIS

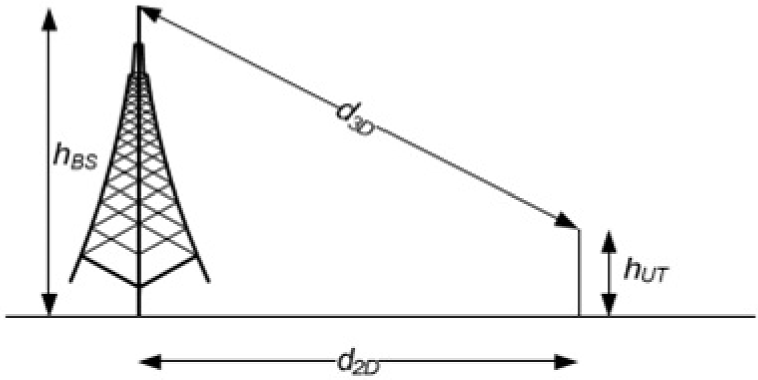
3.1 Millimeter Wave Channel Modeling

For any new frequency bands the channel modeling is essential to understand the critical performance related aspects. For mmW too channel models are used for its characterization. Channel model parameters include carrier frequency, bandwidth, 2D or 3D distance between the transmitter and the receiver, environmental effects, and other requirements of standardized systems. However, this study focuses on PL and shadowing models developed in the past (Akdeniz et al., 2014; Haneda et al., 2016). The LOS probabilistic models also depend on 2-D distance (T-R); do not depend on frequency as shown in Figure 1. PL and shadowing model: cause the difference between P_t and P_r signals.

3.2 Path Loss and Shadowing Model

The PL and shadowing effects cause the difference between the transmitted and the received signal power. This model includes attenuation of transmitted signals with distance (path-loss), blocking of signals with large obstacles (shading), and a combination of multiple copies of the same transmitted signals with rapid variation of the received signal (multipath fading). These issues have been studied

Figure 1. Definition of d_{2D} and d_{3D} for outdoor UTs (ETSI, 2016; Marcona, 2018)



in (Haneda et al., 2016; Rappaport et al., 2015; Mahmud et al., 2014). The mmW channel modeling projects for 5G technology are explained below based on the concepts developed in (Rappaport et al., 2017; and Marcona, 2018):

1. **METIS:** It is used for mobile and wireless communications enablers for the Twenty-twenty Information Society (METIS). This model exists in different forms such as WINNER II and WINNER+.
2. **MiWEBA:** It expanded mmW evolution for backhaul and access applications. It is capable of supporting beamforming at the transmitter as well as beam combining at the receiver.
3. **QuaDRiGa:** This model is originally based on 3D WINNER II model, Quasi Deterministic Rwadio Channel Generator model that supports 3D channel representation at different mmW frequencies.
4. **5GCM:** This model is based on extensive measurements at the 28 GHz, 38 GHz, 60 GHz, and 73 GHz. Multiple channel models of this type were proposed by NYU WIRELESS under the title of 5GCM.
5. **3GPP TR 38.901:** It provides a channel models ranging from 0.5 GHz to 100 GHz. In order to develop channel models, it is an extension of 3GPP TR 36.873. This model is presented in Zhao (2018), Marcona (2018), and it was developed in 2017.

The requirements of a new channel model that will support 5G operations across frequency bands up to 100 GHz should preferably base on the existing 5G mmW channel model (Zhao, 2018). Three basic types of large-scale PL models to predict mmW signal strength over distance (Haneda et al., 2016) are: Close-in (CI) reference distance PL model, modified intercept PL model, and floating intercept (FI) PL model.

3.2.1 CI Reference Distance PL Model

The CI path loss model accounts for the frequency dependency of PL by using a close-in reference distance based on Friis's law as given below (Hemadeh et al., 2017; Rappaport et al., 2017) in equation (1):

$$PL_{(dB)} = PL_{o} + 10n_{p} \log\left(\frac{d}{do}\right) + S_{\delta_s} \tag{1}$$

where d_o (m) is the free-space reference distance, and PL_o indicates the reference free-space loss distance d_o and n_p is the exponent. Whereas S_{δ_s} denotes the lognormal shadowing. The free space PL at frequency f_c in GHz at 1 m calculated in Rappaport et al. (2017) is shown in equation (2):

$$PL_o\left(f,1m\right) = 20\log\left(\frac{4pf\left[GHz\right]\times 10^9}{c}\right) \tag{2}$$

The lognormal distribution (in dB) with zero mean and $standard\ deviation\ \delta_s\left(dB\right)$ is shown in equation (3):

$$S_{\delta_s}\left(x\right) = \frac{1}{\sqrt{2\pi\delta_s}}e^{\left(-\frac{x^2}{2\delta_s^{\ 2}}\right)} \tag{3}$$

3.2.2 Modified Intercept PL Model

A linear approach is used in this model with a slight modification of equation (1) which has been expressed in (Hemadeh et al., 2017; Rappaport et al., 2017):

$$PL_{(dB)} = \alpha_p + 10\beta_p\log\left(d\right) + S_{\delta_s} \tag{4}$$

where α_p and β_p account for the floating intercept and the linear slope, respectively. The differences between equation (1) and equation (4) lie at a time (α_p and β_p) instead of (n_p) which results in higher degrees of freedom in calibrating the model to fit the measured PL values.

3.2.3 Floating Intercept (FI) PL Model

The FI PL models are given as shown in equation (5). These models are suitable for LOS applications. Though they can also be applied for NLOS scenarios, the errors are larger when compared with the other models:

$$PL_{(dB)} = 10\alpha_p\log\left(d\right) + \beta_p + 10\gamma_p\log\left(f_c\right) + S_{\delta_s} \tag{5}$$

where α_p, β_p, and γ_p indicate the slope of the PL with logarithm of the distance, the floating offset value in dB, and the frequency dependence of PL respectively.

3.3 System Modeling for Capacity Analysis

When mmW is used in HetNets, the main problem that emerges in HetNets is inter-cell interference (ICI) for in-band deployment when microwave frequencies are used for both macro and small cells. Fractional frequency reuse is a good solution in these scenarios. However, out of band deployments are more significant to minimize ICI. It also provides more bandwidth for each stage of HetNets (Rappaport et al., 2015).

Hence, a dense deployment is used for macro cell sites that constantly operate at their optimum throughput. For the small cell tiers, the ICI is not considered as the main limiting factor. This scenario has been depicted in Figure 2. In Figure 2, it is assumed that small cells are used at 73 GHz mmW band where the users are uniformly distributed. Furthermore, it is assumed that the cells are completely in LOS, and the users are inside the small cells. The lower probability that a UE inside the coverage of a small cell implies that less amount of the macro cell area is covered by the small cells using the probabilistic model. With this setup and following the outcomes of Sakaguchi et al. (2015), the maximum range of the mmW small cells (i.e., d) can be estimated using the distance-dependent PL model and has been shown in Equation (6):

$$P_t = SINR - G_t - G_r + L_{t,sys} + L_{r,sys} + P_L + L_{atm} + L_{rain} + L_{other} + N \tag{6}$$

This Equation (6) is the link budget for the small cells. In this equation, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, the L-terms are losses in the transmitter ($L_{t,sys}$), receiver ($L_{r,sys}$), atmosphere (L_{atm}), rain (L_{rain}), and other attenuations (L_{other}). P_L is the path loss between the source and the sink and the term N represents the thermal noise.

The purpose of calculating the link budget is to identify the received power on the receiver side. To evaluate the receiver power, we consider the distance and frequency-dependent PL calculated in the previous section. However, the sensitivity of the receiver is expressed as shown in Equation (7):

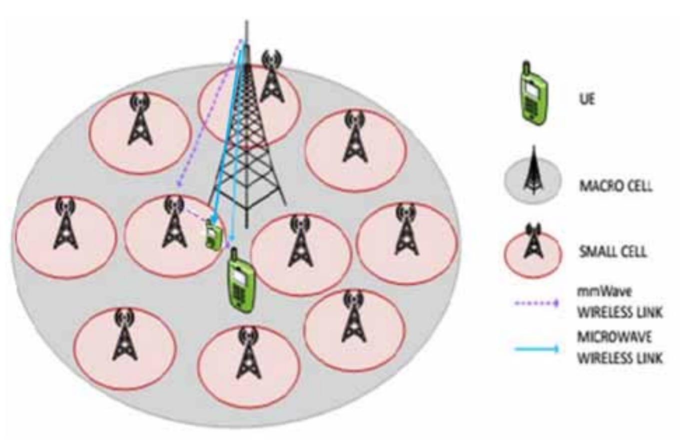
$$S_{r(sens)} = \left(\frac{S}{N}\right)_{dB} + N \tag{7}$$

In (7), $\frac{S}{N}$ state the SNR requirement in dB and N is the thermal noise.

In the calculation of the noise level, K_b is the Boltzmann constant, T_k is the receiver system temperature in Kelvin, B is the bandwidth, and N_f indicates the receiver's noise value as given in Akdeniz et al. (2014). The link budget calculations can be shown as a function of PL, shadowing (SW) and antenna gain (AG) as shown in Equation (8):

$$P_r = P_t - P_L\left(d\right) + AG - SW \tag{8}$$

Figure 2. Network model performance evaluation of single macro cell in mmW small cells (Haneda et al., 2016)



In order to ensure adequate performance at the receiver, the minimum received power in Equation (8) should be greater than or equal to the required receiver sensitivity (i.e., $P_r \geq S_{r(sens)}$). Thus we have the Equation (9) in terms of SNR, and other power terms when $P_r \ is \ just \ equal \ to \ S_{r(sens)}$:

$$\left(\frac{S}{N}\right)_{(\max)} = P_t - P_L\left(d\right) - N \tag{9}$$

Finally, we increase capacity using Shannon's formula for point-to-point communication as presented in Saha and Aswakul (2017). Thus we have:

$$C = B\left[\log_2(1 + SINR)\right] \tag{10}$$

Equation (10) represents the channel capacity of a SISO channel which a bandwidth B. However, for MIMO channel it is different. In mmW systems the performances are not interference limited, rather they are noise limited. Due to this, the effect of interference is negligible due to the high PL and SINR (Cetinkaya, 2017). For MIMO systems, the capacities grow in proportion with the number of antennas min(n_t ; n_r) as presented in Cetinkaya (2017). Thus we have (where, n = min(n_t ; n_r) and both $n_t \gg 1, and$; $n_r \gg 1$):

$$C = n \times B\left[\log_2(1 + SINR)\right] \tag{11}$$

4. THE EFFECTS OF SINR ON CAPACITY

Consider that system capacity is approximately the same as UE throughput, which is the same meaning as SNR and SINR; both are closely related to the maximum bit rate (channel capacity).Common ways of increasing the SINR, either by increasing the transmission power or by bringing the UE closer to the BS, thus reducing propagation losses. The capacity expression of co-channel interference and noise is complex. It is presented as Equation (12):

$$SINR = \frac{P_r \cdot \left|h\right|^2}{I + P_n} \tag{12}$$

In the numerator P_r denotes the average received power and $\left|h\right|^2$ the fading channel gain (assuming unit mean). In the denominator, I is the interference from the users in the neighboring cells. This interference is due to small-scale fading or the physical location of the user in the other cells, which is reusing the same channel. The user throughput (U) can simply be expressed as shown in Equation (13):

$$U = \frac{T_c}{M} = N_c * \frac{T_c}{N_x} \tag{13}$$

Table 2. Parameters assumptions for capacity calculations and Simulations Cetinkaya (2017)

Parameters	Values
Bandwidth of mmW femto-BS, Carrier Frequency	2 GHz, 73 GHz
Bandwidth of microwave BS, Carrier Frequency	20 MHz, 2 GHz
N_F, T_K, K_b	7 dB, 290 K, 1.38x10^{-23} J/K
3GPP UMa LOS PL model of HF macro BS (Rappaport et al., 2017; ETSI, 2016)	22 log(d) + 34.02 + S_{δ_s} , if 10 < d <100m and 40 log(d) –11.02+ S_{δ_s} , if 100 < d<1000m; $\delta_s = 4$
3GPP UMa NLOS PL model of HF macro BS (Rappaport et al., 2017; ETSI, 2016)	39.1log(d) + 19.56 + S_{δ_s} , with $\delta_s = 6$
METIS UMi Street Canyon LOS PL model of HF femto BS (Rappaport et al., 2017; ETSI, 2016)	22log(d) + 34.02 + S_{δ_s} , if 10 < d <100m and 40log(d) – 3.36 + S_{δ_s} , if 100 < d<1000m; $\delta_s = 3$
METIS UMi Street Canyon NLOS PL model of HF femto BS (Rappaport et al., 2017; ETSI, 2016)	36.7log(d) + 30.53 + S_{δ_s} , with $\delta_s = 4$
UMi mmW outdoor channel PL model of mmW femto-BS (Cetinkaya, 2017; Markano, 2018)	$20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\,\alpha_{LOS/NLOS}\log\left(d\right) + S_{\delta_s}$ LOS: $\alpha_{LOS} = 1.9$ and $\delta_s = 4.6$ where as NLOS: $\alpha_{NLOS} = 3.3\ and\ \delta_s = 12.3$
Maximum transmit power of HF for macro-cell, HF for femto-cell and mmW frequency for femto-cell respectively	16 dB, –8 dB and –1 dB
Number of users per macro-cell	10 – 1000
The height of HF macro BS, HF femto-BS, mmW femto-BS and user	25 m, 10 m, 3 m and 1.5 m
Number of small cells per macro cell	10 – 200

where N_x is number of users and N_c is the number of BS antennas. Thus, M is the ratio of N_x to N_C. This expression can be diversified into different regimes based on the following SNR regimes.

4.1 High SNR Regime

The capacity of MIMO is a function of the distribution of singular values λ_i of random channel matrix h. The performance gain can be most evident in the high SNR regime. Therefore, to have a large capacity, we need multiple transmit and receive antennas instead of using SISO (Tse & Biswanath, 2005). The channel capacity of high SNR regime can expressed as below:

$$C = B\left[\log\left(1 + \frac{SNR}{n_t}\sum_{i}^{n_t}\left|h_i\right|^2\right)\right] \tag{14}$$

4.2 Low SNR Regime

In particular, let us look at the low and the high SNR regimes. We observe that:

$\log_2\left(1+SNR\right) \approx \text{SNR}\log_2\left(e\right)$, when SNR ≈ 0, for low SNR regime

$\log_2\left(1+SNR\right) \approx \log_2\left(SNR\right)$, when SNR >> 1, for high SNR regime

However, channel capacity for low SNR regime can be expressed as follows:

$$C = n_r * \text{SNR} \ \log_2\left(e\right) \tag{15}$$

In general, to better understanding of the useful contrast, MIMO scenarios are as follows:

- MISO channel with large transmit antenna scenario:

$$C_{n_t 1} = \log\,(1 + \text{SNR}) = C_{AWGN} \tag{16}$$

- SIMO channels with a large receive antenna scenario:

$$C_{1 n_r} = \log\,(\,n_t\ \text{SNR}) \ = \log\left(SNR\right) + \log\left(n_r\right) \tag{17}$$

The difference between high and low SNR regimes is bandwidth-limited (the higher the SNR, the smaller is the impact capacity) and power-limited (SNR is low and the capacity is linear in the SNR). It is noteworthy that for the low SNR regime there is need of large system margin in the receiver. However, for the high SNR regime, a large system margin is not needed.

5. RESULTS AND DISCUSSIONS

In this section, we present the results and findings of the technical analysis. Here, we provide the estimation of the key noise parameters in the 73 GHz range mmW and based on that we create different scenarios for simulations. Considering equation (7) and its specifications for each tier as shown in Table 3 and 4, we can calculate the associated thermal noise.

Table 3. Analytical results of thermal noise for tier networks setup-1

	Carrier Frequency	Bandwidth	Transmit power	Thermal noise (N)
Macro-cell	2GHz (HF)	20MHz	16dB	-124
Femto-cell	2GHz(HF)	20MHz	-1dB	-124

Table 4. Analytical results of thermal noise for tier networks setup-2

	Carrier Frequency	Bandwidth	Transmit power	Thermal noise (N)
Macro-cell	2GHz (HF)	20MHz	16dB	-124
Femto-cell	73GHz(mmW F)	2000MHz	-8dB	-104

Now, considering the above values for each tier network and PL model, we determine the SINR as shown below:

$$SINR_{\max 1} = 16 - (-124) - P_L(d) = 140 - P_{L1}(d)$$
$$SINR_{\max 2} = -1 - (-114) - P_L(d) = 113 - P_{L2}(d)$$
$$SINR_{\max 3} = -8 - (-104) - P_L(d) = 96 - P_{L3}(d) \quad (18)$$

Using the relations of SINR and the corresponding PL model, the maximum capacities can be shown in equation (19):

$$C_{\max i} = B\log_2\left[1 + 10^{\left(\frac{\mathrm{SINR}_{\max i}}{10}\right)}\right] \quad (19)$$

Now using the equations (18) and (19), we can develop different scenarios for simulation for the mmW frequencies. We have simulated four different scenarios and show their results as graphical plots.

5.1 Simulation Results for mmW Frequencies, PL and SNR

We verify our theoretical analysis based on simulation results. When we compare the mmW frequency ranges (as shown in Figure 3) to show that the path loss is increases as the operating frequency increases. Hence, PL and frequency are not related linearly rather they follow logarithmic relationship as given in Hemadeh et al. (2017). The path losses are much larger for the higher frequencies. It indicates that small cells are the appropriate choices for higher mmW.

In Figure 4, P_r vs. distance relationships has been shown. It shows that P_r reduces logarithmically for small distances. Then the rate of reduction reduces. Figure 4 also indicates that microwave

Figure 3. Free space loss at mmW frequencies

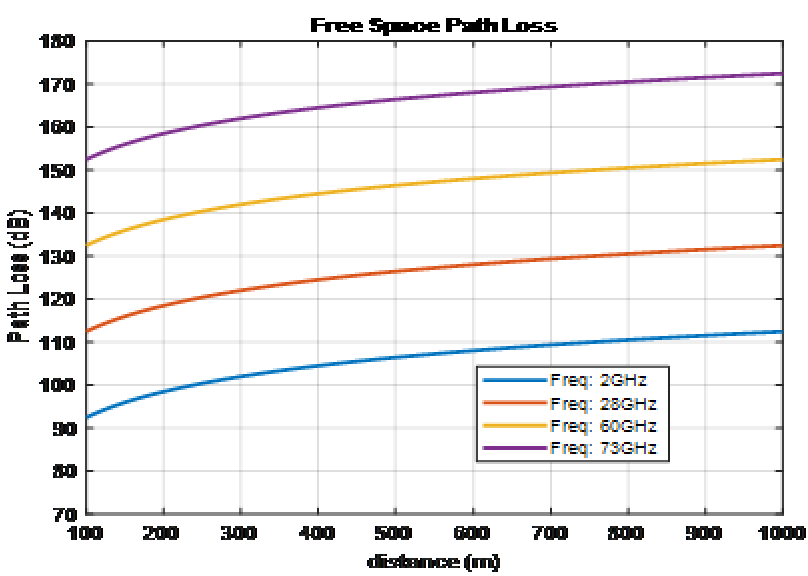
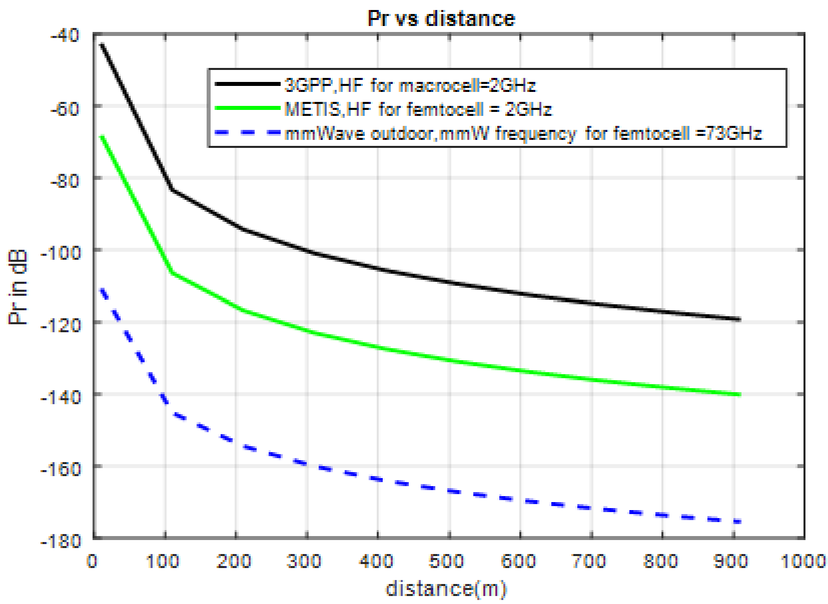


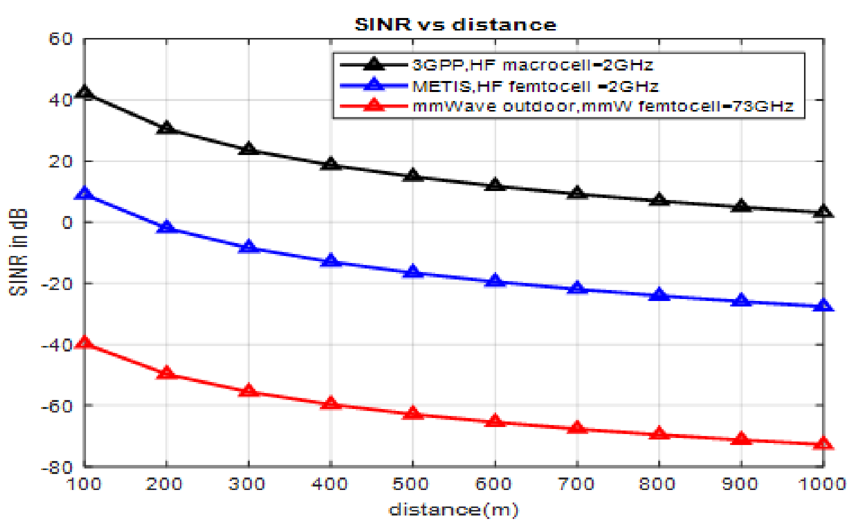
Figure 4. Received power at microwave (HF) and mm Wave frequencies BS



frequencies have higher power losses at higher frequencies over distance. Though, mmW have higher PL than microwave frequency (due to blockage) as studied in Hemadeh et al. (2017). All these characteristics are clear from Figure 4.

The result of Figure 5 shows that the SINR and the distance between BS and UE are inversely proportional to each other. In addition, the HF macro-cell BS tier for 3GPP PL has a better SINR value compared to the HF femto-cell BS tier for the 2 GHz METIS PL model. The SNR show the expected decreased behavior as the distance from BS to UE increases as given in Ikuno (2013). These

Figure 5. Shannon SINR vs. Distance



are typical behavior of mmW at 73 GHz which directly indicates that small cells are the right choice for these frequencies.

5.2 SISO Antenna Systems for Capacity Analysis

From the result of the Figure 6(a) for NLOS and Figure 6(b) for LOS, as below indicates that, when the bandwidth is small and the SNR per degree of freedom is high, and then the capacity is insensitive to small changes in SNR. However, increasing bandwidth yields a rapid increase in capacity because the increase in degrees of freedom more than pays for the decrease in SNR. Moreover, we observe the following behavior from our results which is very similar to the outcomes as presented in Tse and Biswanath (2005):

1. In NLOS scenario, SNR is low and hence Shannon capacities enhance slowly with bandwidth.
2. In LOS scenario, SNR is high and the system capacity improved highly with bandwidth.

However, based on the mmW outdoor model for 73 GHz frequency, the output in Figure 7 show that the LOS communication has higher capacity, i.e., approximately 150 Gbps increase than that of NLOS scenario over the entire separation distance between BS and UE.

5.3 Spectral Efficiency and Data Rates Comparison for MIMO Systems

We have seen that in the high SNR regime, the capacity increases linearly with the minimum number of transmit and receive antennas, while in the low SNR regime; the capacity increases linearly with the number of receive antennas such as SIMO and MISO Scenarios. Thus, Figure 8 shows that MIMO has better performance than SIMO and MISO (expresses AWGN capacity with poor performance) for fixed SNR values as studied in Tse and Biswanath (2005), and Alshammari (2017).

However, as we have shown below in Figure 9, the result indicates that at moderate to high SNR, the capacity of an $N_t \times N_r$ channel is about N times the capacity of a 1×1 system. Hence $N_t \times N_r$ more performance than $1 \times N_r$ or $N_t \times 1$, it means 16x16 has better efficiency performance than 2x2 MIMO system.

Figure 6a. Effect of SNR variations on the NLOS capacity

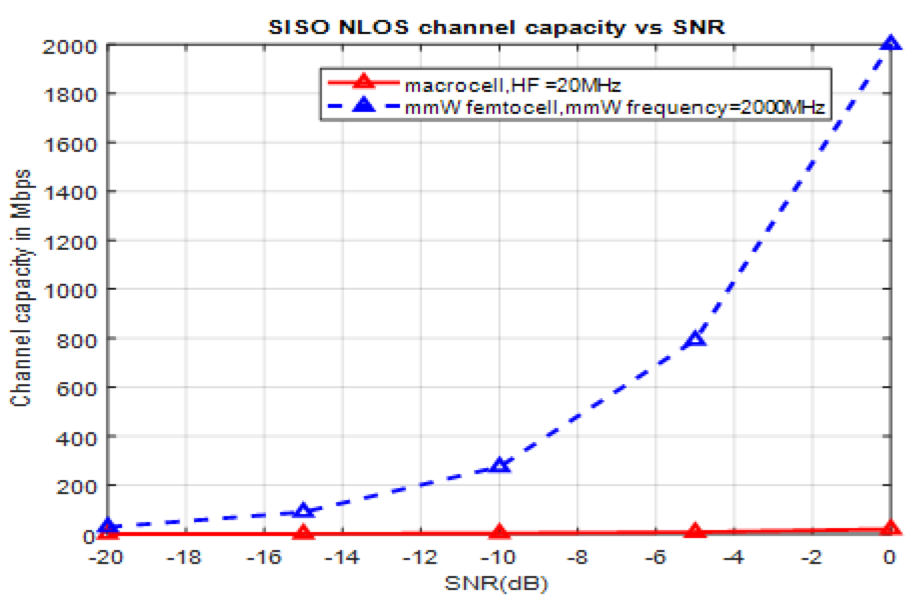


Figure 6b. Effect of SNR variations on the LOS capacity

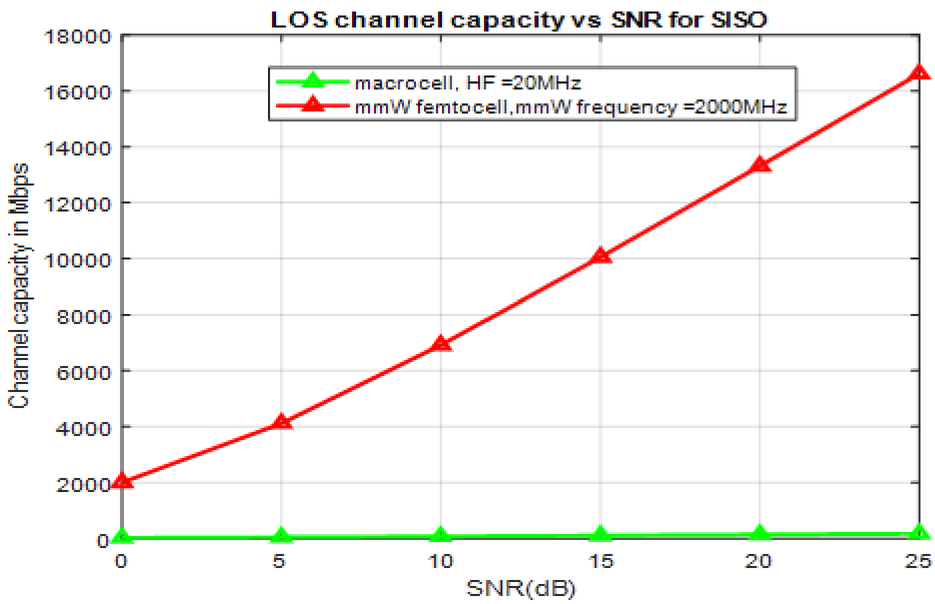
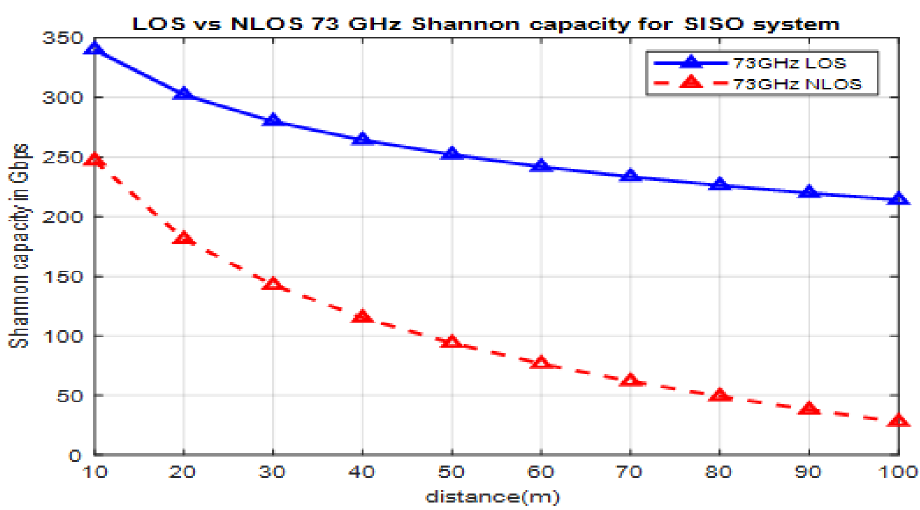


Figure 7. Shannon capacity comparison of LOS vs. NLOS for SISO system



5.4 Channel Capacity (User Throughput) Over-Dense Deployments

Another way to increase the capacity of the channel is by increasing the number of BS antennas. Figure 10 results show that, in a small area with a fixed number of users, the user bit rate always increases when more cells are added; assuming users are spread equally across the system area.

Figure 8. The spectral efficiency of MISO, SIMO, and MIMO as a function of N, for SNR = 20 dB

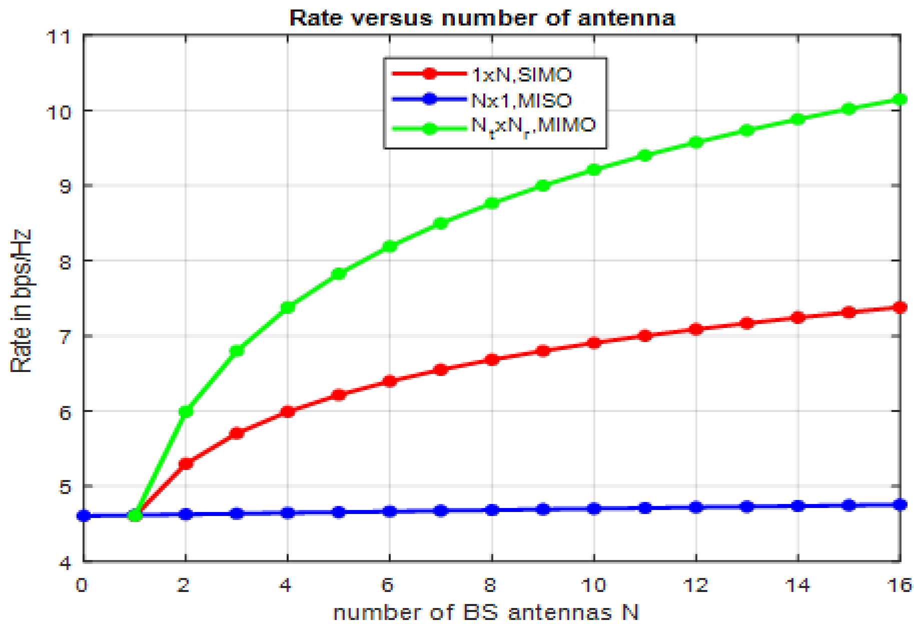


Figure 9. Spectral efficiency over SNR improved by MIMO model

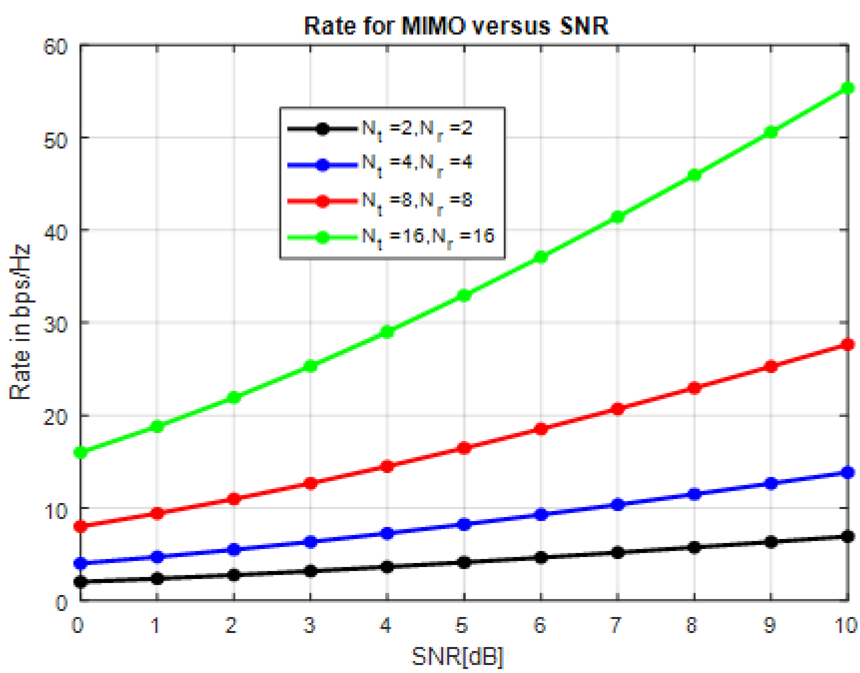


Figure 10a. Impact of users' capacity with 20 MHz

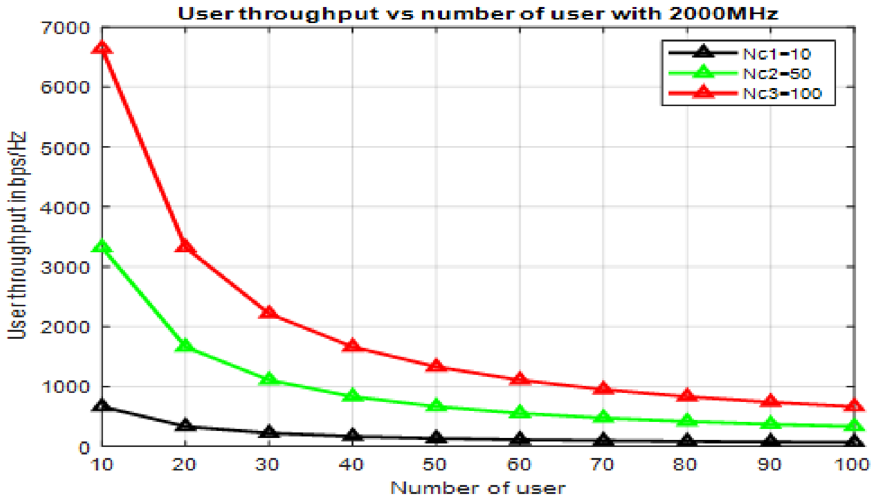
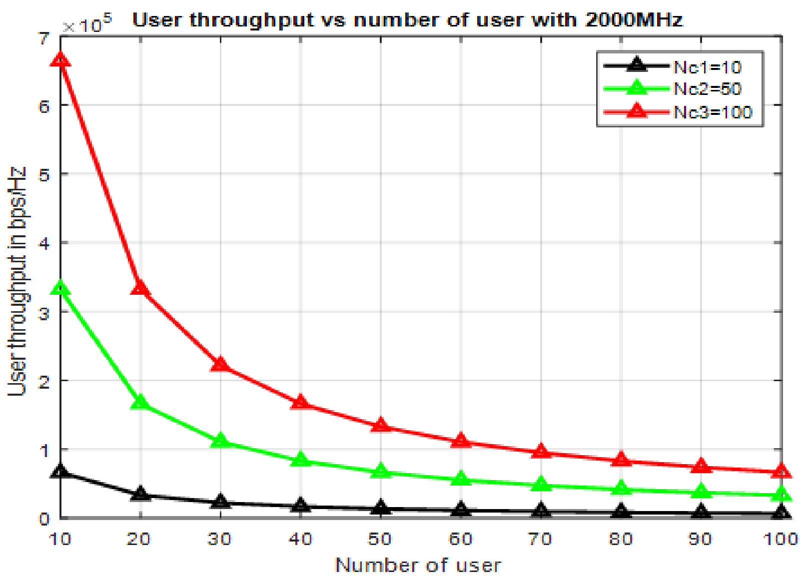


Figure 10b. Impact of user's capacity with 2000 MHz



6. CONCLUSION

5G systems are going to change the communication landscape to a large extent. Currently, in the non-standalone mode frequency bands in the sub-6 GHz range are being used for 5G. However, it is not enough when 5G will be adopted widely in the standalone mode. mmW frequency bands promise a lot to the 5G communication systems. This article showed that mmW communication has been considered as a potential candidate for outdoor 5G systems that provides a much larger system capacity than conventional frequency systems. Here, we have focused on the 2 GHz and 73

GHz mmW models for both LOS and NLOS scenarios. Our results show that the mmW outdoor system has the highest spectral efficiency and the Shannon potential for macro- and femto BS tiers in both LOS and NLOS scenarios. In addition to that, the MIMO system can be used as advanced network solution to increase the overall system capacity. These models provide the basis for the capital expenditure estimation, and also help in the estimation of some of the parameters of the operational expenditure of the 5G networks. These models can also be used as the theoretical basis for 5G networks' planning and dimensioning. However, there are also further scopes to extend these models for other higher frequency bands such as the W band (75 GHz to 110 GHz) for terrestrial uses. Similarly, there are scopes for bands beyond the W-band. Overall, we found that the higher is the frequency of mmW, the smaller should be the size of the cells. This is the direct implication that the 5G and beyond 5G systems those plan to use 73 GHz and higher must deploy the small cells and MIMO for the maximum benefits.

COMPETING INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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