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MIMO-Terahertz in 6G Nano-Communications: Channel Modeling and Analysis

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Abstract: With the development of wireless mobile communication technology, the demand for wireless communication rate and frequency increases year by year. Existing wireless mobile communication frequency tends to be saturated, which demands for new solutions. Terahertz (THz) communication has great potential for the future mobile communications (Beyond 5G), and is also an important technique for the high data rate transmission in spatial information network. THz communication has great application prospects in military-civilian integration and coordinated development. In China, important breakthroughs have been achieved for the key techniques of THz high data rate communications, which is practically keeping up with the most advanced technological level in the world. Therefore, further intensifying efforts on the development of THz communication have the strategic importance for China in leading the development of future wireless communication techniques and the standardization process of Beyond 5G. This paper analyzes the performance of the MIMO channel in the Terahertz (THz) band and a discrete mathematical method is used to propose a novel channel model. Then, a channel capacity model is proposed by the combination of path loss and molecular absorption in the THz band based on the CSI at the receiver. Simulation results show that the integration of MIMO in the THz band gives better data rate and channel capacity as compared with a single channel.

Keywords: Wireless communication; 6G mobile communication; terahertz communication; MIMO; channel modeling

ntroduction

Motivation

In the past 30 years, the average wireless transmission rate has doubled every 18 months, and the speed demand has driven the rapid development of wireless communications. The highest frequency band allocated by China Mobile for the 4G Time Division Long Term Evolution (TD-LTE) network is 2.6 GHz [1]. Although the fifth-generation (5G) mobile communications standard has not yet been completed, the 33-46 GHz band frequency range of the time-sharing duplex (TDD) network is under consideration. Currently, 28 GHz frequency is mainly used for the 5G communication test. It can be seen that the increasing carrier frequency and decreasing wavelength are the development trend of wireless communication. Terahertz (THz) communication with higher frequency and shorter wavelength are expected to become the dominant direction of mobile communication in the future [2].

THz communication came into being based on traditional radio communication. The frequency of the THz wave is 0.1~10 THz, the wavelength is 3 mm~30 μm, and the band is between microwave and far-infrared light. The long band of the THz wave partially overlaps the band of the millimeter-wave (wavelength is 10~1 mm), and the short band of the THz wave partially overlaps with the infrared light (wavelength is 1~760 nm) transition zone [3]. Compared with microwaves, the THz wave frequency is higher, which can achieve high-speed wireless transmission that microwaves cannot meet, the beam is narrower, the directionality is better, and the positioning is more accurate. Compared with infrared light, THz wave can penetrate sand and dust smoke and can work normally in windy or dusty weather. The photon energy of the THz wave is about one-fortieth of the visible light, and the THz wave is used as information carrier energy efficiency is high. THz communication has unique properties, such as opaque atmosphere, high rate, large capacity, good directivity, small scattering, good security and high confidentiality. Terahertz waves are in the field of transition from electronics to photonics, which combines the advantages of microwave communication and optical communication. As an extension of the microwave, terahertz wave provides much wider communication bandwidth than the microwave and has larger transmission capacity and faster speed. This is the biggest advantage of terahertz communication. In 2013, the speed of terahertz high-speed wireless communication has exceeded 100 Gbps. Besides, due to the narrow beam, the THz wave has better directivity which can achieve better confidentiality and anti-interference and anti-interception capabilities. Compared with optical communication, the transmission of terahertz waves is less affected by harsh environments such as smoke and sand. Besides, the wavelength of the THz wave is short, so the antenna can be made very small and the device can be made into a nanometer level to realize communication between nanometer devices.

At present, the research and application in the field of THz communication gets attention worldwide. Many countries have proposed THz communication research programs. At present, some foreign research groups have done a lot of research and experiments on THz communication and reported some THz communication laboratory demonstration systems and have obtained some experience. The main THz communication research programs are NASA and the US Air Force Scientific Research Institute. The office of research laboratory (AFOSR) and the Sensor Research Division of the US air force research laboratory (AFRL) are research projects for compact and innovative SiGe-based THz sources and detectors for air force imaging, communications and early warning. Another US air force applied research program is safe short-range atmospheric communications. Besides, the research plan includes the wireless area networking of terahertz emitters and detectors (WANTED) project funded by the EU fifth framework program and NanoTera engineering (ballistic nano-devices for THz data processing).

The novel electromagnetic properties exhibited by metamaterials are mainly derived from its sub-wavelength structure rather than the intrinsic properties of the material. One can adjust the intensity of its response to electromagnetic waves by changing the shape, size and arrangement of its microstructure spectrum range. It is precise because of the unique properties of metamaterials that it provides new ideas and means for the development and application of THz technology. Since THz technology has great potential application prospects in recent years, people have made a lot of efforts to fill this “THz gap” and achieved some important results such as the generation and detection of THz radiation, THz quantum cascade lasers and so on. However, compared with the rapid development of THz radiation generation and detection technology, there is lack of considering the control of THz wave technology. The development of THz devices has been slow such as THz filtering, phase control, switching and modulation. As we all know, many materials in nature have no electromagnetic response in the THz band. For a long time, people have not been able to find a suitable material to manufacture corresponding devices to efficiently control the transmission of THz waves. The realization and rapid development of metamaterials have brought new opportunities for the development and application of THz technology.

Literature Review

With the development of nanotechnology, applications based on wireless nano-networks are possible [4]. The sensor nodes and wireless gateways in the wireless nano-network are composed of nanomaterials and the size is only micron level with simple processing functions which can perform simple tasks such as environmental sensing, numerical calculation, data storage etc. [5]. Due to the advantages of small size, sensor nodes can be used in many special scenarios to complete more elaborate monitoring work and achieve a wider range of sensor network deployments [6]. At the same time, the terahertz frequency band has also been proved to be the best frequency band for communication between nano-nodes [7–10]. The application of terahertz communication technology to wireless nano-networks will give creative ideas for biological applications, real-time control of industrial processes and military fields brand new solution [11]. Although nano-devices have made great progress in design and manufacturing, their ability to perform tasks independently is still limited. To expand the capabilities of a single nano-device, it is necessary to collaborate and share information with other nano-devices. However, how to make these devices communicate reliably is one of the biggest challenges now facing [12]. In wireless nano-networks, the communication methods between nano-devices are mainly molecular communication and nano-electromagnetic wave communication. The main idea of molecular communication is to encode the transmitted information into a special molecule and then send the information to the designated node through spontaneous diffusion or active transmission. Nano-electromagnetic wave communication relies on traditional electromagnetic wave communication for information transmission.

Nano-technology was first proposed by Nobel prize-winning physicist Richard Feynman in his speech entitled “There is enough space at the bottom”. The application of nanotechnology in the field of wireless communication has prompted the generation of wireless nano-nodes [13]. Nano-nodes are miniature sensors that combine the advantages of new nano-materials. It cannot only perform simple tasks such as sensing, computing, data storage and driving but also identify and detect nanoscale data such as compound identification of 10 parts per billion, detection of harmful viruses or bacteria, etc. As the functions of these devices become more and more diversified, it is necessary to control and coordinate their multiple functions which brings several challenges for nano-scale communication research.

Nano-communication refers to the information transmission technology between nano-nodes. This method of coordinating and sharing information expands the processing capacity of a single nano-node [14]. At present, there are still many restrictions on the communication between nano-nodes such as the size of nano-nodes, design complexity, energy consumption [15] and other issues that will limit its direct application at the nano-scale. Using new nanomaterials as a new generation of nano-electronic components will overcome the main shortcomings of existing technologies [16]. These new materials include graphene and its derivatives namely carbon nanotubes (CNT) which are a new type of single-layer sheet-like structure composed of carbon atoms and are considered to be the most representative of wireless nano-network materials candidate material [17].

The properties of the nanomaterial itself determine its bandwidth, delay and power in communications and recent research on graphene and its derivatives shows that the terahertz frequency band (0.1 THz~10.0 THz) is the most suitable for the nanometer’s frequency band of node communication. Besides, the authors in [18] proposed that a 1 µm long graphene nano-antenna has good performance in the THz frequency band. The characteristics of the transmission information and the terahertz frequency band is consistent with the predicted operating frequency of graphene [19].

Contributions

Because the wavelength of the terahertz band is very short [20] when the nano-nodes communicate in the terahertz band, a large number of unconnected antennas can be deployed in a limited space to form a large antenna array which provides convenience for the realization of MIMO [21,22]. At present, most researches on terahertz channels are about energy acquisition and information capacity analysis [23–25], while there are few studies on multiple inputs and multiple-output (MIMO) in the terahertz band. Because of this, this paper proposes a MIMO model suitable for the terahertz frequency band and analyzes the channel model with traversal capacity as a metric [26,27].

Paper Organization

The rest of the paper is outlined as follows. In Section 2, the channel model of MIMO in the THz band is described. In Section 3, the MIMO-THz channel capacity is analytically derived and discussed. In Section 4, the numerical results are analyzed and evaluated while Section 5 concludes the paper.

Channel Model

The bandwidth of the terahertz band is very large which support the terabit transmission rate per second and the terahertz band itself has frequency selectivity [28]. In nano-communications, due to the limitations of the energy of nano-devices and other factors, the distance between the sending end and the receiving end is relatively close, but the antenna spacing is much smaller than the distance between the sending end and the receiving end. In the short-distance transmission, the anti-interference of the terahertz band is very good. Because of the above characteristics, its MIMO channel is modeled as follows. The simplified MIMO channel model in the terahertz channel is shown in Fig. 1.

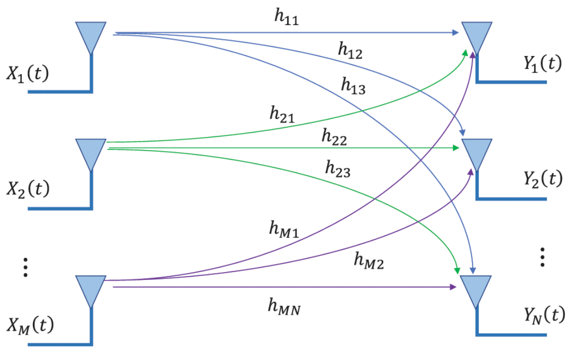

Figure 1: Simplified MIMO channel in terahertz communication

As shown in Fig. 1, it is assumed that there are M antennas at the transmitting end and N antennas at the receiving end. The signals transmitted on the antenna array can be expressed as

$$x(t) = [x_1(t)x_2(t)\ldots x_M(t)]^{\mathrm{T}} \tag{1}$$

among them, the symbol $[\cdot]^{\mathrm{T}}$ represents the transpose of the matrix and $x_j(t)$ is the signal of the j th antenna port at the transmitting end.

Similarly, the signals on the antenna array at the receiving end are

$$y(t) = [y_1(t)y_2(t)\ldots y_N(t)]^{\mathrm{T}} \tag{2}$$

Among them, $y_i(t)$ is the signal of the i th antenna port at the receiving end. In signal transmission, there is the influence of noise factors which can be expressed as

$$w(t) = [w_1(t)w_2(t)\ldots w_N(t)]^{\mathrm{T}} \tag{3}$$

Among them, $w_k(t)$ is the noise signal on the k-the channel. Besides, the channel gain moment A_n on the nth path is [29,30]

$$A_n = \begin{bmatrix} a_{11}[n] & a_{12}[n] & \ldots & a_{1M}[n] \\ a_{21}[n] & a_{22}[n] & \ldots & a_{2M}[n] \\ \vdots & \vdots & \cdots & \vdots \\ a_{N1}[n] & a_{N2}[n] & \cdots & a_{NM}[n] \end{bmatrix} \tag{4}$$

Among them, $a_{ij}[n]$ represents the channel coefficient of the j th antenna at the sending end and the i th antenna at the receiving end on the n th path, which can be calculated by the following expression

$$a_{ij} = \sqrt{P_j} B v_{ij} \tag{5}$$

Among them, Pj is the average power of the signal on the transmitter $x_j(t)$; B is a composite matrix of $i \times j$; v_{ij} is the weight of the channel from the j th antenna at the sending end to the i th antenna at the receiving end. It is a complex Gaussian random variable, where $E\left\{\left|v_{ij}\right|^2\right\} = 1$, and the mean value is 0. We set the total number of MIMO channel paths in terahertz communication to L and the delay to σ. In summary, the signal relationship between the discretized receiver and transmitter can be expressed as

$$y(t) = \sum_{n=1}^{L} A_n x(t - \sigma) + w(t) \tag{6}$$

Channel Capacity Analysis

To quantify the potential of the MIMO channel model in the terahertz band in nano-communications, the channel capacity is used as a performance metric. In the analysis, the terahertz frequency band is regarded as a single transmission window with a width of 10 THz. Through the terahertz channel access control transmission protocol [31], channel state information (CSI) can be obtained at the receiving end, but it cannot be assumed that the transmitter end also knows the channel information. Therefore, this paper mainly studies the traversal capacity using channel state information at the receiving end.

As mentioned in the previous section, the terahertz frequency band is highly frequency-selective, and at the same time, its molecular absorption noise is non-white [21]. Therefore, when calculating the capacity of MIMO channels in THz communication, the total capacity is obtained by dividing the total bandwidth into multiple narrow sub-bands and calculating their capacities [28]. The frequency band is divided into n sub-channels, and the bandwidth of each sub-channel is Δf. The traversal capacity of the channel is expressed as

$$C = \Delta f \sum^{n} \ln\left(I_n + \frac{\xi}{M} A_n A_n^{\mathrm{T}}\right) \tag{7}$$

When the sub-band width is small enough, each sub-channel can be regarded as a non-selective flat channel, and the power spectral density of the noise can be considered locally flat at this time, then Eq. (7) can be used to calculate the channel capacity. Where ξ is the signal-to-noise ratio (SNR) of the channel, and its value can be expressed as

$$\xi = \frac{S}{WP} \tag{8}$$

where S is the power spectral density at the transmitting end; W is the noise power spectral density; P represents the channel transmission path loss. In the terahertz frequency band, the total path loss and noise influence are mainly determined by the frequency, the transmission distance and the composition of the molecular medium. The noise mainly includes electronic noise of the system, antenna noise, molecular absorption noise and other additional noise. Since the influence of electronic and antenna noise in the present environment is very low [32–35], the main focus is on molecular absorption noise. It can be seen from [27] that the noise power spectral density W can be expressed as

$$W = kB \int T_0 \left(1 - e^{-k(f)d}\right) df \tag{9}$$

Among them, T_0 is the reference temperature; d is the transmission distance; $k(f)$ is the medium absorption coefficient; k is the Boltzmann constant. The path loss is mainly composed of transmission loss P_{spread} and molecular absorption attenuation P_{abs}, and its value P can be obtained by the following expression [26]:

$$P = P_{\text{spread}} + P_{\text{abs}}$$

$$= 20 \log\left(\frac{4\pi fd}{c}\right) + k(f)d\ 10 \log e \tag{10}$$

where c is the speed of light in free space.

imulation Results and Analysis

In this section, the proposed channel model of the MIMO in terahertz communication is simulated and analyzed (Tab. 1 summarizes the simulation parameters). The traversal capacity C in Eq. (7) is used as a metric which is mainly affected by the signal-to-noise ratio ξ in Eq. (8). The signal-to-noise ratio is mainly determined by the molecular absorption noise power spectral density W in Eq. (9), the path loss power spectral density P and the input power spectral density S in Eq. (10). At the same time, to make the simulation as close to reality as possible, the total energy of the signal is set to 500 pJ. This is mainly because, in nano-communication, the nano-nodes mainly obtain energy through the tablet-type nano-generator and store it into the battery and due to the size and mechanism of the nano-node, its energy is about 500 pJ [24].

Table 1: Simulation parameters

Parameter	Value
Total energy of signal	500 pJ
Number of BS antennas M	8
Number of receiver antennas N	7
Frequency	2.2 THz
SNR ξ	20 dB

When CSI is unknown at the transmitting end, the cumulative distribution function (CDF) of MIMO channel traversal capacity in terahertz communication is shown in Fig. 2, where M is the number of transmitting antennas and N is the number of receiving antennas. The Figure shows the channel CDF when the number of transmitting and receiving antennas is 4-4, 5-5, 6-4, 4-7, and 8-3 respectively. It can be seen from Fig. 2 that the capacity of the MIMO system in terahertz communication has been significantly improved with the increase of the number of antennas at the transmitting end and the receiving end.

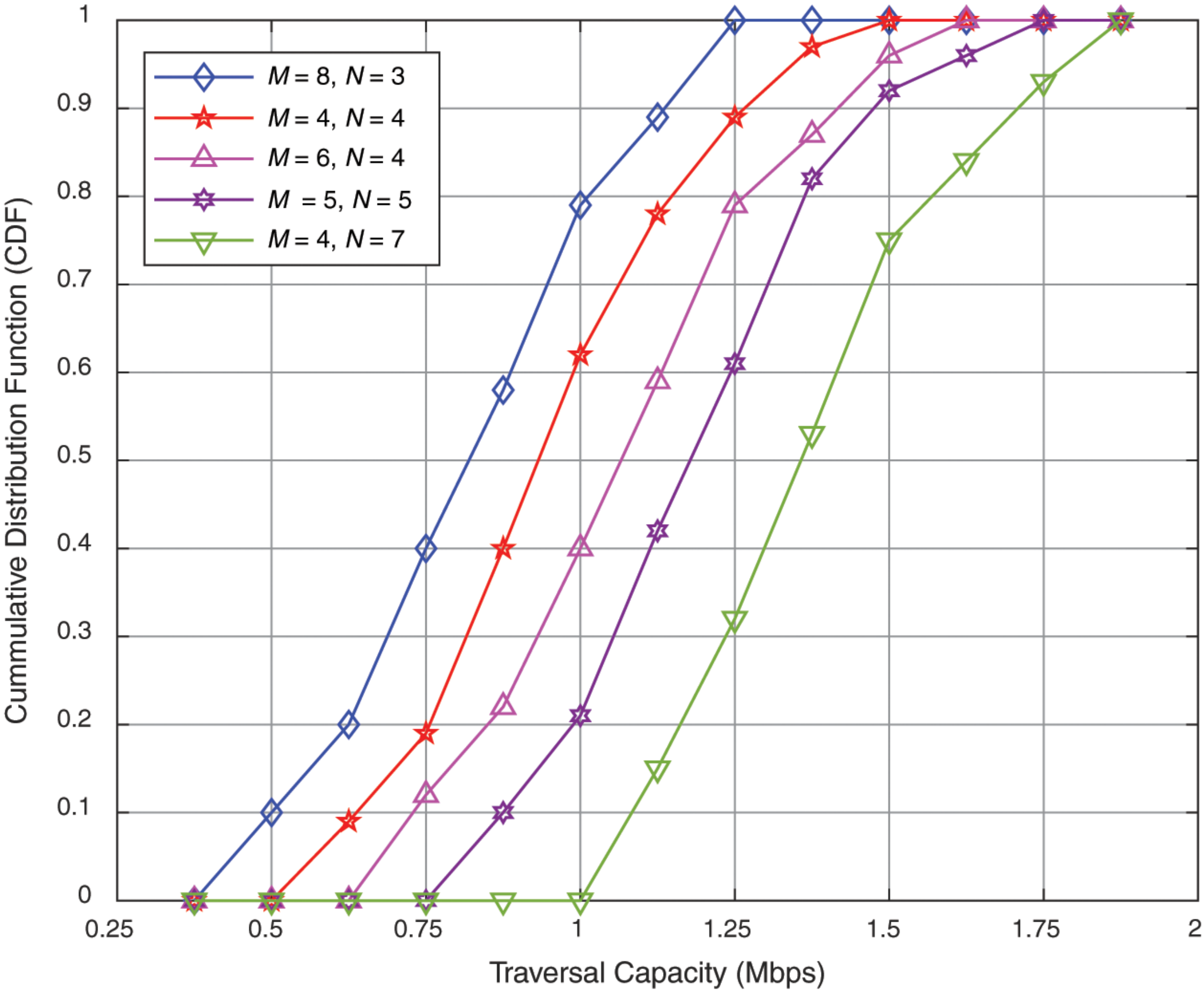

Figure 2: Cumulative distribution of MIMO channel capacity in terahertz communication

In Fig. 3, five sets of data for the transmitter and receiver antennas are set to 4-4, 2-2, 1-1, 2-3, and 3-6 respectively under different signal-to-noise ratio (SNR) and the variation of MIMO capacity is evaluated. With the increase of the signal-to-noise ratio, the channel capacity generally shows an upward trend. For the same signal-to-noise ratio, the MIMO convenience capacity of different antenna configurations also varies in magnitude. Compared with a single channel, the MIMO channel capacity has almost doubled, showing that different antenna configurations have a great impact on the capacity of the channel.

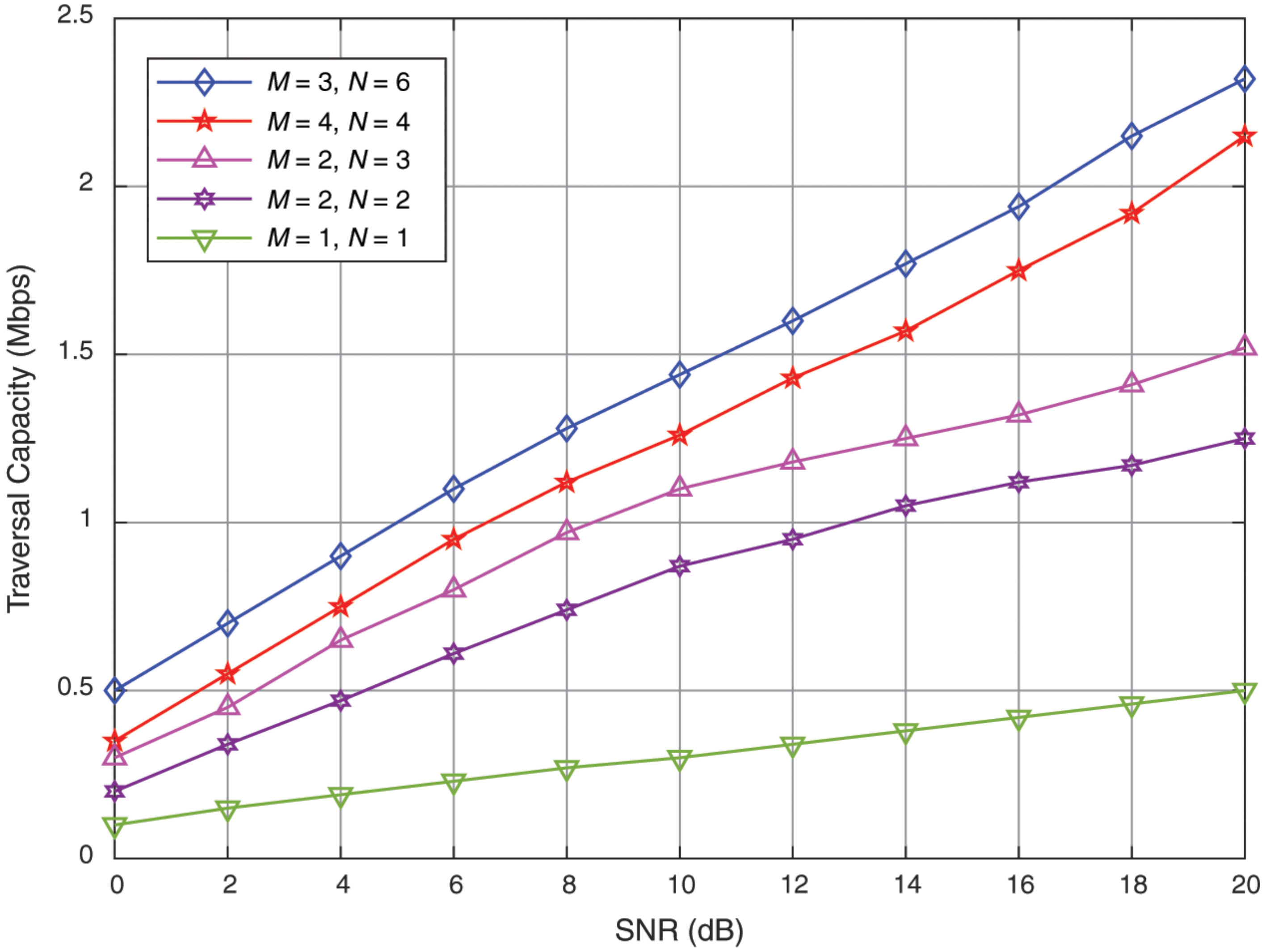

Figure 3: Traversal capacity of MIMO channel in terahertz communication

It is proposed in Section 3 that the CSI of the receiving end is used to calculate the traversal capacity. It is not yet possible to assume that the receiving end can also obtain CSI, which makes the current system an open-loop system as compared with the transmitter end. Knowing the channel information of the closed-loop system, the two systems will differ in capacity.

As shown in Fig. 4, set the number of antennas at the sending end and the receiving end to be 4-4 and 6-6 respectively. At this time, the capacity comparison under the two different situations of known and unknown channel information is shown in Fig. 4. When the receiving end informs the sending end of the channel information through feedback, the channel becomes a closed-loop system. At this time, the channel capacity can be calculated by water injection method. The results in Fig. 4 clearly shows that due to the use of the receiver to obtain channel information to calculate the capacity, the capacity is lost and the closed-loop system with known channel information at the transmitter can provide a larger amount than the existing open-loop system. Of course, this is only when the signal-to-noise ratio is low. When the signal-to-noise ratio is high, it can be seen that even a closed-loop system with known channel information will not greatly improve the capacity.

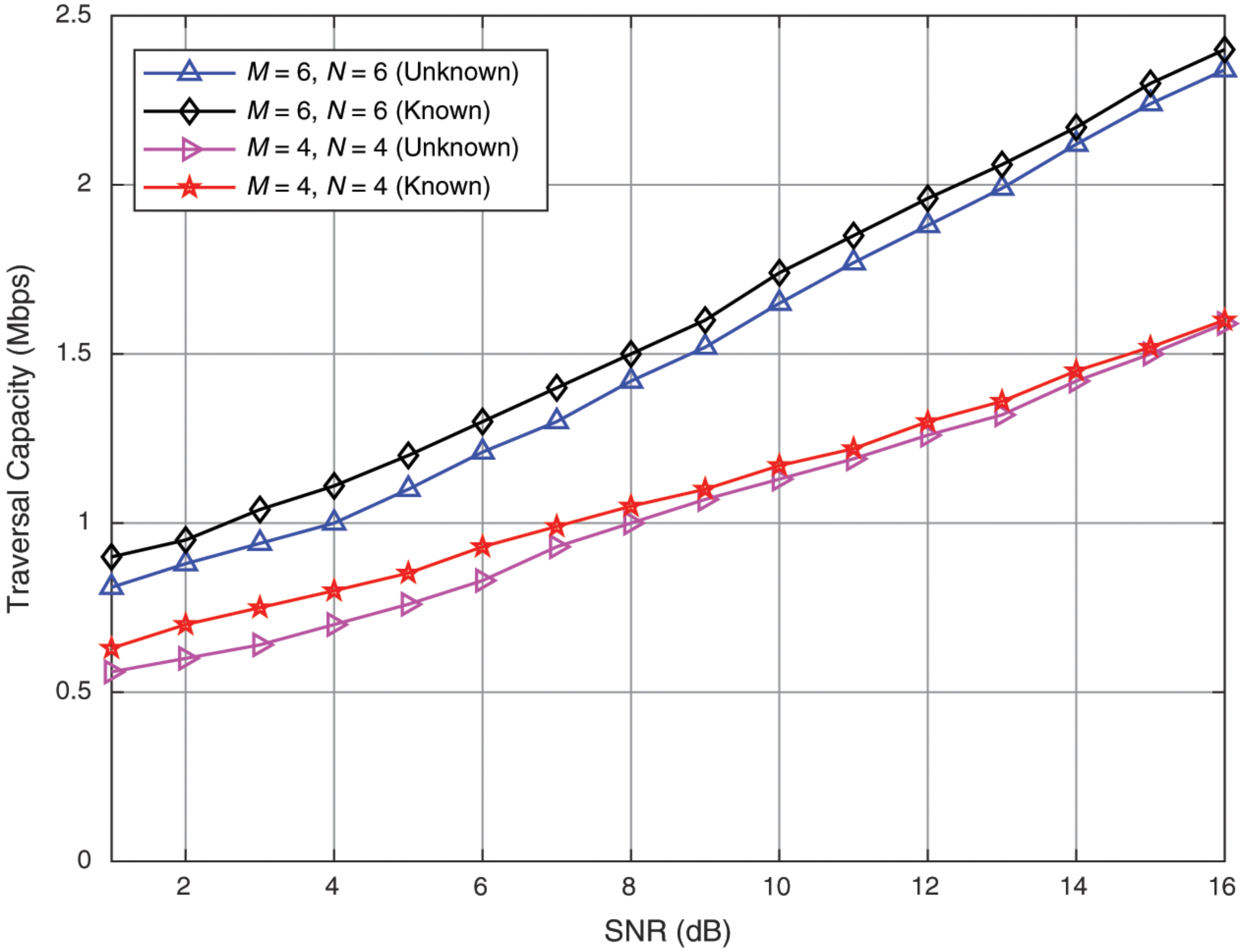

Figure 4: Traversing capacity when the transmitter CSI is unknown and known

Fig. 5 compares the spectral efficiency of the proposed study with reference [28] against the transmit power. It can be seen that the spectral efficiency of both algorithms increases with increasing transport power. However, the spectral efficiency of the proposed study is better than reference [28] which verifies its effectiveness.

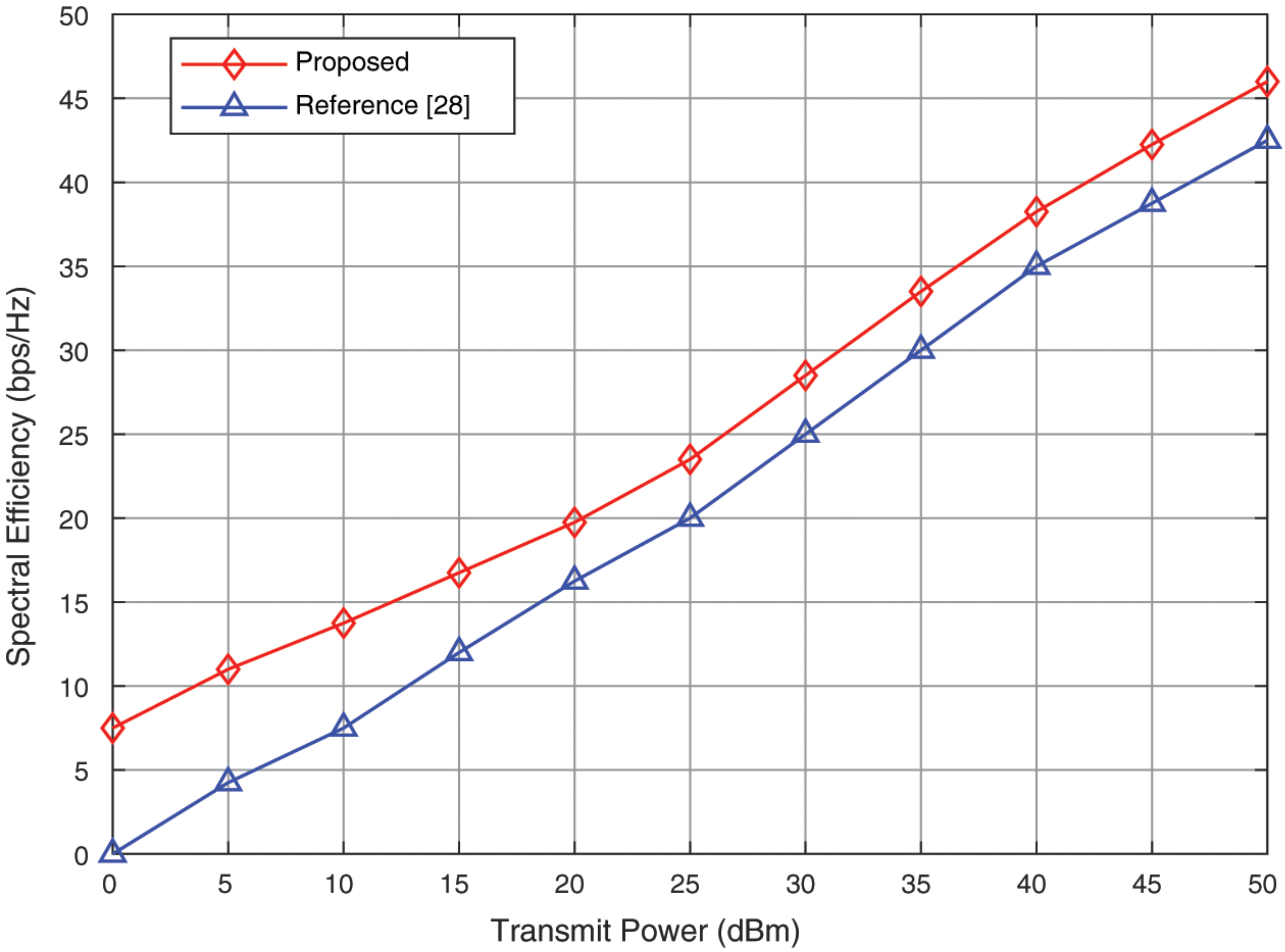

Figure 5: Comparison of the spectral efficiency *vs.* different values of transmit power

To evaluate the effectiveness of the proposed study from energy efficiency perspective, Fig. 6 compares the energy efficiency of the proposed study with reference [28]. It is clear from Fig. 6 that the energy efficiency of the proposed study is better than that of reference [28] scheme under each value of transmit power, which indicates the effectiveness of the proposed study.

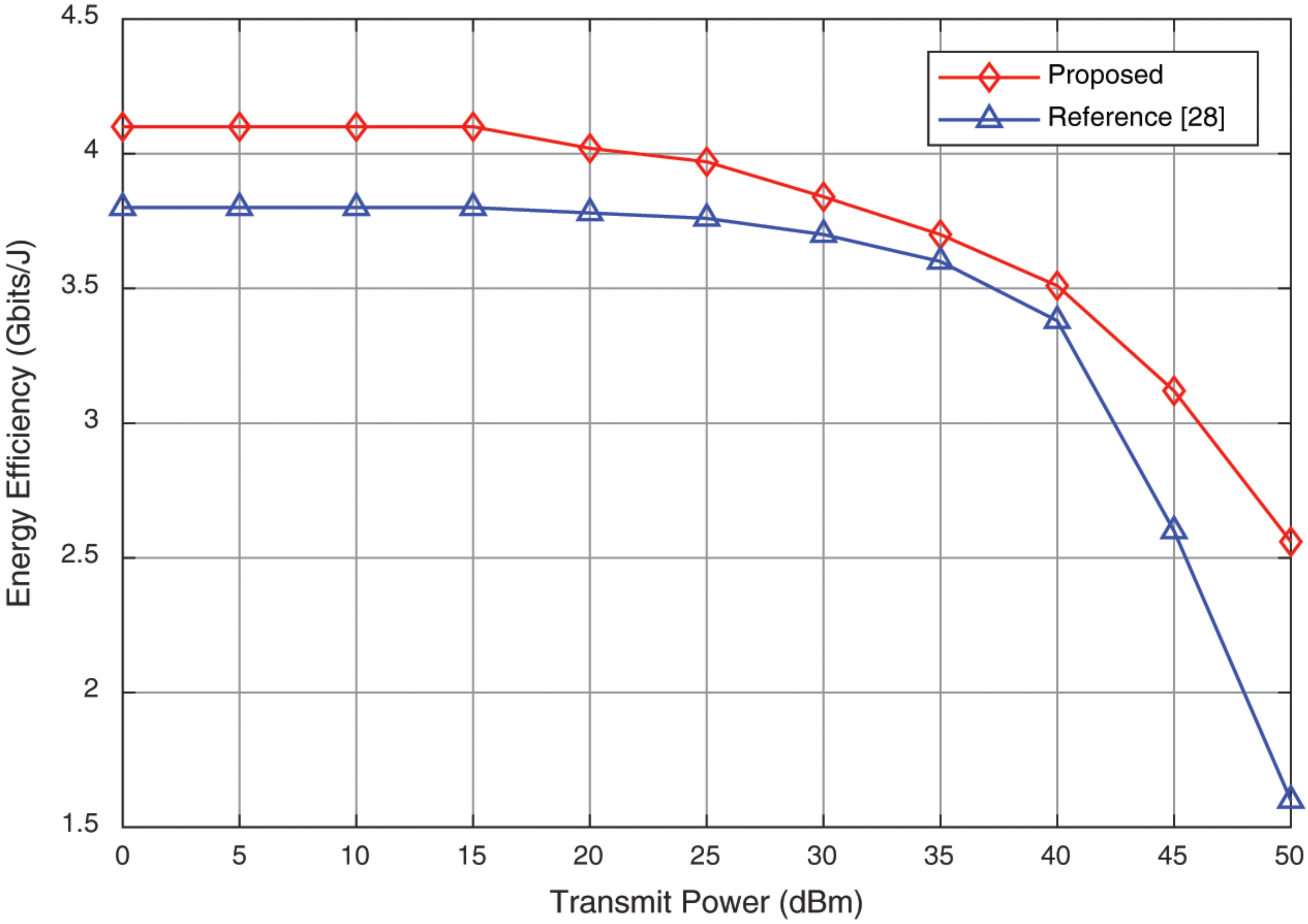

Figure 6: Comparison of the energy efficiency *vs.* different values of transmit power

onclusions and Future Recommendations

This paper proposes a MIMO channel model suitable for terahertz communication and simulates the model. From the simulation results, it can be seen that the channel model has higher channel capacity and supports higher transmission compared to a single-channel bit rate that is consistent with the characteristics of the terahertz band. High channel capacity and transmission bit rate provide support for new information coding and modulation techniques. Compared with the MIMO technology in the traditional communication field, the terahertz communication for nano-communication MIMO technology is still in its infancy. In the next step, we will improve the channel mechanism and make further research on the estimation and equalization of MIMO channels in the context of THz communications.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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