

A Discussion About Achievable Data Rates of 6G MIMO Channels in Urban Microcells

Victor Fernandes, Marlon da S. Borges, Roberto B. Di Renna, Ândrei Camponogara, Moisés V. Ribeiro

Abstract—Aiming to bridge the gap between practical data rates and simulated achievable data rates (ADRs), this work focuses on ergodic ADR analyses of 6G point-to-point multiple-input multiple-output channels in the frequency bands of 7.8 GHz and 15 GHz, when an urban microcell scenario is considered. Numerical results showed that the realistic ADRs are 46% of those obtained from ideal models, and the discrepancy between them grows as the number of antenna elements and signal-to-noise ratio (SNR) increase. Moreover, SNR-based metrics lead to biased performance comparisons across frequencies, whereas a TX-power-based framework enables fairer assessment. This framework reveals the inherent limitations of millimeter-wave communications, particularly at longer distances and under non-line-of-sight (NLOS) conditions. A comparison of the 7.8 GHz frequency band with the conventional 5G bands shows that it offers a compelling compromise between coverage and data rate, combining a wider bandwidth than the 3.5 GHz band with more favorable propagation characteristics than the 26 GHz band.

Keywords—wireless communication, data rate, urban microcell, sixth-generation, multiple-input multiple-output.

I. INTRODUCTION

The International Telecommunication Union (ITU) has orchestrated research efforts to address the future of cellular network technologies through International Mobile Telecommunication (IMT). ITU has released its IMT-2030 vision for 6G [1], identifying two candidate frequency bands on the upper mid-band spectrum to meet urban area demands. The frequency range 3 (FR3) in 6G technology is set to transform wireless communication, offering a broader available bandwidth than frequency range 1 (FR1) and a lower carrier frequency than frequency range 2 (FR2), as defined by the 3rd Generation Partnership Project (3GPP) releases [2].

Relying on FR3, 6G can achieve robust data rates while maintaining widespread coverage, supporting seamless connectivity for a growing range of devices and applications.

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Among the various technologies underpinning 6G, multiple-input multiple-output (MIMO) systems play a crucial role in achieving the ambitious performance targets of this new mobile technology generation. Recently, advanced MIMO techniques have been introduced to enhance the throughput and reliability of communications [3].

Improvements in enhanced Mobile Broadband (eMBB) are one of the key aspects for 6G, aiming to provide ultra-high-speed wireless connectivity for data-intensive applications. The data rate is a critical factor for these applications, and millimeter wave (mmWave) MIMO systems are of utmost relevance for bridging the gap between data rate demands and network capacity [4]. To meet users' growing demand for higher data rates, cellular networks must optimize channel resources, a fundamental functionality in wireless communications. Understanding and maximizing the use of channel resources is essential for delivering the high data rates expected by network users. Accordingly, the quantification of spectral efficiency, capacity, and achievable data rates (ADRs) [5], [6] provides a solid basis for designing next-generation cellular networks capable of satisfying projected user requirements.

These three complementary performance measures jointly capture the theoretical limits and practical performance of next-generation wireless networks and have been extensively explored in the wireless communications literature. For instance, in [7], the so-called modulation-specific data rate (MSDR) was analyzed when implementation impairments are considered; however, only single-input single-output (SISO) and single-input multiple-output (SIMO) channels were adopted. For MIMO channels, Molisch *et al.* [8] showed that the capacity in microcellular environments is about 30% smaller than would be anticipated from an idealized model. Also, in [9], it was considered that the small-scale fading coefficients follow the Rayleigh or Rician distribution. Although this effort has its unique contribution, the MIMO channel capacity was not further investigated in the main frequency band candidates of 6G. For 6G, Björnson *et al.* [10] investigated the downlink user data rates in the upper mid-band. Simulations showed that this frequency band could be a golden opportunity for maintaining the favorable coverage characteristics of sub-7 GHz bands while maintaining the typical spectral efficiency of mmWave bands. In this sense, relying on a realistic channel model for evaluating real-world channel measures [11] and considering it in the 6G context constitutes a relevant investigation.

In this regard, this work provides a discussion on ADRs of 6G point-to-point (P2P) MIMO channels, particularly within the context of FR3 for 6G, when realistic MIMO channel

$$h_{m,k}(f) = \sum_p \alpha_{m,k,p} e^{j\Phi_{m,k,p}} e^{-j2\pi f\tau_{m,k,p}} e^{-j2\pi d_T m \sin(\theta_{m,k,p})} e^{-j2\pi d_R k \sin(\phi_{m,k,p})} \quad (1)$$

models obtained from NYUSIM 4.0 are considered [11]. Numerical simulations show that ADRs obtained with realistic MIMO channel models are 46% of the ones obtained from the well-established and ideal models, and the discrepancy between these models grows as the number of antenna elements and signal-to-noise ratio (SNR) increase. Moreover, using transmitter power rather than SNR is essential for a realistic and fair comparison of ergodic ADRs across different frequency bands. The ergodic ADRs in mmWave-based communications degrades significantly with increasing link distance and under non-line-of-sight (NLOS) conditions. Lastly, a comparison between the 3.5 GHz, 7.8 GHz, and 26 GHz bands is presented and discussed, demonstrating that the 7.8 GHz band offers an attractive trade-off between achievable data rates and communication range due to its wider available bandwidth compared to the 3.5 GHz band and its lower carrier frequency compared to the 26 GHz band.

II. SYSTEM MODEL

In a MIMO channel model with N_T transmitter (TX) and N_R receiver (RX) antenna elements, the channel frequency response (CFR) of the complex envelope of a frequency-selective channel follows [8] and is reproduced in (1), where p denotes the p -th resolvable multipath component, while $m \in \{0, 1, \dots, N_T - 1\}$ and $k \in \{0, 1, \dots, N_R - 1\}$ denote the m -th TX and k -th RX antenna elements, respectively; $\alpha_{m,k,p}$ is the amplitude of the channel gain, $\Phi_{m,k,p}$ denotes the phase of the multipath component, $\tau_{m,k,p}$ represents the time delay, $\theta_{m,k,p}$ and $\phi_{m,k,p}$ denote the azimuth angle of departure and angle of arrival; and d_T and d_R are the antenna element spacing at the TX and RX, respectively.

Under the assumptions that the signals transmitted through the antennas are uncorrelated from each other, and the additive noise is circularly symmetric complex white Gaussian uncorrelated from the transmitted signal, the ergodic ADR for MIMO channels can be expressed as [8], [9]

$$C = \mathbb{E} \left\{ \int_B \log_2 \left[\det \left(\mathbf{I}_{N_T} + \frac{\text{SNR}}{N_T} \mathbf{H} \mathbf{H}^\dagger \right) \right] df \right\}, \quad (2)$$

in which $\mathbb{E}\{\cdot\}$ denotes the expectation operator; $\mathbf{I}_{N_T}$ is the $N_T \times N_T$ identity matrix; $\mathbf{H} \in \mathbb{C}^{N_T \times N_R}$ represents the MIMO channel matrix model, with $h_{m,k}(f)$ components in the (m,k) -th position. Here, $\text{SNR} = P_R/P_N$ refers to the SNR at the RX's input, where P_R is the RX power and P_N denotes the power of the additive noise. The superscript $\dagger$ denotes the Hermitian transpose operator, and B is the radio-frequency (RF) bandwidth. Full reception diversity and maximum ergodic ADR is obtained if $\mathbf{H} = \mathbf{I}_{N_T}$ and $N_T = N_R$, indicating uncorrelated reception across all N_R antennas. Note that (2) can be used to evaluate the ergodic ADR for both the downlink and uplink directions in a communications system; however, due to the chosen simulation parameters (see Table I), we will exclusively analyze the downlink.

TABLE I: Simulation Parameters.

Parameter		Description
Scenario Type		UMi
Antenna Polarization		Co-Pol.
BS	Height	20 m
	Array Type	URA
	Antenna Spacing	0.5λ
	Antenna Azimuth HPBW	60°
	Antenna Elevation HPBW	20°
UE	Height	1.5 m
	Array Type	URA
	Antenna Spacing	0.5λ
	Antenna Azimuth HPBW	360°
	Antenna Elevation HPBW	45°

Considering [7] and an M -ary digital modulation, the so-called MSDR for the aforementioned MIMO channel model is given by

$$C_M = \min \left(\left[\min(N_T, N_R) \right] \frac{C_S}{T_b}, C \right), \quad (3)$$

where $T_b = B^{-1}$ is the symbol period and $C_S = \log_2(M)$ is the modulation efficiency with M being the constellation size of the chosen digital modulation. Furthermore, interference is not considered in this work to isolate and quantify the fundamental impact of propagation conditions, bandwidth, carrier frequency, antenna configuration, and transmit power on the ADRs. The focus is on point-to-point MIMO links with uniform rectangular arrays (URAs) at both the TX and RX, operating in an urban microcell (UMi) scenario, where performance is primarily limited by path loss, blockage, and noise, especially at higher carrier frequencies.

III. NUMERICAL RESULTS

The NYUSIM 4.0 simulator generates sample functions of the MIMO channel matrix for various conditions and parameters. For understanding the NYUSIM 4.0 simulator and its parameters, see [11] and references therein. Considering outdoor environments, the channel models in the NYUSIM 4.0 offer a more realistic wireless channel characterization than the stochastic channel model from 3GPP. Indeed, the 3GPP TR 38.901 outdoor channel model may have unrealistic parameters in comparison to real-world measurements, showing the need for using a realistic MIMO channel model that is capable of providing a better characterization of the environment for 6G applications [11]. Also, the analyses hereby offer a realistic approach to the user-experienced data rate due to the 10-year data acquisition in vast measurement setups and application scenarios [11]. A summary of the main chosen parameters for numerical simulations is listed in Table I.

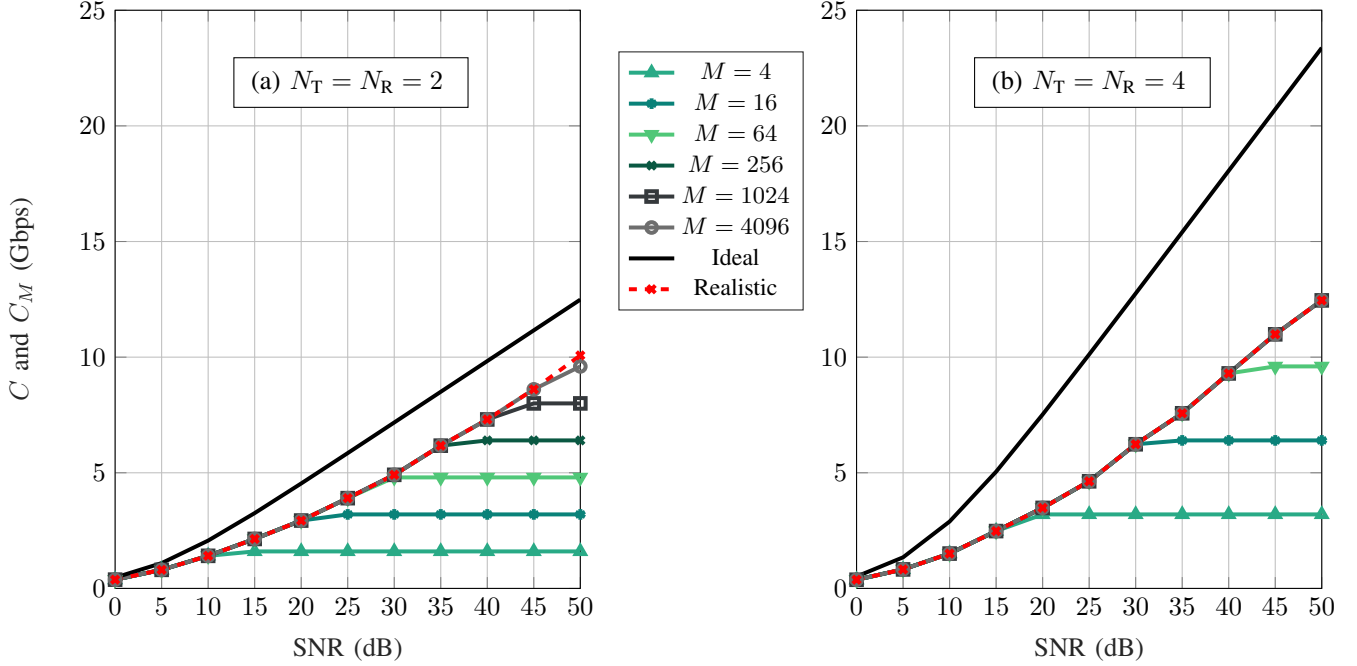


Fig. 1: Ergodic ADRs and MSDRs versus SNR with $f_c = 7.8$ GHz, $B = 400$ MHz, and $N_T = N_R$.

The ergodic ADR evaluated with (2) is labeled as a “Realistic” scenario because the MIMO channel matrix $\mathbf{H}$ is provided by NYUSIM 4.0. In contrast, it is labeled as “Ideal” if the MIMO channel matrix is $\mathbf{H} = \mathbf{I}_{N_T}$. Furthermore, it is assumed $P_N = kTB$, in which $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and $T = 293$ K is the absolute temperature. Moreover, the TX power, P_T , is equally distributed among N_T TX antenna elements, $N_T = N_R$, and $d_T = d_R = 0.5\lambda$, where λ is the wavelength. Also, the expectation in (2) is obtained using Monte Carlo simulation with 2,000 equiprobable sample functions of the MIMO channel matrix $\mathbf{H}$, whereas the NYUSIM 4.0 generates distinct realizations from random variables for the numbers of time clusters, subpaths, delays, phases, elevation, and azimuth angles in each sample function. The TX antenna azimuth and elevation half power beamwidth (HPBW) are made equal to 60° and 20° , respectively, while the RX antenna azimuth and elevation HPBW are set to 360° and 45° , respectively. The choice for these TX and RX antenna HPBWs represents typical downlink UMi scenarios, in which the base station (BS) has sectorial antennas and the user equipment (UE) is a mobile handheld device.

A. Achievable Data Rate versus SNR

For comparing the ergodic ADR and MSDR, it is assumed $\text{SNR} \in \{0, 5, \dots, 50\}$ dB, $f_c = 7.8$ GHz, $B = 400$ MHz, and $M \in \{4, 16, 64, 256, 1024, 4096\}$. Fig. 1 shows the ergodic ADRs (i.e., C) and the MSDRs (i.e., C_M) as functions of the SNR for (a) $N_T = N_R = 2$ and (b) $N_T = N_R = 4$, both using the same y-axis limits. Note that the upper bounds of MSDR are given by the ergodic ADR for low values of SNR (i.e., $C_M = C$) and by the modulation-limited data rate (i.e., $C_M = \lceil \min(N_T, N_R) \rceil \frac{C_S}{T_b}$) for high values of SNR, respectively. As $\text{SNR} \rightarrow \infty$, then $C \rightarrow \infty$ in the ideal

scenario at a higher rate than the realistic one. Relying on [8], a comparison between the curves in Figs. 1(a) and 1(b) confirms the improvements when the number of TX and RX antenna elements increase, and, most importantly, the ergodic ADR for the realistic scenario is around 6/13 (46%) of the ones from the ideal scenario. This is obtained with $N_T = N_R = 4$ and $\text{SNR} = 30$ dB, where it can be observed that the discrepancy between ideal and realistic scenarios consistently grows as the number of antenna elements and SNR increase.

Similar results as shown in Fig. 1 can also be obtained by varying the carrier frequency f_c while keeping all other parameters unchanged. This behavior arises because the data rates are expressed as a function of the SNR. In other words, SNR-based representations of data rates do not provide a fair basis for comparing different frequency bands. It is important to emphasize that, under this formulation, the attenuation of the signal along the link path is implicitly embedded in the SNR calculation. Specifically, the effects of signal attenuation, commonly referred to as path loss, are absorbed into the SNR. Since SNR is evaluated at the receiver, key physical parameters—such as carrier frequency, transmission distance, and propagation environment—are not explicitly reflected when assessing data rates solely as a function of SNR.

For a fixed SNR value, signal power losses are significantly higher at FR2 frequencies than at FR1 frequencies, implying that substantially higher TX power is required in FR2 to achieve the same SNR. While using hybrid communication systems can alleviate this power demand per communication medium [12], using SNR as a comparative metric conceals the markedly different TX power requirements needed to sustain identical SNR levels across FR1 and FR2. Moreover, TX power is subject to regulatory constraints, which may be violated when performance is evaluated exclusively in terms of

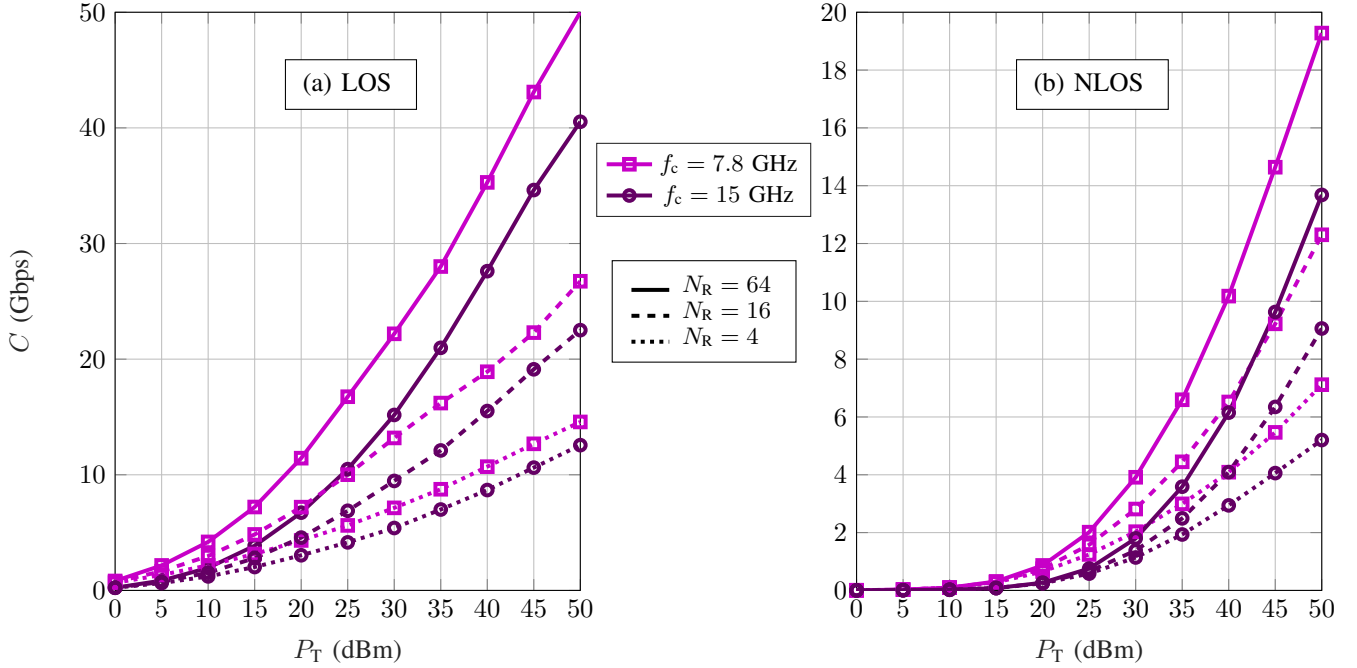


Fig. 2: Ergodic ADRs versus TX power with $d = 50$ m and $B = 400$ MHz for distinct values of f_c , and $N_T = N_R$.

SNR. For example, under free-space propagation conditions, achieving an SNR of 30 dB over a 500 m link requires TX power levels close to 40 dBm at 3.5 GHz, but exceeding 50 dBm at 26 GHz. This illustrates that SNR-based analyses can obscure physically and regulatorily infeasible TX power demands, whereas TX power constitutes a more realistic and fair performance metric. Accordingly, the analysis of ergodic ADRs in the following is conducted as a function of TX power under realistic scenarios.

B. Ergodic Achievable Data Rate versus TX Power

The frequency bands of 4.6 GHz, 7.8 GHz, and 15 GHz were identified on the IMT-2030 vision for 6G [1]. The main role of the 15 GHz band will be to serve users in dense urban areas, while the 7.8 GHz band could provide connectivity to a broader range of devices and applications. Both bands above 7 GHz are in the FR3, and they can provide a bandwidth of up to 400 MHz. On the other hand, the 4.6 GHz band is located on the legacy sub-7 GHz band and is intended to provide coverage and support high mobility in suburban and rural areas, being out of the scope of this work.

Although it is expected that $N_T > N_R$ in practical downlink cellular communications, increasing N_T with fixed N_R may not represent a gain in ADR since P_T is distributed among these TX antenna elements. Also, a BS connects with an enormous number of UEs, which makes the numerical superiority of N_T over N_R not realistic from a UE perspective. Thus, future 6G P2P communications could achieve a good compromise with $N_T = N_R$. Hence, it is assumed $N_T = N_R \in \{4, 16, 64\}$, which may represent, respectively, legacy 5G UEs, 6G UEs, and future 6G UEs in the 15 GHz band [2], [10]. The selected numbers of TX and RX antenna elements correspond to MIMO and massive MIMO configurations.

In this context, Fig. 2 shows the ergodic ADRs as functions of P_T under (a) line-of-sight (LOS) and (b) NLOS conditions between the TX and RX, respectively, considering $d = 50$ m, $P_T \in \{0, 5, \dots, 50\}$ dBm, $f_c \in \{7.8, 15\}$ GHz, and $B = 400$ MHz. From Fig. 2, it can be noted that the 7.8 GHz band has higher ergodic ADRs than the 15 GHz band in both LOS and NLOS conditions. Also, if $N_T = N_R$, then a significant ADR gain is achieved by increasing the number of antenna elements. The primary distinction between the two frequency bands lies in their propagation characteristics, including path loss and frequency-dependent channel behavior. Consequently, a fair and simple comparison is enabled by expressing performance in terms of P_T rather than SNR.

By assuming the 7.8 GHz band for 6G, a comparison with the 5G bands may provide some insights. To be fair, it is considered $N_R = 4$ of legacy 5G UEs. Additionally, mmWave signals can provide coverage for a cell radius of 200 m under NLOS conditions, while they can reach up to 500 m in lightly populated urban and suburban areas [11]. In this regard, Fig. 3 shows the ergodic ADRs as functions of P_T under (a) LOS and (b) NLOS conditions, for $d \in \{50, 200, 500\}$ m and for the parameter pairs $\{f_c, B\} = \{(3.5 \text{ GHz}, 100 \text{ MHz}), (7.8 \text{ GHz}, 400 \text{ MHz})\}$, and $(26 \text{ GHz}, 400 \text{ MHz})$. The 3.5 and 26 GHz bands are subbands from the FR1 and FR2, while the selected distances are typical for picocell and microcell deployments.

Fig. 3 shows that ergodic ADRs in mmWave-based communication (e.g., 26 GHz) exhibit degraded performance as the link distance increases or under NLOS conditions. In contrast, the 3.5 GHz band is well-suited for power-limited transmission due to its favorable propagation under NLOS conditions. Also, it is possible to note the optimal trade-off of the 7.8 GHz band between data rate and communication range under both LOS

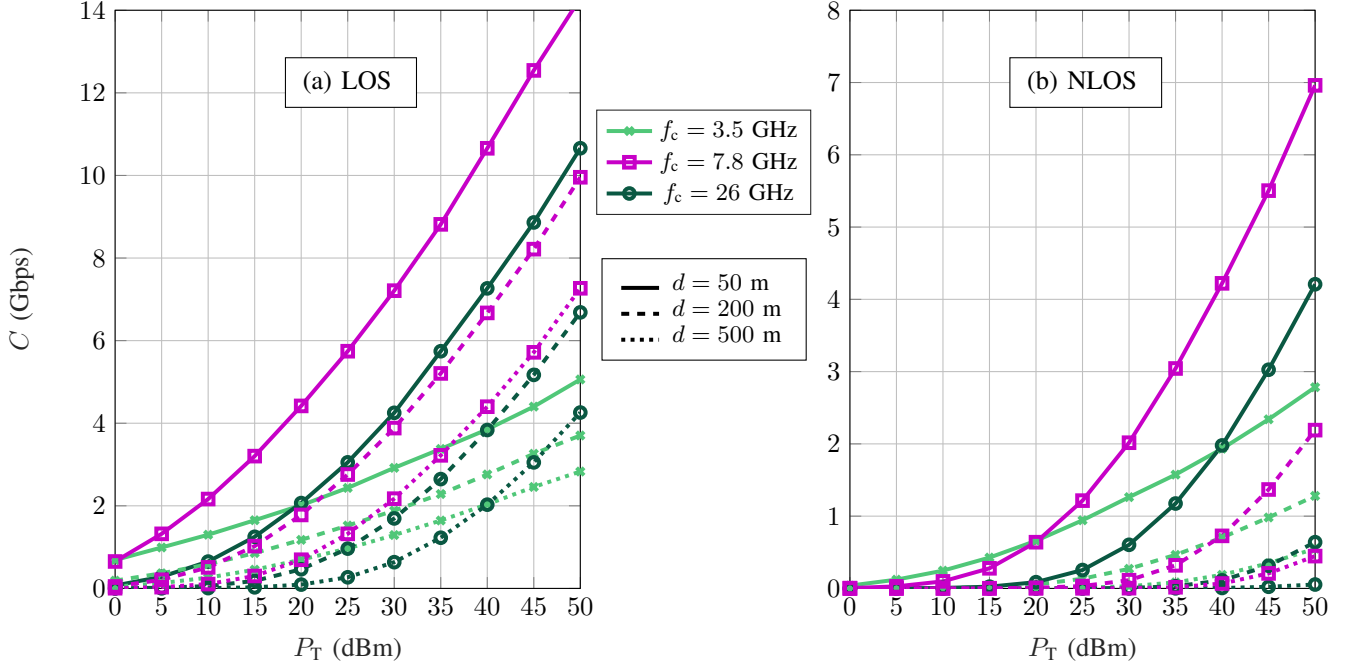


Fig. 3: Ergodic ADRs versus TX power with $N_T = N_R = 4$ and distinct values of f_c , B , and d .

and NLOS conditions, consistent with findings in [10]. The LOS condition can be seen as the most likely due to the short range of microcells. In this context, the 7.8 GHz band presents $C > 7$ Gbps for the LOS case and $P_T = 50$ dBm, even for $d = 500$ m and given assumptions, which is sufficient for most applications nowadays for a typical cellular network user.

IV. CONCLUSION

To bridge the gap between ideal and practical wireless systems, this work evaluated the ergodic ADR for 6G P2P MIMO channels in an urban microcell environment. The results showed that realistic ADRs reach only about 46% of the values predicted by ideal models, with the gap increasing as the number of antenna elements and the target SNR grow. These findings indicate that the gains expected from massive antenna systems are significantly reduced under realistic propagation conditions, emphasizing the importance of considering practical channel effects in data rate evaluations.

Unlike most previous studies that rely only on SNR-based analysis, this work showed that TX-power-based evaluation is essential for realistic ADR assessment. High SNR targets at FR2 frequencies often require impractical transmit power levels, revealing the limitations of mmWave communications, especially at larger link distances and under NLOS conditions. In comparison, the main candidate frequency band for 6G offers a more balanced trade-off between coverage and throughput by combining a wider bandwidth than FR1 with a lower carrier frequency than FR2.

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