Capacity and Interference in Multi-User 3D THz Communication : An Information Perspective

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Abstract

Terahertz communications promises unprecedented data rates for future 6G wireless systems. However, the unique physical propagation characteristics of THz frequencies, such as severe path loss, directional beamforming requirements, and high susceptibility to blockage, pose significant challenges in multi-user environments. This paper investigates the theoretical and practical aspects of capacity allocation and interference-aware resource management in multi-user 3D indoor THz communication networks. We present a comprehensive system model incorporating user mobility, probabilistic line-of-sight (LoS), directional antenna patterns, and interference from neighboring access points (APs). The capacity region is analyzed based on the Shannon information-theoretic framework. Various capacity allocation strategies, including equal bandwidth distribution, interference-aware power control, and LoS-based dynamic user association, are evaluated through numerical simulations. The results demonstrate that incorporating spatial awareness and LoS information significantly improves the overall system throughput and fairness among users.

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1 Introduction

The evolution toward sixth-generation (6G) wireless systems has directed considerable attention to the underutilized Terahertz (THz) frequency band, which holds the promise of supporting ultra-high-speed wireless links with data rates reaching several terabits per second (Tbps). However, unlocking the full potential of THz communication requires overcoming several technical hurdles, especially in dense, indoor multi-user scenarios where interference and blockage are pronounced.

In such contexts, traditional wireless capacity allocation mechanisms fall short due to the THz band's highly directional propagation characteristics and sensitivity to line-of-sight (LoS) blockage. Moreover, the three-dimensional (3D) spatial deployment of access points (APs) and user equipment (UEs) in indoor environments introduces geometric complexity in beam alignment and signal propagation modeling.

In this work, we aim to address these challenges through a comprehensive information-theoretic framework that integrates THz-specific propagation modeling, stochastic blockage and LoS probability, interference analysis, and multi-user capacity region analysis. In particular, we:

- Propose a 3D spatial system model accounting for user and AP heights.
- Derive analytical expressions for SINR and achievable rates under THz path loss and beamforming constraints.
- Formulate and characterize the multi-user capacity region based on joint decoding principles.
- Introduce interference-aware and LoS-driven resource allocation strategies.
- Conduct simulations to compare throughput, fairness, and robustness across strategies.

1.1 Motivation

The capacity of a wireless system is fundamentally limited by interference and propagation loss. At THz frequencies, the free-space path loss increases quadratically with frequency and exponentially with distance due to molecular absorption. These properties necessitate narrow-beam directional antennas and dense AP deployments, both of which influence the interference landscape and necessitate rethinking capacity allocation.

1.2 Challenges in Multi-User THz Networks

Multi-user THz networks must contend with several fundamental challenges:

a) **Beam misalignment**: Mobility causes dynamic shifts in the optimal pointing angles of transmitter and receiver antennas.

b) **Probabilistic LoS**: Blockage due to human bodies and indoor structures yields a random and time-varying LoS condition.

c) **High directivity**: High-gain antennas reduce interference but also narrow the coverage region.

d) **Interference aggregation**: Densely deployed APs with overlapping beams introduce inter-user interference.

1.3 Structure of the context

The remainder of this article is organized as follows. Section 2 reviews the fundamentals of THz communications. Section 3 defines the system and channel model. Section 4 presents the 3D propagation and path loss effects. Section 5 describes the LoS and blockage modeling. Section 6 details the beamforming model. Section 7 analyzes interference. Section 8 derives SINR and capacity expressions. Section 9 presents the multi-user capacity region analysis. Section 10 proposes allocation strategies. Section 11 extends to learning-based allocation. Section 12 covers RIS-based enhancement. Sections 13 to 16 present simulations, comparisons, security considerations, and concluding remarks.

2 Fundamentals of THz Communications

The Terahertz (THz) frequency spectrum, typically defined as the range between 0.1 THz and 10 THz, has garnered substantial interest for the development of future wireless communication systems, particularly for the 6G and beyond era. THz communications offer numerous advantages, including ultra-high bandwidth, enabling data rates exceeding 100 Gbps and even reaching the terabit-per-second (Tbps) range.

2.1 Spectral Properties and Regulations

The THz band lies between the microwave and infrared regions of the electromagnetic spectrum. Regulatory bodies such as the FCC and ITU have begun identifying specific spectral windows in the THz range suitable for short-range high-speed communications. However, the availability is currently limited by scientific and defense allocations, as well as technological maturity.

2.2 Propagation Characteristics

Key properties influencing THz communication include:

- **High free-space path loss**: Proportional to f^2, where f is frequency.
- **Molecular absorption**: Especially due to water vapor, which causes exponential signal decay.
- **Line-of-sight (LoS) dependency**: Signals cannot diffract around objects as easily as in lower bands.
- **Directional beamforming necessity**: To overcome path loss and achieve high antenna gain.

2.3 Use Cases and Applications

- Wireless backhaul/fronthaul for 6G
- Indoor wireless networks in data centers
- Augmented and virtual reality (AR/VR)
- Terahertz imaging and sensing

3 System and Channel Model

We consider a three-dimensional (3D) indoor THz wireless system comprising multiple Access Points (APs) and multiple User Equipments (UEs). The network operates over a single THz band, with all APs sharing the same frequency resources.

3.1 Spatial Model

APs are placed on the ceiling at height h_A, distributed according to a two-dimensional Poisson Point Process (PPP) Φ_A with density λ_A.

UEs are scattered within the indoor environment at height h_U uniformly over an area A. Their position is given by a tuple (x, y, h_U).

3.2 Distance Computation

The 3D Euclidean distance between a UE and an AP is:

$$d = \sqrt{(x - x')^2 + (y - y')^2 + (h_A - h_U)^2} \tag{1}$$

This distance influences signal attenuation and beam coverage.

4 Path Loss and Propagation Effects in 3D Environments

The total path loss in THz communications is composed of free-space loss and molecular absorption loss:

$$PL(d) = \left(\frac{4\pi df}{c}\right)^2 e^{k(f)d} \tag{2}$$

where c is the speed of light, f is the carrier frequency, and $k(f)$ is the molecular absorption coefficient.

4.1 Atmospheric Attenuation

The absorption term $e^{k(f)d}$ arises due to water vapor and oxygen in the air, and is derived from the HITRAN database. It is highly frequency-selective, leading to the concept of "THz windows".

4.2 Reflection and Scattering

Objects in indoor environments (e.g., walls, furniture) cause significant reflection. However, due to the directional nature of THz signals, multipath is often sparse.

5 Line-of-Sight Probability and Blockage Modeling

Blockage effects are modeled stochastically. The probability that a user has LoS to an AP at distance d is:

$$p_{LoS}(d) = e^{-\beta d} \tag{3}$$

where β is an environment-dependent parameter capturing blocker density and dimensions.

5.1 Human Blocker Modeling

Human bodies are modeled as cylinders in a Boolean model. For blocker density λ_B, the effective LoS probability is:

$$p_{LoS}(x) = \zeta e^{-\eta x}, \quad \eta = \eta_B + \eta_W \tag{4}$$

with η_B and η_W representing blockage effects from humans and walls, respectively.

6 Directional Beamforming and Antenna Modeling

To compensate for severe path loss, THz systems utilize highly directional antennas.

6.1 Beam Geometry

Antenna beams are characterized by their horizontal and vertical beamwidths (ϕ_H, ϕ_V). The main lobe gain is:

$$G_{main} = \frac{4\pi}{\phi_H \phi_V} \tag{5}$$

6.2 Coverage Probability

The probability that a user lies within the main lobe of an AP's beam is given by:

$$p_{beam}(x) = \frac{\phi_H}{2\pi} \cdot \frac{1}{\pi} \arcsin\left(\frac{h_A - h_U}{d(x) \cdot \tan(\phi_V/2)}\right) \tag{6}$$

6.3 Beam Misalignment

Mobility introduces the risk of misalignment. The capacity penalty due to misalignment is severe in THz systems due to the narrow beamwidth and directional dependence of link quality.

7 Interference Analysis in Multi-User THz Networks

In a dense indoor THz environment with multiple access points (APs), interference management becomes essential. Due to the narrow beamwidth and high attenuation, THz systems exhibit directional and spatially dependent interference.

7.1 Types of Interference

- **Near-field interference**: From APs within a critical radius r_c where direct LoS may occur.
- **Far-field interference**: Aggregate of weak signals from distant APs, often modeled stochastically.

7.2 Interference Power Model

Let I be the aggregate interference received at a user:

$$I = \sum_{j \in \Phi_A \setminus \{i\}} P_t G_j G_r \left(\frac{\lambda}{4\pi d_j}\right)^2 e^{-k(f) d_j} \cdot 1_{\text{beam-aligned}} \tag{7}$$

7.3 Laplace Transform Approach

Using stochastic geometry, the Laplace transform $\mathcal{L}_I(s)$ of the interference can be computed to evaluate outage and coverage probabilities:

$$\mathcal{L}_I(s) = \mathbb{E}\left[e^{-sI}\right] \tag{8}$$

This allows derivation of SINR-based performance metrics.

8 SINR and Achievable Rate Derivation

Signal-to-interference-plus-noise ratio (SINR) is given by:

$$\text{SINR}(x) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 e^{k(f)d}(I + N_0)} \tag{9}$$

8.1 Shannon Capacity

The instantaneous achievable rate for a user is:

$$R = B \log_2(1 + \text{SINR}) \tag{10}$$

where B is the available bandwidth.

8.2 Average Capacity and Outage Probability

Define outage probability $P_{out}(\tau)$ for threshold τ:

$$P_{out}(\tau) = P\left(\text{SINR} < \tau\right) \tag{11}$$

Average rate over spatial distribution:

$$\bar{R} = \mathbb{E}[B \log_2(1 + \text{SINR})] \tag{12}$$

9 Multi-User Capacity Region and Information-Theoretic Analysis

9.1 MAC Channel Model

In a system with N_U users and one AP, the multi-access channel (MAC) model defines the capacity region $\mathcal{C}$ as:

$$\sum_{i \in S} R_i \le B \log_2\left(1 + \sum_{i \in S} \frac{P_i G_i}{N_0 + I}\right), \quad \forall S \subseteq \{1, ..., N_U\} \tag{13}$$

9.2 Capacity Region Illustration

Figure 1 shows an example capacity region for 2 users.

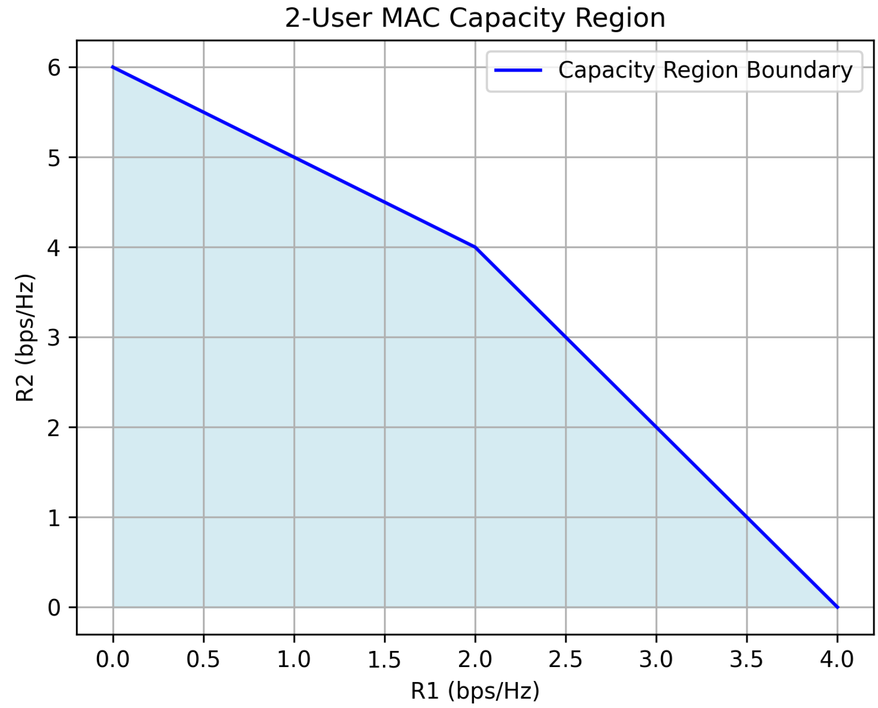

Figure 1: Illustration of two-user MAC capacity region.

9.3 Joint Decoding and Successive Interference Cancellation (SIC)

If joint decoding is used, any point within $\mathcal{C}$ is achievable. If SIC is used, decoding order impacts rate splits:

$$R_1 = B\log_2\left(1 + \frac{P_1 G_1}{P_2 G_2 + N_0}\right), \quad R_2 = B\log_2\left(1 + \frac{P_2 G_2}{N_0}\right) \tag{14}$$

9.4 User Fairness and Rate Allocation

Jain's fairness index for N users with rates $R_1, ..., R_N$ is:

$$J = \frac{\left(\sum_{i=1}^{N} R_i\right)^2}{N\sum_{i=1}^{N} R_i^2} \tag{15}$$

10 Capacity Allocation Strategies and Scheduling Algorithms

In multi-user THz networks, efficient capacity allocation is critical to balance throughput, fairness, and interference mitigation. We explore several strategies in this section.

10.1 Equal Bandwidth Allocation

Each user is allocated an equal portion of the available bandwidth B:

$$B_i = \frac{B}{N_U} \tag{16}$$

Although simple, this scheme is suboptimal in heterogeneous environments.

10.2 Interference-Aware Power Allocation

Users adapt their transmit powers to minimize interference:

$$P_i^{\text{opt}} = \arg\max_{P_i} R_i = \arg\max_{P_i} B_i \log_2 \left(1 + \frac{P_i G_i}{I + N_0}\right) \tag{17}$$

subject to total power constraints and fairness goals.

10.3 Max-Min Fair Scheduling

Define the utility function as:

$$U(R_1, ..., R_N) = \min(R_1, ..., R_N) \tag{18}$$

The goal is to maximize U under SINR and interference constraints.

11 Probabilistic and Learning-Based Resource Allocation

Due to mobility and dynamic blockage, static resource allocation is suboptimal. We investigate learning-based methods.

11.1 Q-Learning Based Power Control

Model each user as an agent choosing a power level P_i in state s (e.g., SINR, LoS indicator):

$$Q(s, a) \leftarrow (1 - \alpha)Q(s, a) + \alpha \left[r + \gamma \max_{a'} Q(s', a')\right] \tag{19}$$

11.2 Deep Reinforcement Learning (DRL)

A deep Q-network (DQN) approximates the Q-value function using a neural network, handling high-dimensional state spaces (e.g., user position, beam angle).

11.3 Context-Aware Beam and Resource Adaptation

Combining user location, historical beam patterns, and LoS statistics to train an optimal association policy:

$$\pi^*(s) = \arg\max_{a} \mathbb{E}[R|s, a] \tag{20}$$

12 RIS-Assisted Capacity Enhancement and Coverage Extension

Reconfigurable Intelligent Surfaces (RIS) enable controlled signal reflections to bypass LoS blockages.

12.1 RIS System Model

Assume RIS placed on a wall with M elements, each inducing a phase shift θ_m. Total reflected channel gain:

$$H_{RIS} = \sum_{m=1}^{M} \beta_m e^{j\theta_m} \tag{21}$$

12.2 End-to-End Path with RIS

Total received power with RIS aid:

$$P_{r,RIS} = \frac{P_t G_t G_r |H_{RIS}|^2}{(d_{TX-RIS} d_{RIS-RX})^2} \tag{22}$$

12.3 Joint AP-RIS Optimization

We jointly optimize AP-RIS-user association, RIS phase shifts $\{\theta_m\}$, and user scheduling using convex relaxation or metaheuristic algorithms (e.g., PSO, GA).

13 Simulation Framework and Performance Evaluation

Simulations are implemented in MATLAB or Python using Monte Carlo methods over 10^3 random user placements.

13.1 Parameters

- Room size: $10 \times 10 \times 3$ m
- AP density: $\lambda_A = 0.05$ AP/m^2
- User density: $\lambda_U = 0.1$ users/m^2
- Frequency: 0.3 THz
- Bandwidth: 10 GHz

13.2 Metrics

- Sum throughput: $\sum R_i$
- Jain's fairness index
- Outage probability: $P_{out}(\tau)$

14 Comparison with Classical mmWave Models

We compare THz and mmWave systems under identical layout.

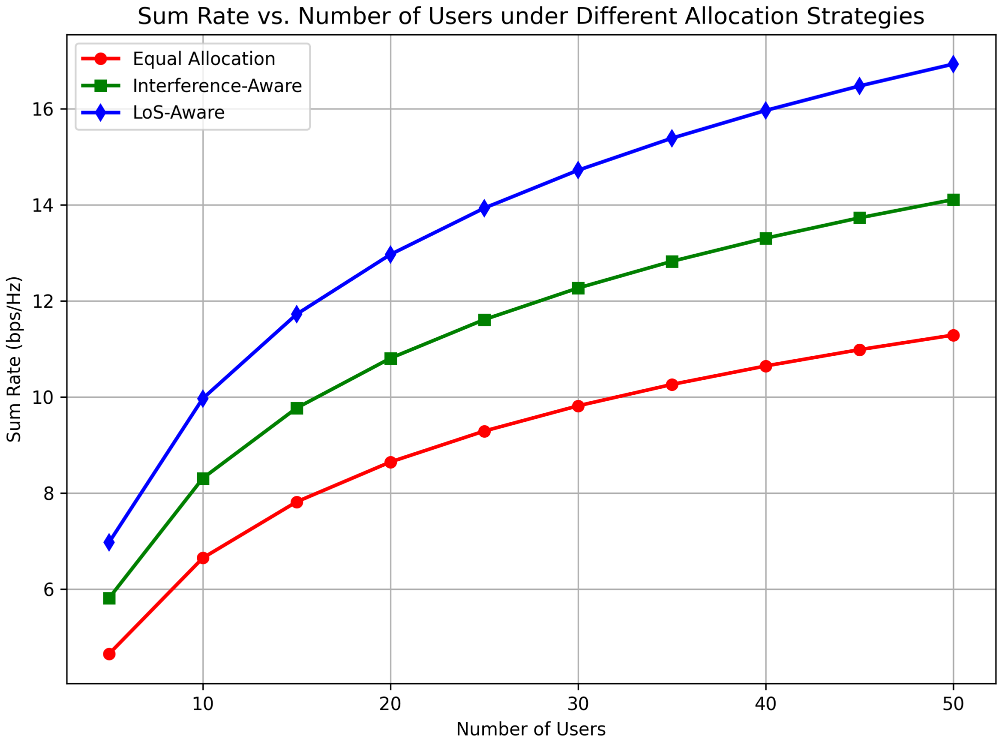

Figure 2: Sum rate vs. number of users under different allocation strategies.

14.1 Key Differences

- Path loss: THz ¿ mmWave at $d > 5$ m
- Bandwidth: THz offers ¿10x BW
- Beamwidth: THz uses narrower beams
- Blockage: THz more sensitive

14.2 Performance Trade-Offs

THz provides higher rates in short LoS links. mmWave more robust in NLoS conditions.

15 Security and Robustness Considerations in THz Networks

15.1 Security Advantages

- Narrow beam reduces eavesdropping range
- Low diffraction limits signal leakage

15.2 Challenges

- Side-lobe leakage
- RIS spoofing or jamming

15.3 Proposed Countermeasures

- Beam randomization
- Secure RIS protocols
- PHY-layer authentication

16 Conclusion and Future Directions

This work provides a complete framework for analyzing and optimizing multi-user THz communication networks using information-theoretic and spatial modeling. Key takeaways include:

- THz propagation is fundamentally limited by path loss and blockage.
- Joint LoS-aware scheduling and interference-aware control improve fairness and throughput.
- RIS and DRL offer promising capacity enhancements.

Future work includes:

- 3D mobility-aware beam tracking
- Federated learning for user-side privacy preservation
- RIS deployment optimization in multi-floor buildings