

Evaluation of Capacity and Power Efficiency in Millimeter-Wave Bands

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Abstract—Millimeter wave (mmWave) spectrum bands have been proposed for commercial wireless communications to relieve the spectrum crunch in the microwave band. The mmWave bands are being vigorously pursued for multiple gigabit data transmission. In this paper, channel models for line-of-sight (LOS) and non-line-of-sight (NLOS) links for specific mmWave frequency bands are presented and then used in the evaluation of green efficiency metrics, maximum achievable capacity, bits/s, and power efficiency, bits/s/Thermal Noise Energy Unit. These efficiency indexes are investigated and illustrated using Monte Carlo simulation as a function of signal to noise ratio, channel model parameters and transmitter-receiver separation distance. The results show that the mmWave bands provide better channel capacity; however, less energy efficiency is achieved.

Keywords—MmWave bands, Channel model, Channel capacity, Power Efficiency

I. INTRODUCTION

Due to increasing demand for broadband wireless communication services and the increasing popularity of smart devices, microwave radio spectrum has become congested. Therefore, it has become essential to allocate the broadband services to mmWave spectrum which provides a massive amount of data transmission capacity [1]. Despite the fact that mmWave band exhibits a massive bandwidth, it faces crucial limitations such as signal propagation, channel characteristics, transmission range constraints and environmental effects. These limitations are discussed in more details in [2], [3]. To utilize the mmWave bands to achieve gigabit data rate, substantial research is required. Several works have been done that discuss the major differences between mmWave and microwave propagation environment. In [4], mmWave propagation characteristics have been studied using image method. The analysis shows that mmWave provides low delay spread and more effective suppression of inter-symbol interference. However, to evaluate the

system performance, channel must be modeled based on real measurements for specific frequency bands. Recently, several efforts have been devoted to accurately model mmWave channel which fits the LOS and NLOS propagation environments. In [5], a channel model and a new stochastic path loss model have been introduced which are suitable for urban areas. Also, the spatial statistical model of the mmWave channel has been provided as a function of key channel parameters including the path loss in [6]. The proposed model has been derived based on real measurements in New York City at 28 and 78 GHz frequency bands for LOS and NLOS links. The mmWave band has already been considered in various commercial wireless systems that employ IEEE 802.15.3c, IEEE 802.11ad and IEEE 802.16.1 standards. The general framework to evaluate the coverage and rate performance in a mmWave cellular network using a distance-dependent LOS probability function is proposed in [7]. Shannon's limits and signal processing challenges for multigiga bit mmWave communication have been discussed in [8]. Also, Madhoo has addressed the opportunity and challenges of utilizing MIMO in LOS mmWave communication systems. An overview of Impulse Radio-Ultra Wide Band (IR-UWB) technology transmitter and receiver has been presented in [9]. The authors have evaluated the design and bit error rate performance of 85 GHz up-conversion system based on IR-UWB technology for FSK modulation scheme. Moreover, the mmWave coverage and rate performance are examined as a function of the antenna geometry and base station density to determine proper coverage and data rate that can be achieved. In [10], coverage and capacity of dense mmWave networks have been analyzed using a theoretical model that incorporates blockage and beamforming. It was found that the mmWave networks have the potential for high coverage and capacity as long as the infrastructure is densely deployed. In addition, in this work, capacity in (bits/s) is introduced and investigated for typical point-to-point LOS and NLOS

at 28 and 73 GHz mmWave transmission system. To show the importance of the huge available bandwidth in mmWave, the efficiency indicators are evaluated for a specific spectrum bandwidth. Since the issue of power consumption is important for a wireless communication system, there are many research efforts that address this problem in the conventional frequency domain. However, the issue of power consumption in mmWave bands has not received much attention in the literature. In [11], energy coverage probability was derived for typical mmWave transmission as a function of network density, beamforming bandwidth and channel parameters. Also, power consumption factor was presented to compare and design of mmWave networks in [12]. The presented power factor has implications for the minimum power consumption per bit required to achieve error-free communication, and may be used to extend Shannons fundamental limit theory in a general way. In this context, power efficiency in (bits/s/TNEU) is introduced as ‘green communication’ indicator and then evaluated in 28 and 73 GHz mmWave bands for LOS and NLOS links. The investigation is done as a function of signal power, signal-to-noise ratio (SNR) and the separation distance between transmitter and receiver, d . This paper is organized as follows: In Section II, mmWave signal propagation and channel model are presented. Section III addresses the definitions of capacity and power efficiency and their relationship; moreover, approaches for evaluation of these efficiencies are introduced. Simulation and numerical results are given in Section IV. Finally, the work is concluded in Section V.

II. MILLIMETER WAVE CHANNEL AND SNR MODELING

Wireless channel introduces critical challenges as a media for reliable high data rate services. Besides noise and interference, the wireless signal is susceptible to small-scale and large-scale fadings that are introduced due to environment dynamics. These effects cause a serious degradation in the signal to noise ratio (SNR) leading to poor overall system performance. In this section, mmWave channel model is presented for 28 and 73 GHz frequency bands that fit the LOS and NLOS transmission links. The 28 and 73 GHz bands were selected since they both are likely to be initial spectrum for the first mmWave cellular system. According to measurement details presented in [5], small-scale fading has a minor impact on mmWave signal propagation and hence only large-scale fading effect is considered in this work. In [6], mmWave channel effects have been addressed and a statistical channel model based on realistic measurements is presented in an urban environment. Accordingly, the LOS and NLOS channel

path loss model is given by

$$L_{N/LOS} = \alpha + \beta 10 \log_{10}(d) + \xi, \quad \xi \sim \mathcal{N}(0, \sigma^2) \quad (1)$$

where $L_{N/LOS}$ is the path loss in dB, d is the distance between transmitter and receiver in meters, α and β are the least square fits of floating intercept and slope over the measured distances up to 200 m, and σ^2 is variance of the lognormal shadowing, ξ . The values of α , β and σ^2 are given in Table I. In this paper, the path loss model given by (1), is used to obtain the received signal power and then SNR is estimated using the model introduced in [7]

$$SNR = 10 \log_{10} \frac{|h|^2 + P_t + G_t + G_r - L}{(KT + 10 \log_{10}(BW) + NF)}, \quad (dB) \quad (2)$$

where P_t is transmission power, KT is the noise power density and NF is the noise figure. The transmitter and receiver antenna gains, G_t and G_r , are calculated according to the exploited frequency band and antenna length l using $G = 20 \log_{10} \left(\frac{\pi l}{\lambda} \right)$. The small-scale fading component, $|h|^2$, is considered less severe in mmWave band and can be neglected [7]. The path loss component L can be calculated from (1).

III. DEFINITION AND EVALUATION OF CAPACITY AND POWER EFFICIENCY

Power and spectrum are independent basic wireless communication system resources and both have to be appropriately traded in order to design an efficient mmWave communication system. Reduction of power consumption in mmWave communication systems has become an important issue; however, efficiently exploiting the mmWave spectrum requires more power consumption due to high attenuation in this band. Therefore, capacity and power efficiency metrics are not consistent and a balance between them deserves careful study. In this section, important measures for utilizing the spectrum and power are introduced with the goal of maximum achievable capacity and power efficiency for mmWave system transmission. Analysis of these two metrics can play a considerable role in the mmWave system standardization.

A. Maximum Capacity

Maximum achievable capacity quantifies the information rate, in bits/s, that can be conveyed over a certain mmWave bandwidth. This index is introduced in terms of specific bandwidth (W) to show the significance of the large bandwidth available in the mmWave spectrum. Also, it indicates how efficiently the spectrum is utilized. According to Shannon’s information theory [13],

the maximum achievable capacity is given by

$$\eta_C = W \log_2(1 + SNR), \quad (\text{bit/s}) \quad (3)$$

where SNR can be obtained from (2) and W is the allocated mmWave bandwidth for the system. Thus, η_C represents the upper bound on the data rate or the throughput that can be attained in a certain mmWave band, W , while maintaining an acceptable quality of service.

B. Power Efficiency

The power efficiency is defined as the maximum bit rate (bits/s) that can be reliably transmitted by a mmWave communication system per unit of transmission power. Since the SNR is a significant measure of mmWave signal power, the definition of energy efficiency [14] is used to link the mmWave channel with the efficiency metric. According to this definition, power efficiency is quantified as the number of bits per thermal noise energy unit (TNEU). It corresponds to the bit rate, in bits/s, communicated using a signal having the same power spectral density (PSD) as that of additive white Gaussian noise (AWGN) recorded at the receiver. Thus, the maximum power efficiency that can be attained in mmWave bands can be written as

$$\eta_p = \frac{W \log_2(1 + SNR)}{SNR}, \quad (\text{bits/s/TNEU}) \quad (4)$$

where SNR can be obtained from (2). This definition indicates the amount of data rate that can be delivered per unit of SNR for certain mmWave bandwidth. These efficiency metrics can be beneficial in the standardization of mmWave cellular networks in which the capacity provides the maximum rate for each frequency range while power efficiency gives insight into how to utilize the power resources in the cell as a function of data rate.

IV. SIMULATION AND NUMERICAL RESULTS

The capacity and power efficiency are evaluated for specific mmWave bands which are 28 and 73 GHz using Monte Carlo simulation. For this evaluation, the mmWave transmission system and statistical channel model are simulated using parameters tabulated in Table I. The efficiency metrics are investigated in terms of transmission power, the separation distance between transmitter and receiver, and the SNR given by (2).

A. Channel capacity

The mmWave channel capacity is used to measure the data rate for a specific bandwidth. Capacity in bits/s

TABLE I: Statistical model and system simulation parameters

Path Loss Parameters		α	β	σ	λ (mm)
28 GHz	NLOS	72	2.92	8.7	10.7
	LOS	61.4	2	5.8	10.7
73 GHz	NLOS	86.6	2.45	8.0	4.1
	LOS	69.8	2	5.8	4.1

System Simulation Parameters	
Allocated bandwidth, W	1.5 GHz
Transmission Power P_t	-10 dBm to 40 dBm
Noise power density, KT	-174 dBm/Hz
Noise figure, NF	6 dB
Transmission distance, d	0 m to 40 m
Transmitter antenna length	0.1 m
Receiver antenna length	0.01 m

is plotted in Fig.1 as a function of the distance between transmitter and receiver for LOS and NLOS links in 28 and 73 GHz frequency bands where the transmission power is fixed at 10 dBm. For a separation distance of 31 m, the capacity is also investigated and plotted in terms of the signal transmission power in Fig.2. For an extensive analysis of mmWave capacity, it is concurrently evaluated with respect to SNR and separation distance. These results are shown in Fig.3. From Fig.1, it

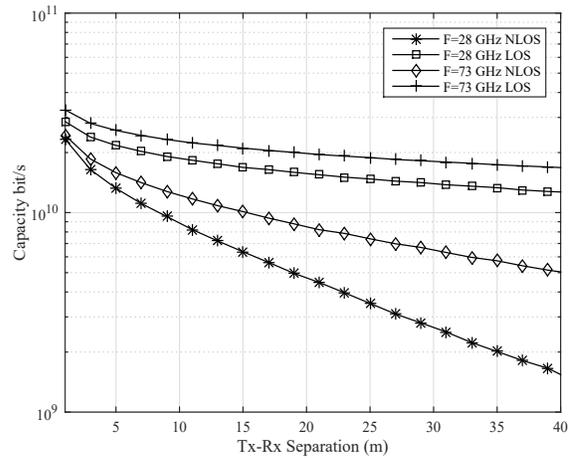


Fig. 1: Capacity of 28 GHz and 73 GHz mmWave bands for NLOS and LOS links as a function of separation distance

is noted that transmitting over LOS link achieves better capacity than NLOS link. In addition, the capacity in

the high-frequency band, 73 GHz, is superior to the low-frequency band which is due to the high antenna gain in 73 GHz band. Also, it is observed that the capacity of LOS link is slightly reduced as the distance increases. Fig.2 shows that the capacity is improved as the transmission power increases; moreover, the best performance is obtained for 73 GHz LOS link while a less capacity is achieved at 28 GHz for NLOS link. For high transmission power, the achieved capacities of the two transmission bands are huddled above 10 Gbits/s. The effect of SNR and the separation distance between

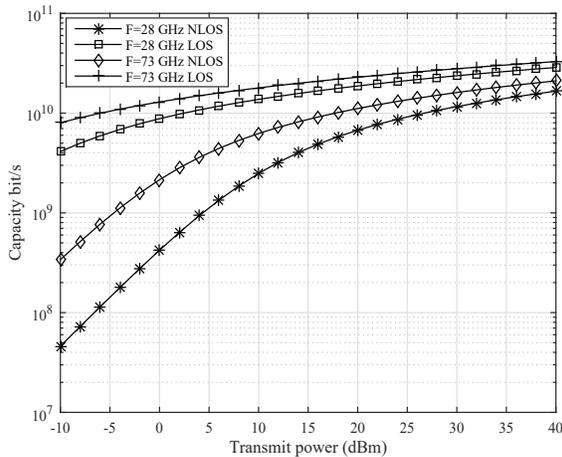


Fig. 2: Capacity of 28 GHz and 73 GHz mmWave bands for NLOS and LOS links as a function of transmission power

receiver and transmitter on the mmWave capacity are addressed for each frequency band and transmission link. The capacity of 73 GHz LOS link is plotted in Fig.3 as a function of SNR and distance, d . It is evident that the capacity improves as SNR increases whereas it is deteriorated as the receiver moves far away from the transmitter. From this figure, the values of SNR that fit a certain capacity for a specific distance can be easily determined.

B. Power efficiency

Power efficiency has been suggested as a ‘green communication’ indicator for wireless communication system design. Since power is a crucial parameter in mmWave systems, we investigated the power efficiency using an index that elucidates the data rate can be transmitted over a mmWave link using signal that power equivalent to the noise power (4). In this section, the

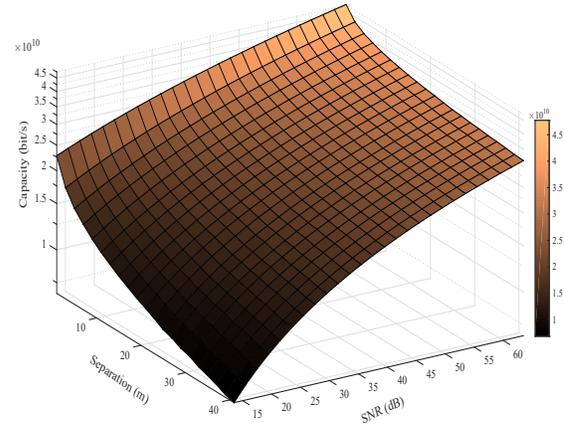


Fig. 3: Capacity of 73 GHz mmWave band for LOS links as a function of SNR and separation distance

power efficiency is examined as a function of the transmission distance, the transmission power and the SNR. Fig.4 shows a comparison of power efficiency of the two chosen frequency bands and transmission links. It is observed that 28 GHz with NLOS attains the optimum efficiency whereas minimal efficiency is achieved by 73 GHz LOS link. The SNR for LOS transmission at the high-frequency band is greater than the SNR for NLOS transmission at the low-frequency band. Also, it shows that the efficiency is improved as the distance increases. Power efficiency versus power transmission is plotted in Fig.5 for the two proposed frequency bands and transmission links. As expected, power efficiency is degraded as the transmission power is increased. The power efficiency is plotted as a function of SNR and receiver distance in Fig.6. It is observed that the efficiency is deteriorated in the high SNR range and enhanced for large separation distance. From this figure, it is noted that trade off exist between distance and SNR.

V. CONCLUSION

In this paper, mmWave statistical channel model has been presented for two frequency bands. Capacity and power efficiency of mmWave wireless transmission systems are introduced in terms of bits/s and bits/s/TNEU, respectively. The efficiency metrics introduced have been evaluated using simulation of mmWave system and the channel models. The investigation of the efficiency is presented as a function of the receiver distance, transmission power and signal-to-noise ratio. Results

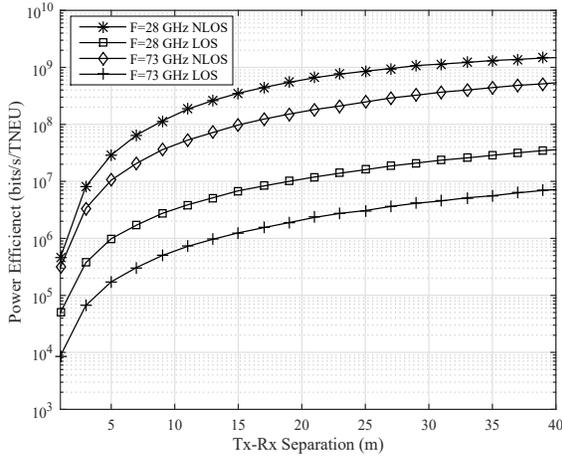


Fig. 4: Power efficiency as a function of separation distance for 28 and 73 GHz bands and LOS and NLOS links

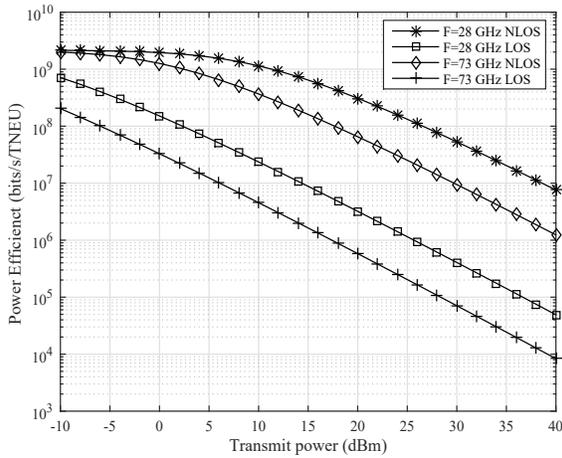


Fig. 5: Power efficiency as a function of transmission power for 28 and 73 GHz links and LOS and NLOS links

show that capacity achieved in the mmWave band is in excess of 10^{10} bits/s. The high-frequency band perform better than the low-frequency band. However, the high-frequency band provides less power efficiency. It is also observed that the NLOS transmission has additional propagation loss compared to the LOS transmission in the two bands and hence the optimum capacity is achieved for LOS links. These results can be effective

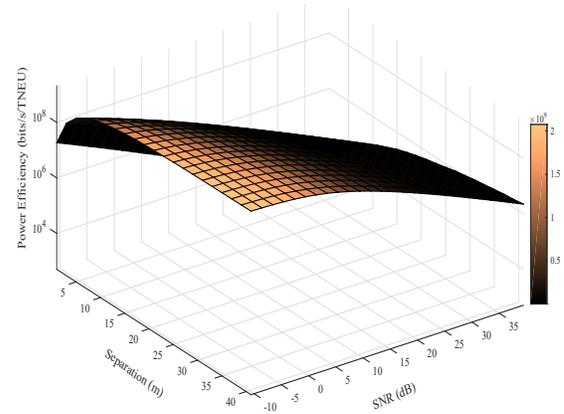


Fig. 6: Power efficiency as a function of SNR and distance for 73 GHz mmWave band and NLOS link

in the dimensioning of mmWave cellular system.

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