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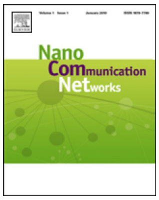

A statistical model for the MIMO channel with rough reflection surfaces in the THz band

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ABSTRACT

Based on the reflection properties of rough surfaces, we propose a statistical multiple-input multiple-output (MIMO) antenna system in the terahertz (THz) band for nanocommunications. Firstly, our analysis of scattering from a rough surface indicates that the reflection from a single surface can be a cluster of rays. Secondly, a new MIMO model for THz communications is proposed. In this model, the number of multipaths is highly dependent on the roughness of the reflecting surfaces. When the surface is ideally smooth, the MIMO channel is sparse and as a result, the capacity is sub-linear with the MIMO scale. On the other hand, when the surface is rough, more degrees of freedom are provided by the scattered rays. Finally, channel capacities with different surface roughness are numerically calculated and compared between different MIMO scales. The results show that in contrast to the GHz range, large scale THz multiple antennas may not provide as much multiplexing gain. Therefore, it is necessary to determine the antenna scale according to the actual propagation environment.

1. Introduction

The THz band (0.1–10 THz) is one of the most promising bands that will satisfy the demand for higher data rates in wireless communications. It has been shown that about 47 GHz of unregulated bandwidth is available around 350 GHz with low atmospheric absorption [1], and that for short transmission distances, the capacity can even be higher than 1 Tbit/s when the frequency is over 1 THz. When the frequency increases and the devices size scales down, wireless communications will fall into the range of nano-scale communications. Recently, many nano-scale devices have been designed for nanocommunications in the THz band, such as graphene based nano transceivers [2] and antennas [3–9]. Some nanocommunication THz channel models have been proposed in the literature. For example, paper [10] analyzes the capacity of a THz channel. Papers [11–14] review the background knowledge and recent research progress in THz technology, and they reveal that some electrical components for THz frequencies are already commercially available.

On the other hand, the multiple-input multiple-output (MIMO) antenna technique is well known to increase the data rate of a wireless communication system [15]. MIMO theory and precoding schemes in the GHz band have already been well presented in the literature. In a GHz channel, it is usually assumed that the elements of a fading channel matrix **H** are independent and identically distributed (i.i.d.), which is based on the assumption of a rich scattering environment that has many multipaths. Under this assumption, the physical channel can be viewed as several parallel sub-channels, and the total capacity scales up linearly with the MIMO dimension. However, for some scenarios in the THz channel and with increasing MIMO dimension, MIMO systems show only beamforming gain but limited multiplexing gain improvement. This is due to the fact that the number of multipaths in the THz channel is limited since the path loss and reflection loss are so

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large that only the single bounce reflection rays are strong enough to link transmitters with receivers. Therefore, the models of the GHz channel cannot directly be applied to the THz channel, and new models for THz MIMO systems must be developed. It is generally agreed that THz MIMO systems have the following characteristics: (i) The scenarios are mainly applied to indoor environments, for example, office buildings or malls [11]. For long distance outdoor communications, smart antennas with high power amplifiers must be applied [1]; (ii) For indoor THz MIMO channels, few multipaths exist between the transmitting and receiving antennas if all the surfaces are smooth [16,17]. The correlations between the received signals on different receive antennas are significantly higher than those in the GHz band. Therefore, the multiplexing gain will be low, and correlated signals have low diversity gain. This situation is very similar to the sparse MIMO channel that has been studied in some theoretical investigations [18,19] as well as in experiments [20].

Most of the existing works on MIMO system models are in the GHz band, but very few papers study THz MIMO systems. Therefore, in this work, we study MIMO channel modeling for THz communications. Besides the different path loss factors, surface roughness is one of the most important differences between THz and GHz MIMO channels. For THz MIMO models, scattering analysis is far more important than in the GHz range. In [1,16,17,21–23], the scattering from rough surfaces is studied for THz channels. When the carrier frequency is very high, the surfaces of reflecting objects can no longer be regarded as smooth. For THz frequencies, the surfaces of indoor objects, such as wallpaper or carpet, are all sufficiently rough such that their scattering cannot be ignored. The authors of [16,23] studied the scattering power from different reflection angles at 300 GHz and measured the multipath loss in an indoor scenario. We use the same method to investigate the reflection properties of THz frequencies and derive a new MIMO model for indoor nanocommunications. In this new model, the scattered rays are included and become increasingly important with rising frequency. When the frequency is high enough, the specular reflection is less dominant and becomes an ordinary ray with very low power gain. In the capacity analysis, we express the channel capacity as the sum of two parts, one is the capacity introduced by specular reflection, the other one is introduced by scattered rays. Since the specular reflection rays are weak in the THz band, the capacity is mainly contributed by scattered rays. Another very important difference between THz MIMO and GHz MIMO systems is that the antenna size is much smaller in the THz regime and, therefore, we can place hundreds of antennas on a single device, which necessitates the performance analysis of very large scale antenna arrays.

The main contributions of our new THz MIMO model are summarized as follows:

- We propose a THz MIMO system model based on the theory of rough surface reflection and point out the importance of rough surfaces to THz MIMO systems.
- We analyze the relationship between the capacity and the roughness factor, as well as the capacities introduced by different rays.
- We compare the spectral efficiency of systems with different numbers of antennas and in environments with different roughness factors. From this comparisons, it can be determined whether the use multiple antennas is necessary, and if so, how many antennas to employ in the THz band. In addition, the tradeoff between costs and gains under different roughness scenarios can be assessed.

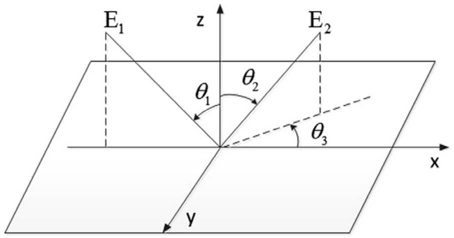

Fig. 1. The scattering reflection geometry.

The remainder of this paper is organized as follows: In Section 2, we provide the background on reflections from small-size to large-size rough surfaces. In Section 3, we model the MIMO system in the THz band and analyze the channel capacity of the MIMO system. The simulation results and data analyses are provided in Section 4. Finally, our conclusions are given in Section 5.

2. Reflection in the THz band

2.1. Scattering from a small rough surface

Reflections in the GHz band are typically viewed as being generated by a smooth surface. Under this situation, only the specular reflection ray is considered and the reflection loss is usually ignored. However, there is growing experimental evidence indicating that this is not the case for the THz band. C. Jansen et al. measured the roughness of some common indoor materials, such as plaster and wallpaper [23]. Their results show that the standard deviation of the surface height is about $\sigma_h = 88\ \mu\text{m}$ for plaster, and $\sigma_h = 90\ \mu\text{m}$ for wallpaper. Compared with the wavelength at GHz frequencies (e.g., 300 mm at 1 GHz), these surface height deviations are rather small and can be safely ignored. For THz frequencies, however, the wavelength is in the order of several hundred micrometers, which is comparable with the surface height deviation. In such a situation, we must take the roughness into consideration and use a new method to model the reflection properties.

Suppose the incident field $\mathbf{E}_1$ is a harmonic plane wave of unit amplitude. We denote the angle of incidence (the angle between $\mathbf{E}_1$ and the $\mathbf{z}$ axis) as θ_1 and the angles of reflection (the angles between the reflected field $\mathbf{E}_2$ and the $\mathbf{z}$ and $\mathbf{x}$ axes) as θ_2 and θ_3, respectively (Fig. 1). Let $\mathbf{P}$ be the point of observation and r the distance from $\mathbf{P}$ to a point (x, y) on the reflection surface. The scattered field $\mathbf{E}_2$ is given by the Helmholtz integral [24]

$$\mathbf{E}_2(P) = \frac{1}{4\pi}\iint_S \left(\mathbf{E}_1 \frac{\partial \psi}{\partial \mathbf{n}} - \psi \frac{\partial \mathbf{E}_1}{\partial \mathbf{n}}\right) \mathrm{d}S, \qquad (1)$$