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Analysis of MIMO Channel Capacity for Terahertz Communication Systems

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ABSTRACT: The primary focus of this paper is to evaluate the channel capacity of a Terahertz (THz) communication system using a Multiple Input Multiple Output (MIMO) technique. By deriving mathematical expressions for channel capacity and considering practical constraints, the paper provides insights into the performance of such systems under various conditions. The channel model used in this work accommodates the channel accuracies and transceivers constraints. To validate the proposed channel capacity, some simulations by taking into account deferent parameters namely SNR (Signal to Noise Ratio), MIMO channel Matrix size, and distance between transmitter and receiver are performed. These simulations are carried out for 3 cases which are: (1) Channel State Information CSI is known to both transmitter (Tx) and receiver (Rx), (2) CSI is known to Rx but unknown to Tx, (3) CSI is unknown to both Tx and Rx. In this study, we introduce a mathematical formulation for a communication channel tailored for Terahertz (THz) applications. Using this channel model, we analyze the capacity of the THz channel. The suggested research has the potential to be applied in the design and enhancement of Terahertz (THz) wireless communication systems, aiding in the advancement of robust and high-capacity wireless networks that can fulfill the requirements of contemporary multimedia applications.

1. INTRODUCTION

The rapid growth in multimedia application services, including voice, text, photos, videos, and internet access has led to an increased demand for high-speed data transmission and reliable communication through wireless systems. To address these needs, utilizing terahertz (THz) frequency bands has emerged as a promising solution due to their vast available bandwidth. Indeed, THz technology is indeed a candidate for use in 6G applications [3]. 6G, the next generation of wireless communication technology following 5G, is expected to bring even higher data rates, lower latency, and new use cases. However, THz channel is a tough environment for data transmission [4–7]. As a result, several efforts have been made on source coding and channel coding (MPEG, Turbo Code . . .) in order to reach the theoretical limit of Shannon capacity for single Input Single output (SISO) systems. But it turned out that the improvements made were still below the threshold really wanted by the mobile telecommunications market. In recent years, it has emerged that a large capacity can be attracted by exploiting the spatial dimension of the channel, i.e., by using MIMO (multiple input multiple output) technique [8, 9]. The data rates offered by this technique have improved the telecommunications market landscape, and several services are made possible by the great potential of this technique [10]. Therefore, the main purpose of this paper is to demonstrate the foundations of multi-antenna communications and mathematically derive the overall capacity of a MIMO system in THz context MIMO. Channel capacity has been studied largely in literature [11, 12]. Others methods are proposed in literature in order to increase the bandwidth usage [13, 14].

Analyzing MIMO channel capacity for THz communication systems indeed presents several challenges due to various factors inherent to this frequency range. in Terahertz frequencies the channel exhibits unique propagation characteristics. THz signals are susceptible to high atmospheric absorption, scattering, and attenuation, which can significantly impact the channel capacity. Understanding and modeling these propagation effects accurately is crucial for analyzing MIMO channels. Therefore, developing accurate channel models for THz communication is a complex task because high carrier frequencies result in short wavelengths, making the modeling of channel impairments such as path loss, shadowing, and multipath fading challenging. The channel environment may also be highly dynamic, requiring sophisticated models. Moreover, the availability of THz communication equipment, including transceivers, amplifiers, and signal processing components, may be limited. Developing and using suitable hardware for experimental validation of theoretical models can be challenging due to the scarcity of commercially available THz communication systems. Another reason that makes THz com-

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munication channel very challenging is that THz environments are susceptible to various sources of noise and interference, including thermal noise, electronic noise, and atmospheric noise. Mitigating these sources of interference becomes crucial for achieving reliable and high-capacity communication. In addition, communication channels may exhibit significant spatial and temporal variations. The environmental conditions, such as humidity and temperature, can impact the channel characteristics, requiring adaptive MIMO strategies to maintain high capacity. These aspects show that the THz channel is a harsh environment for signal transmission. Thus, the study of channel capacity is a necessity.

Many researches have done on channel modeling for THz bands, while only a few scientific publications on the channel capacity for THz bands have been published. The conclusion is that several measurements and simulations in different context have been done; however, the THz channel capacity has been poorly explored. In this work, an analytical MIMO channel capacity for THz frequency range, based on decomposition of MIMO channel matrix is proposed. An expression of Channel capacity of each case of Channel State Information (CSI) is presented. First, CSI known at the transmitter (Tx) and receiver (Rx) is studied. Then, singular value decomposition (SVD) is used to determine the channel capacity when CSI is known to Rx but unidentified to the transmitter. In addition, we propose a new decomposition of channel capacity matrix to calculate and simulate the channel capacity of THz when CSI is unknown to both Tx and Rx. Channel matrix will be generated by using Kronecker model. Moreover, simulations of channel capacity have been carried out to validate the proposed channel expression in terms of signal-to-noise ratio (SNR) and distance between transmitter and receiver. Here are some key aspects of this work:

- The paper focuses on quantifying the channel capacity, which represents the maximum data rate that can be reliably transmitted over the THz communication channel. This analysis is essential for understanding the system's potential capabilities.
- The paper considers practical constraints, which could include factors like path loss and absorption.
- The research utilizes a channel model that accurately represents the behavior of the THz communication channel, accounting for channel inaccuracies and the limitations of transceivers. This model is crucial for making realistic capacity predictions. In this work, the channel model in time domain is detailed.
- To validate the proposed channel capacity analysis, the paper conducts simulations. These simulations were done by taking into account key parameters such as SNR, MIMO channel matrix size, and the distance between the transmitter and receiver. The simulations explore three different scenarios: CSI Known to Both Tx and Rx: In this case, both the transmitter and receiver have accurate CSI. CSI Known to Rx but Unknown to Tx: The receiver has access to CSI, but the transmitter does not. CSI Unknown to Both Tx and Rx.
- The research findings have practical implications in the design and optimization of THz wireless communication systems. These systems aim to meet the increasing demand for high-capacity and reliable wireless networks, particularly for modern multimedia applications.

The rest of the paper is organized as follows. Literature review is presented in Section 2. Section 3 introduces the system model while Section 4 discusses the channel capacity over THz frequencies. Results and simulation will be presented in Section 5.

2. LITERATURE REVIEW

In fact, it is essential to study the capacity of the MIMO channel to be able to push THz technology in terms of data rate. Indeed, the capacity of the MIMO channel was studied for the THz system [11–14]. Authors in [11] have discussed the channel capacity and evaluate performance over a suggested channel model. Moreover, they theatrically evaluated the channel capacity in the electromagnetic (EM)-based wireless underground sensor networks (WUSNs). It has been demonstrated that even for 76 to 80 GHz, THz system provides high channel capacity which allows high data rate over wireless system. In [12], a channel capacity is investigated for a THz system. It has been proved that a data rate about terabit par second can be obtained with a distance of 2 m and transmit power of about 1 watt. In addition, for the non-line-of-sight (NLOS) configuration they obtain a capacity of 100 Gigabit per second (Gbps). In [13], a channel capacity expression for short range communications has been carried out. To enhance channel capacity of THz, they increase the number of antenna and use CSI at both transmitter and receiver. Moreover, the authors have provided the channel capacity of a 4×4 MIMO system with a separated distance of 2 m. In [14], the capacity was analyzed for THz wireless networks. It has been demonstrated that the capacity of a THz system might be 100 Tbit/s and decrease with path loss in some bands. The authors of [15] have proposed PS-4096-QAM in THZ band to increase the channel capacity. Based on this technique, they achieved a data rate about 352-Gbit/s. In [16], the authors have proposed a dense wavelength division multiplexing (DWDM) based radio over fiber optic for THz band. The data rate allowed by this technique is 256 Gbps. In [17], an experimental demonstration was carried out by using 4-PAM signal. The maximum capacity allowed by this technique is 60 Gbps. The authors in [18] proposed radio over fiber (RoF)-based polarization-division multiplexed (PDM) differential quadrature phase-shift keying (DQPSK) DWDM system to improve the capacity for optical network. The maximum capacity allowed by this technique is in the order of 1.792 Tbps. In [19], the authors introduced a novel approach centered on multiband on-off keying (MB-OOK) modulation in combination with a noncoherent receiver for THz system. They discussed in [19] the performance of a differential MB-OOK transceiver in the context of a THz channel model. Remarkably, they achieved a data rate of 54.24 Gbps while maintaining a Bit Error Rate (BER) of 10^{-3} for distances under 35 meters between the transmitter and receiver. Shurakov et al. have proposed in [20] an empirical investigation into the behavior of human body blockage in indoor environments for THz frequencies. In the context of point-to-point transmissions covering distances between 3 and 7 meters, the authors of [20] observed that the mean attenuation fell within the range of 8 to 15 dB. The precise attenuation value within this range depends on factors such as the height of the line-of-sight (LoS) path and the distance between the transmitter and receiver (Tx-to-Rx). For more details about the channel modeling for THz bands one can refer to [21–25].

3. CHANNEL MODEL

In [26], a channel model of THz is given based on the total path loss caused by absorption and spreading loss for short communication system. In the following, we provide a channel model for LoS configuration. The channel transfer function model considering LoS configuration that will be used in simulation is given by

$$H(f,d)=\frac{c}{4\pi f d}\exp\left(-\frac{1}{2}\gamma(f,T_k,p)\,d\right)\exp(-j2\pi f\tau) \quad (1)$$

where d is the distance between the transmitter and receiver, and $\gamma(f,T_k,p)$ is the molecular absorption coefficient.

In the time domain, as a radio signal traverses the communication channel, the channel effectively functions as a linear filter. Consequently, we can define and understand a channel by examining its impulse response. When we take into account the motion of either the transmitter or receiver, we can express the impulse response as $h(d,t,\tau)$.

$$h(d,t,\tau)=\sum_{l=1}^{N}\sum_{k=1}^{R_l}\hat{\mu}_{k,l}(t)\,e^{j\lambda_{k,l}(t)}\delta(\tau-T_l-\Delta\tau_{k,l}(t)) \quad (2)$$

where $h(d,t,\tau)$ represents the time-varying impulse response t of the channel; τ represent the delay; and d represents the distance between the transmitter and receiver. Consequently, N corresponds to the count of distinguishable paths detectable by the receiver. Each of these discernible paths can be represented using an amplitude $\hat{\mu}_{k,l}(t)$ and a phase shift θ_l associated with the delay τ_l. At elevated frequencies, certain frequencies are absorbed by substances like oxygen and water vapor. Oxygen, in particular, absorbs specific lines that occur at higher frequencies. Therefore, to model the transmission channel effectively, it is imperative to incorporate the absorption coefficient. For this purpose, $\hat{\mu}_{k,l}(t)$ can be expressed as follows:

$$\hat{\mu}_{k,l}(t)=\mu_{1,1}^{2}\frac{c}{4\pi f d}\exp\left(-\frac{1}{2}\gamma(f,T_k,p)\,d\right)e^{-\frac{T_l-T_1}{\rho}}e^{-\frac{T_l-T_1}{\gamma}} \quad (3)$$

where ρ is the inter-cluster of the different radius, and γ is the intra-cluster of the different radius.

In a MIMO (Multiple Input, Multiple Output) system featuring a bidirectional impulse response, the impulse response of each individual sub-channel can be formulated using the following relationship:

$$h^{ij}(t,\tau)=\iiint h_k\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) D_{T_x}(\varphi_d)\,D_{R_x}(\varphi_a)\,g(t-\tau)\,d\tau d\varphi_d d\varphi_a \quad (4)$$

where τ denotes the time delay; φ_d represents the departure direction; φ signifies the arrival direction; r_{Tx}^{j} corresponds to the transmitter's location indexed as j, while r_{Rx}^{i} indicates the position of receiver i. Additionally, $D_{T_x}(\varphi_d)$ and $D_{R_x}(\varphi_a)$ respectively symbolize the antenna patterns at the transmitter and receiver. Lastly, $g(\tau)$ represents the pulse response of the transmitting and receiving antennas.

When there is no cross-polarization of the antennas, meaning that only vertical or horizontal polarization is taken into account, the impacts of delay spreading and angular spreading are elucidated by the following equation:

$$h\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right)=\sum_{k=1}^{N}h_k\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) \quad (5)$$

where N represents the count of paths connecting the transmitter and receiver, and h_k denotes the influence of path k. In the case of plane waves, the contribution of each individual path is articulated as:

$$h_k\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) = a_k\delta(\tau-\tau_k)\,\delta(\varphi_d-\varphi_{a_k})\,\delta(\varphi_a-\varphi_{d_k}) \quad (6)$$

where a_k signifies the complex amplitude; τ_k represents the delay spread of path k; φ_{d_k} indicates the departure direction of path k; and φ_{a_k} denotes the arrival direction of path k.

In the typical scenario where both vertical and horizontal polarizations are taken into account, the bidirectional impulse response is expressed as follows:

$$h\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right)=\begin{pmatrix} h_k^{11}\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) & h_k^{12}\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) \\ h_k^{21}\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) & h_k^{22}\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right)\end{pmatrix} \quad (7)$$

In the context of wave planes, the contribution of each individual path $h_k\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right)$ is as follows:

$$h\left(r_{Tx}^{j},r_{Rx}^{i},t,\tau,\varphi_d,\varphi_a\right) = \begin{pmatrix} a_k^{11} & a_k^{12} \\ a_k^{21} & a_k^{22}\end{pmatrix}\delta(\tau-\tau_k)\,\delta(\varphi_d-\varphi_{a_k})\,\delta(\varphi_a-\varphi_{d_k}) \quad (8)$$

In this context, the complex amplitude is represented as a polarimetric matrix, which considers the characteristics of the scatters. Furthermore, Equation (8) illustrates that the bidirectional impulse response exclusively characterizes the propagation channel and is, therefore, entirely unaffected by factors such as antenna type, configuration, system bandwidth, or the shape of the transmitted waveform.

4. MIMO CHANNEL CAPACITY

The performance of MIMOs systems is typically evaluated in terms of communication system capacity. In the following, the information theory is introduced to assess MIMO system capacity.

4.1. Deterministic Capacity

The deterministic capacity is used when the impulse response of the transmission channel is constant. The channel capacity measures the maximum amount of data that can be sent through a transmission channel and received with an undeniable error. Channel capacity can be expressed as:

$$C = \max_{p(s)} \mathcal{M}(s;r) \tag{9}$$

with $\mathcal{M}(s,r)$ being the mutual information which allows measuring the dependence between two random variables. For two discrete random variables s and r, the mutual information is given by:

$$\begin{aligned}\mathcal{M}(s,r) &= \mho(s) + \mho(r) - \mho(s,r) \\ &= \mho(r) - \mho(r|s)\end{aligned} \tag{10}$$

$\mho(.)$ is the entropy of a variable $(.)$ which measures uncertainty on the realization of $(.)$. $\mho(r|s)$ is the conditional entropy.

In the case of a SISO connection with an input signal s, a transmission channel gain h and a Gaussian additive white noise (BBAG) n, the signal at reception can be expressed by:

$$r = hs + n \tag{11}$$

the mutual information is expressed as:

$$\mathcal{M}(s,r) = \mho(r) - \mho(n) \tag{12}$$

The entropy $\mho(X)$ associated with the variable X is expressed as:

$$\mho(X) = \mathbb{E}\left[-\log_2(p(x))\right] \tag{13}$$

$\mathbb{E}(.)$ Esperance

Thus

$$\mathcal{M}(s,r) = \log_2\left(\pi e(|h|^2 P_T + \sigma_n^2\right) - \log_2\left(\pi e \sigma_n^2\right) \tag{14}$$

$$\mathcal{M}(s,r) = \log_2\left(\frac{|h|^2 P_T}{\sigma_n^2} + 1\right) \tag{15}$$

$$P_T = \mathbb{E}\left(|s|^2\right) : \text{ Total power at the trasmetter}$$

$$\sigma_n^2 = \mathbb{E}\left(|b|^2\right) : \text{ Total power at the receiver}$$

The capacity of a deterministic channel is expressed by Shannon's formula and is given by the following equation.

$$\mathcal{C}_{\text{SISO}} = \log_2\left(\frac{|h|^2 P_T}{\sigma_n^2} + 1\right) \frac{\frac{bits}{s}}{\text{Hz}} \tag{16}$$

For the MIMO system the channel capacity is expressed as follows:

$$\mathcal{C}_{\text{MIMO}} = \max_{p(s):\mathbb{E}(s^H s)\leq P_T} \mathcal{M}(s;(r|H)) \frac{\frac{bits}{s}}{\text{Hz}} \tag{17}$$

where

$$\mathcal{M}(s,r) = \log_2(\det(\pi e R_r)) - \log_2(\det(\pi e R_n)) \tag{18}$$

which is equivalent to

$$\mathcal{M}(s,r) = \log_2\left(\det\left(I_{N_R} + HR_s H^H (R_n)^{-1}\right)\right) \tag{19}$$

4.2. CSI Unknown to Both Tx and Rx

If the transmitter and receiver do not have any information about the behavior of the channel, it will be assumed that it will allocate with equality the total power p on all the transmitting and receiving antennas. Thus, assuming that the emitted signals are uncoupled, it follows that the covariance matrix of the transmitted signal fulfills the condition given by the following equation.

$$R_s = \frac{P_T}{N_T} I_{N_T} \tag{20}$$

$$\begin{aligned}\mathcal{M}(s,r) &= \log_2\left(\det\left(I_{N_R} + \frac{SNR}{N_T} HH^H\right)\right); SNR \\ &= \frac{P_T}{\sigma_n^2} \frac{\frac{bits}{s}}{\text{Hz}}\end{aligned} \tag{21}$$

where SNR is the signal to noise ration; N_T is the number of transmitting and receiving antennas; I_{N_R} is the identity matrix $N_R \times N_R$; H represents the normalized matrix of the channel. $(.)^H$ denotes the transpose conjugate of the matrix.

Considering 2×2 MIMO, one can decompose H in the form $H = g * F$

$$\begin{aligned}H &= \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \\ &= \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix} * \begin{pmatrix} 1 & \frac{h_{12}}{h_{22}} \\ \frac{h_{21}}{h_{11}} & 1 \end{pmatrix}\end{aligned} \tag{22}$$

The elements of the matrix can be inferred from the following expressions:

$$h_{11} = g_{11} + g_{12}\frac{h_{21}}{h_{11}} \tag{23}$$

$$h_{12} = g_{11}\frac{h_{12}}{h_{22}} + g_{12} \tag{24}$$

$$h_{21} = g_{22}\frac{h_{21}}{h_{11}} + g_{21} \tag{25}$$

$$h_{22} = g_{21}\frac{h_{12}}{h_{22}} + g_{22} \tag{26}$$

Thus,

$$g_{11} = h_{11}h_{22}\left(\frac{h_{11} - h_{22}}{h_{11}h_{22} - h_{12}h_{21}}\right) + h_{22} \tag{27}$$

$$g_{12} = h_{11}h_{12}\left(\frac{-h_{11}+h_{22}}{h_{11}h_{22}-h_{12}h_{21}}\right) \tag{28}$$

$$g_{21} = \frac{h_{11}h_{22}h_{21}-h_{22}h_{21}h_{11}}{h_{21}h_{12}-h_{11}h_{22}} \tag{29}$$

$$g_{22} = h_{22}-\frac{h_{12}h_{11}h_{21}-h_{12}h_{21}h_{11}}{h_{21}h_{12}-h_{11}h_{22}} \tag{30}$$

This decomposition can be generalized for the case of an $h_{N_R N_T}$ MIMO system where the channel matrix is expressed by:

$$H = \begin{pmatrix} h_{11} & \cdots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R1} & \cdots & h_{N_RN_T} \end{pmatrix} \tag{31}$$

This matrix can be decomposed into:

$$H = \begin{pmatrix} g_{11} & \cdots & g_{1N_T} \\ \vdots & \ddots & \vdots \\ g_{N_R1} & \cdots & g_{N_RN_T} \end{pmatrix} * \begin{pmatrix} 1 & \cdots & \frac{h_{1N_T}}{h_{N_RN_T}} \\ \vdots & \ddots & \vdots \\ \frac{h_{N_R1}}{h_{11}} & \cdots & 1 \end{pmatrix} \tag{32}$$

The important thing in this decomposition is that the elements of the G Matrix can be measured, so we can get information about the state of the channel. To do this, it is necessary to study the behavior of this matrix in terms of correlation and channel capacity and then compare it with that of the original Matrix [H]. Using Equation (18) and introducing the decomposition of [H] given by Equation (32), the channel capacity can be written as:

$$M(s,r)=\log_2\left(\det\left(I_{N_R}+\frac{SNR}{N_T}\begin{pmatrix} g_{11} & \cdots & g_{1N_T} \\ \vdots & \ddots & \vdots \\ g_{N_R1} & \cdots & g_{N_RN_T} \end{pmatrix} * \begin{pmatrix} 1 & \cdots & \frac{h_{1N_T}}{h_{N_RN_T}} \\ \vdots & \ddots & \vdots \\ \frac{h_{N_R1}}{h_{11}} & \cdots & 1 \end{pmatrix} * \begin{pmatrix} g_{11} & \cdots & g_{1N_T} \\ \vdots & \ddots & \vdots \\ g_{N_R1} & \cdots & g_{N_RN_T} \end{pmatrix}^H * \begin{pmatrix} 1 & \cdots & \frac{h_{1N_T}}{h_{N_RN_T}} \\ \vdots & \ddots & \vdots \\ \frac{h_{N_R1}}{h_{11}} & \cdots & 1 \end{pmatrix}^H\right)\right) \tag{33}$$

In this equation, it is difficult to measure the Matrix $\begin{pmatrix} g_{11} & \cdots & g_{1N_T} \\ \vdots & \ddots & \vdots \\ g_{N_R1} & \cdots & g_{N_RN_T} \end{pmatrix}$. However, $\begin{pmatrix} 1 & \cdots & \frac{h_{1N_T}}{h_{N_RN_T}} \\ \vdots & \ddots & \vdots \\ \frac{h_{N_R1}}{h_{11}} & \cdots & 1 \end{pmatrix}$ can be easily measurable, without computational complexity, in the receiver. If it is demonstrated that the channel capacity is based on [H], the total channel capacity can be estimated from the capacity measurement based only on [G], then the measurement of [G] will be useful in determining the state of the channel. This information could then be used to adopt the optimal strategy of the Transceiver System, in an adaptive context. On the other hand, knowledge of the Matrix [G] will reduce the complexity of the task of the receiver. It is well known that the capacity of the MIMO channel is limited by several factors. The most important of these factors is the correlation between the sub-channels of the channel Matrix.

For a completely uncorrelated channel Matrix, the capacity of the MIMO system reaches its maximum and growths linearly with respect to the number of antennas. This capacity decreases due to the existence of correlation between the elements of the channel Matrix. For a random channel, the capacity is also random (statistical).

The average ergodic capacity is calculated by the formula:

$$\mathcal{M}(s,r)=\left\langle \log_2\left(\det\left(\delta_{kl}+\frac{SNR}{N_T}R_{kl}\right)\right)\right\rangle \tag{34}$$

where R_{kl} represents the elements of the instantaneous channel correlation matrix, and δ_{kl} represents the delta function.

4.3. CSI Identified to Rx But Unidentified to Tx

If the CSI is known at the receiver, the singular value decomposition method (SVD) can be exploited. In this case, the capacity of the MIMO system can be easily evaluated. According to the method of decomposition into singular values of the MIMO channel Matrix H, we have:

$$H = USV^H \tag{35}$$

where $(.)^H$ refers to the complex conjugate transpose; V and U are unitary matrices having dimensions $(N_R \times N_R)$ and $(N_T \times N_T)$, respectively; and S is a matrix containing the singular values of H of dimensions $(N_T \times N_R)$. Thus C_{SVD} can be given by:

$$\begin{aligned} C_{SVD} &= \log_2\left(\det\left(I_{N_R}+\frac{SNR}{N_T}SS^H\right)\right) \\ &= \sum_{k=1}^{N}\log_2\left(1+\frac{SNR}{N_T}\lambda_{H,k}^2\right) \end{aligned} \tag{36}$$

$\lambda_{H,k}$ denote the singular values MIMO channel.

4.4. CSI Known to Both Transmitter and Receiver

When the channel variation is leisurely in time, the receiver provides CSI for the transmitter. In this case, an optimal allocation of power can be exploited using the water-filling (WF) method. The idea behind the water-filling technique is to assign more power to sub-channels with the highest signal-to-noise ratio, and this is in order to maximize the transmission rate of each sub-channel. The water-filling concept maximizes MIMO channel capacity under strain of the total power available at the broadcast.

Supposing that the channel behavior is known to the Tx by the use of a back-forward sub-channel, the MIMO system capacity given by Formula (36) can be further increased by making the allocation of power at the level of the transmitter according to the principle "water filling" [27]. In fact, the principle of water filling presents itself as a problem of maximizing the utility function (36) under the constraint [27]:

$$\sum_{k=1}^{N_T} P_k = P_T \tag{37}$$

where P_k is the power allocated to the K^{ith} transmitting antenna. It is known that the normalized capacity per bandwidth unit of our system is given by:

$$_{WF}=\sum_{k=1}^{N_T} \log_2\left(1+\frac{P_k}{\sigma_n^2}\lambda_k\right)\frac{\frac{\text{bits}}{\text{s}}}{\text{Hz}} \tag{38}$$

where λ_k is the kth singular value of the MIMO channel Matrix, and σ_n^2 is the variance of the noise signal.

Following the Lagrange multiplier theorem, we will introduce the function [28]:

$$Z=\sum_{k=1}^{N_T} \log_2\left(1+\frac{P_k}{\sigma_n^2}\lambda_k\right)+Q\left(P_T-\sum_{k=1}^{N_T} P_k\right) \tag{39}$$

where Q is the Lagrange operator.

According to the water-filling technique, the powers allocated to the transmitting antennas P_k, $k=1,\dots,N_k$, are obtained by solving the following equation

$$\frac{dZ}{dP_k}=0 \tag{40}$$

Also, we obtain:

$$P_k=Q\ln 2-\frac{\sigma_n^2}{\lambda_k} \tag{41}$$

µ satisfies the constraint of total power in (29).

To get a rigorous and logical result from a practical point of view and given that an allocated power can never be negative, we have:

$$P_k=\left(Q\ln 2-\frac{\sigma_n^2}{\lambda_k}\right)^+ \tag{42}$$

The power received at the sub-channel of index k is thus expressed

$$P_{r_k}=\left(\lambda_k Q\ln 2-\sigma_n^2\right)^+ \tag{43}$$

Thus, the channel capacity is given by:

$$C_{WF}=\sum_{k=1}^{N_T} \log_2\left(1+\frac{P_{r_k}}{\sigma_n^2}\right)\frac{\frac{\text{bits}}{\text{s}}}{\text{Hz}} \tag{44}$$

Finally, the channel capacity with WF is given by:

$$C_{WF}=\sum_{k=1}^{N_T} \log_2\left(\frac{Q\ln 2}{\sigma_n^2}\lambda_k\right) \tag{45}$$

Previous studies have emphasized the importance of a thorough environment description in Single Input Single Output (SISO) simulations. In the realm of Multiple Input Multiple Output (MIMO), investigated impact of channel modeling on MIMO channel capacity must be considered. Previous findings underscored the significance of avoiding overly simplistic channel models, as these can lead to inaccurate assessments of channel capacity. Here, our objective is to extend the exploration of geometric and atmospheric modeling effects on a broader scale by considering the entire environment. Analyzing the characteristic parameters of the MIMO channel will provide insights into the precision required for describing the environment accurately. Thus, we aim to determine whether characteristic parameters of the MIMO channel exhibit sensitivity to environmental modeling approximations. In this context, obtaining sufficiently representative results is crucial for identifying the pertinent insights needed for such a study. Implementing appropriate transmission scenarios becomes essential to ensure the reliability of our findings.

5. SIMULATION RESULTS

To analyze the performance of MIMO channel capacity in THz band, we will first present the transfer function of the MIMO channel to be able to put it in the expression of the capacity of the MIMO channel. Simulating and plotting the channel transfer function for Terahertz (THz) communication typically involves using specialized software tools and considering the characteristics of THz channels. In this work, MATLAB Software is used to plot the channel transfer function and channel capacity. To perform the simulation, we first choose an appropriate channel model for THz communication. The channel model used in this work is presented in Equation (1). This channel model includes THz-specific propagation effects, such as atmospheric absorption and scattering. We then, define the THz frequency range and bandwidth for the simulation. THz frequencies used in this work span from 0.1 THz to 1.2 THz. The proposed channel model is used to simulate the channel capacity of THz system. Figure 1 shows the MIMO channel transfer function as a function of frequency. From this figure it is found that the THz channel is a frequency selective channel and has very selective frequency bands. The frequency selectivity of the THz channel causes interferences between symbols, which negatively affects the performance of the MIMO system.

On the other hand, Figure 2 presents the total loss as a function of frequency. It is clear that from Figure 2, there are some

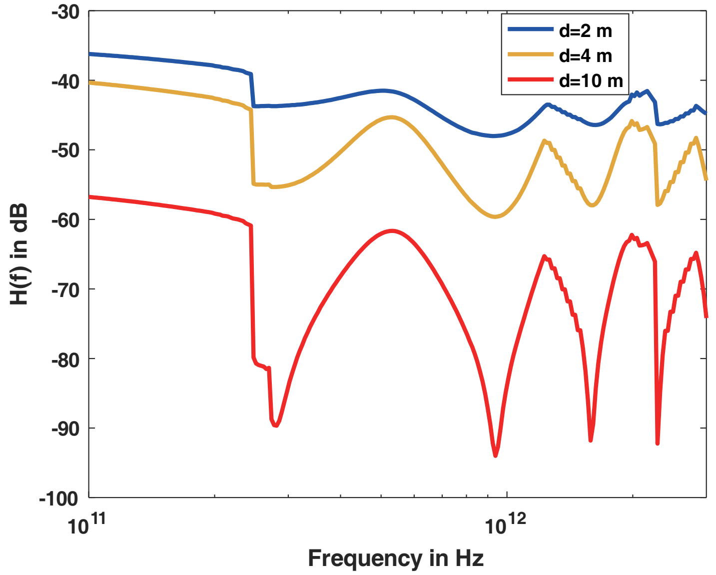

FIGURE 1. Channel transfer function for different values of d.

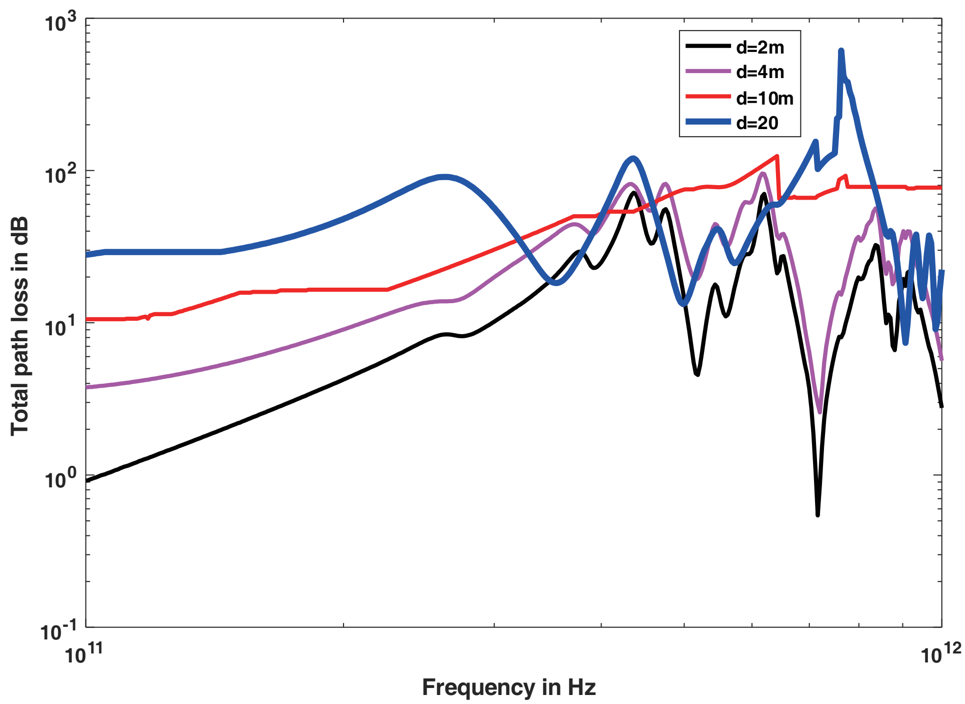

FIGURE 2. Total path loss versus frequency.

frequency bands where we cannot transmit data properly because of the loss produced by the channel. Therefore, it is necessary to take into account these frequencies for the realization of the system including modulation techniques. Some frequency bands have high path loss which create transmission windows on which the transmission signal cannot be transmitted effectively. It means that we should take into account these transmission windows when designing the THZ system.

In the following, we consider a correlated MIMO channel of dimension ($N_T \times N_R$). The channel Matrix is generated according to Kronecker's model. It is proposed to simulate the capacity of the MIMO system in the following cases:

1. CSI known to the transmitter and receiver
2. CSI identified to receiver but unidentified to transmitter
3. CSI unknown to the transmitter and receiver

The decomposition and correlation procedure will be studied for several MIMO systems of dimension $N_T \times N_R =$

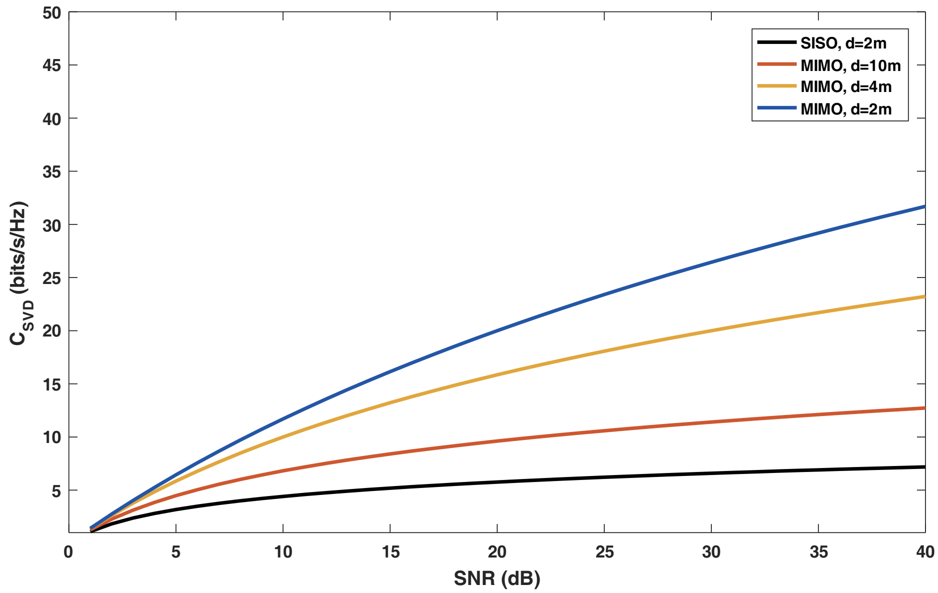

FIGURE 3. Proposed channel capacity of MIMO system compared to SISO system.

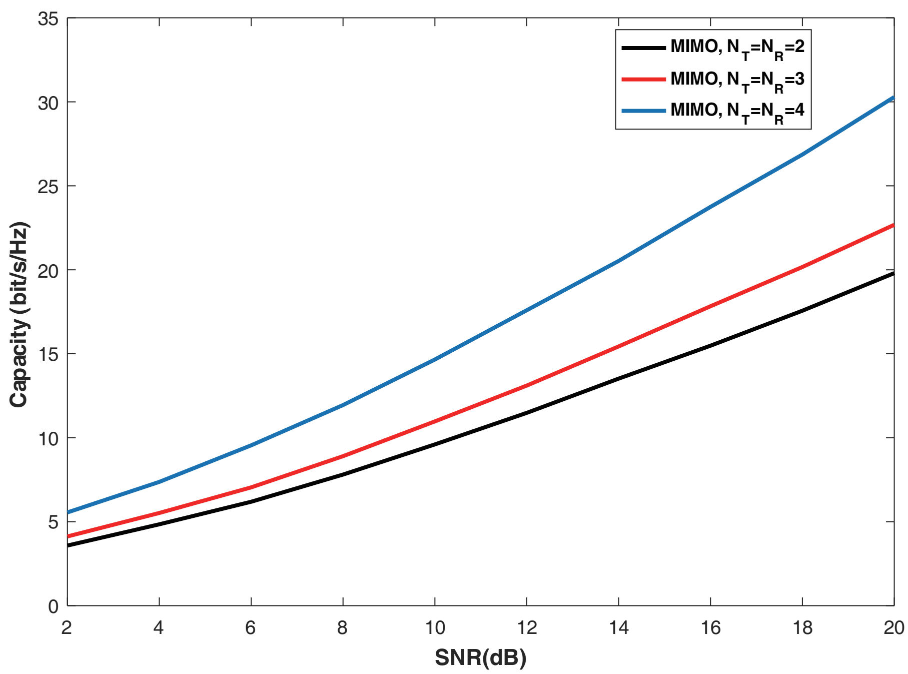

FIGURE 4. Proposed MIMO channel capacity versus SNR for defferent number of antennas.

$2 \times 2 \ldots 8 \times 8$ of correlation used is the uniform model. To support the theoretical foundations presented in Section 2, we choose to present some simulations on the MATLAB computing software. The performance evaluation of the MIMO channel capacity according to the three scenarios described above is obtained based on the SNR whose variation is presented in Figure 3, Figure 4, and Figure 5. It can be seen from these figures that the channel capacity increases with SNR in the three scenarios. From Figure 3, on one hand, it is noted that the greater the distance is between the transmitter and receiver, the more the capacity of the MIMO system decreases, i.e., the more the transmitter moves away from the receiver, the more the capacity of the MIMO system decreases. Indeed, as distance between transmitter and receiver increases, the channel becomes more attenuat because attenuation is proportional to the distance between the receiver and transmitter. On the other hand, MIMO system outperforms SISO system for a given SNR. By exploiting spatial diversity, the performance of MIMO system is better than that for SISO system.

In addition, it can be observed from Figure 4 that the number of antennas plays an important role on the behavior of MIMO

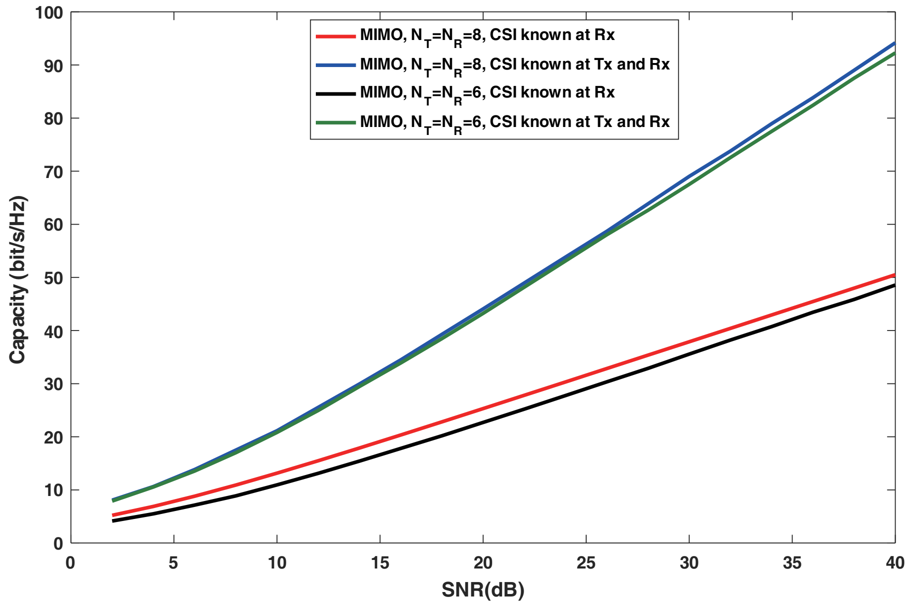

FIGURE 5. Proposed Channel capacity versus SNR of MIMO system according to case 1&2.

channel capacity. The larger the Matrix dimensions of the channel is, the greater the capacity increases. In fact, the channel capacity is propositional to the number of antennas in a MIMO system, because the greater the number of antennas we have, the more data we can transmit.

Similarly in Figure 5, we present the capacity of the MIMO channel for two cases cited above (case 1&2). It is found that the channel capacity provided in the CSI known to the transmitter and receiver is much greater than that one provided when CSI is known to Rx but unknown to Tx case. It can be concluded that when CSI is known at both sides of the transmission link, MIMO performance is better at the cost of complexity. So, It is confirmed that MIMO channel capacity suffers from degradation when the CSI is not known at both sides of the transmission link.

6. CONCLUSION

In this work, expressions for channel capacity for THz MIMO channel capacity based on decomposition of channel matrix and correlation are given. We perform some simulations for channel parameters such as channel transfer function and total path loss, as well as for channel capacity. These simulations considered for channel capacity are carried out for the 3 cases mentioned above by varying the number of antennas and distance between receiver and transmitter. To do that, we established an appropriate channel model for the terahertz (THz) wireless communication system. Simulation results have demonstrated that the more the transmitter moves away from the receiver, the more the capacity of the MIMO system decreases. Furthermore, it is noted that MIMO channel capacity suffers from degradation when the CSI is not known at both sides of the transmission link. In addition, as the number of antennas increases, the channel capacity increases. In perspective, it would be possible to expand the analysis of $16T_xX16R_x$ configuration. It would be possible to include measurements in the process of calculation of channel capacity, by including other types of environments or by adopting different configurations. Furthermore, a massive MIMO measurement campaign, implementing the Scan 64 network as a base station and the virtual UPA antenna array on the mobile side, could prove relevant.

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