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ADVANCING UAV CONNECTIVITY: COOPERATIVE THz COMMUNICATION IN FUTURE NETWORKS

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ABSTRACT:*Unmanned Aerial Vehicles (UAVs) have gained significant attention due to their potential in various applications, including communication networks, agricultural monitoring and emergency services. This paper analyzes the performance of a flying ad-hoc network (FANET) with CSMA/CA and RTS/CTS access mechanisms in UAV-based communication networks. The performance of the MAC protocol is evaluated under Direct Transmission (DT) and Cooperative Transmission (CT) modes with variable UAVs, CW size, SNR and transmission path distances. We estimated the path loss, outage probability, successful data transmission probability, and throughput of the proposed network. Simulation results show that the probability of a successful transmission increases with a larger contention window. CT mode consistently outperforms the DT mode in throughput under the RTS/CTS mechanism. Based on the analysis, it is observed that the optimal CW size as 32, UAVs as 35 and access mechanism as RTS/CTS-CT mode. These values of the proposed protocol maximize successful data transmission probability, throughput and overall system efficiency.*

KEYWORDS:Cooperative Communication, UAV Networks, MAC Protocol, Throughput, Efficiency.

Introduction:

The rapid evolution of wireless communication technologies has led to the development of sixth-generation (6G) networks, which demand ultra-high data rates, low latency, and seamless connectivity. To meet these stringent requirements, terahertz (THz) communication has emerged as a key enabler due to its large bandwidth, low interference, and high data transmission capacity. Simultaneously, unmanned aerial vehicles (UAVs) are being widely deployed in modern wireless networks, particularly in intelligent transportation systems (ITS), disaster management, surveillance, and remote sensing applications [1-3].

Despite their advantages, UAV networks face significant challenges, including high mobility, frequent topology changes, and communication reliability issues. Additionally, the THz band, while promising, is susceptible to severe signal attenuation and environmental absorption effects [4-6]. Addressing these challenges, this study proposes a cooperative THz communication system for UAV-based Flying Ad Hoc Networks (FANETs), designed to enhance network performance and ensure reliable data transmission. The high mobility of UAVs and vehicles, which can cause frequent disconnections and packet loss. To overcome this, it explores cooperative communication, where multiple nodes collaborate to transmit data, improving reliability and reducing interference [7-9]. In [10], authors considered an algorithm to select between Direct Transmission (DT) and Cooperative Transmission (CT), introducing new control packets to support cooperative communication. In [11], cooperative terahertz (THz) communication is proposed for flying ad hoc networks, which is a particular kind of network made up of a collection of small UAVs linked in an ad-hoc fashion and working together to accomplish high-level objectives. The frequency spectrum for wireless communication has been expanding continuously in order to meet the demand for bandwidth. For the forthcoming 6G and beyond, communications in the THz range will be vital, similar to how mm Wave-band communications are currently influencing the 5G of wireless mobile communications. In [12], the world is experiencing an explosion in demand for ultra-high data rates with far greater expectations in the next few years. These expectations, given the bandwidth-demanding applications such as augmented and virtual reality and other beyond-5G applications, motivate the exploration of higher-frequency communication in the terahertz bands. However, THz communication is faced with many technical challenges, primarily due to the high susceptibility to blockages that limit its applications.In [13], terahertz wireless communication is a promising technology that will enable ultra-high data rates, and very low latency for future wireless communications. Intelligent Reconfigurable Surfaces (IRS) aiding Unmanned Aerial Vehicles are two essential technologies that play a pivotal role in balancing the demands of Sixth-Generation (6G) wireless networks. In practical scenarios, mission completion time and energy consumption serve as crucial benchmarks for assessing the efficiency of UAV-IRS enabled THz communication. In [14], unmanned aerial vehicles and Terahertz technology are envisioned to play paramount roles in next-generation wireless communications. Hence, this paper presents a novel secure UAV-assisted mobile relaying system operating at THz bands for data acquisition from multiple ground user equipment's towards a destination. We assume that the UAV-mounted relay may act, besides providing relaying services, as a potential adversary called the untrusted UAV relay. In [15], 6G wireless networks require very low latency and an ultra-high data rate, which have become the main challenges for future wireless communications. To effectively balance the requirements of 6G and the extreme shortage of capacity within the existing wireless networks, sensing-assisted communications in the THz band with unmanned aerial vehicles is proposed. In this paper, we proposed an algorithm to determine the most suitable transmission mode for optimal performance. The standard currently supports only direct transmission and does not facilitate cooperative communication. To address this limitation, modifications have been made to the RTS/CTS mechanism, introducing new control packets, including Relay Request to Send (RRTS), Offer to Relay (OR), Relay Ready to Relay (RRR), Relay Clear to Relay (RCR), and Relay Acknowledgement (RACK). These changes alter the standard packet control mechanism. Since rapid topology changes often disrupt communication stability, cooperative communication offers a solution by mitigating mobility-induced channel disturbances, thereby improving data transmission. This study also explains the control packet exchange mechanism for different transmission modes. The rest of the paper is structured as follows: Section 2 explains the proposed model. Section 3 presents the throughput estimation. Section 4 explains the results and discussion. Section 5 draw the conclusion and future scope.

2. Proposed Model:

The primary objective of this paper is to design and analyze a cooperative THz communication system for UAV-based FANETs in 6G and beyond. FANETs face significant challenges such as signal attenuation, reduced communication reliability, and degraded network performance, particularly in the THz band. To address these issues, this work leverages cooperative communication techniques integrated with an optimized MAC protocol. Specifically, the study focuses on enhancing UAV network reliability through a cooperative MAC design that improves transmission efficiency by evaluating key performance metrics such as successful transmission probability, collision probability, and throughput by mitigating THz communication impairments like high path loss and signal degradation using cooperative relaying mechanisms and validating the proposed system through numerical simulations that demonstrate its effectiveness in improving data transmission reliability and reducing failures compared to direct transmission methods.This section explores the CT-MAC protocol of DT mode for UAV communication in detail. Figure 1 illustrates a UAV network comprising a source, a relay, and a destination node. The first step involves selecting the most efficient data transmission mode, followed by choosing the most appropriate relay. This section also introduces the control packet exchange mechanism and presents a modified control packet format. Additionally, the CT-MAC protocol's time schedule is discussed for different transmission modes like DT and CT, offering diverse communication strategies.

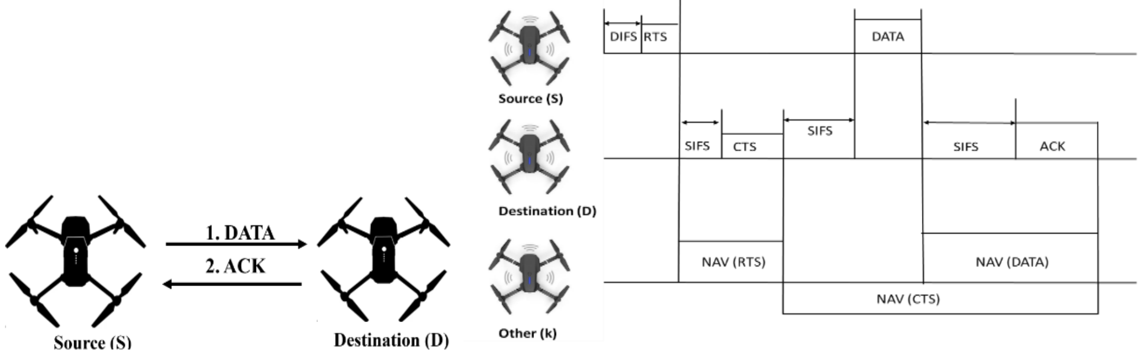


Fig 1. (a) CT-MAC Protocol of DT mode (b) Time period of the control packet exchange.

DT mode in the CT-MAC protocol involves direct transmission via RTS/CTS. Fig 1(a) presents the CT-MAC protocol for DT mode, whereas Fig 1(b). outlines the time period of the control packet exchange mechanism. Initially, an RTS is transmitted, and a CTS is acknowledged by node S before data transmission occurs. For the transmission to be considered successful, node D must send an ACK to source node S. In CT mode, an RTS is sent before CTS to initiate data transmission. Both RTS and CTS packets carry signal-to-noise ratio (SNR) information. Vehicle nodes, including S, select the relay node based on the highest SNR value. The term "OR" represents an auxiliary relay that can broadcast to the entire network. After the distributed coordination function inter-frame space (DIFS) period, vehicle nodes transmit an RRR to both K and D, allowing other nodes to assess the range and network allocation vector (NAV) within the RRR. Following a short inter-frame space (SIFS) interval, node K transmits data to the optimal relay (R), which then forwards the data to H. The optimal relay plays a crucial role in ensuring efficient data delivery. Once the transmission is completed, K receives an ACK to confirm successful delivery. If K does not receive an ACK within the SIFS interval, R retransmits the data to H. Before initiating a new data transmission, UAVs must wait for the DIFS period, which is shown in Figure 2. Figure 2(a) represents the CT-MAC protocol for CT mode, while Figure 2(b) presents the control packet exchange mechanism for this mode.

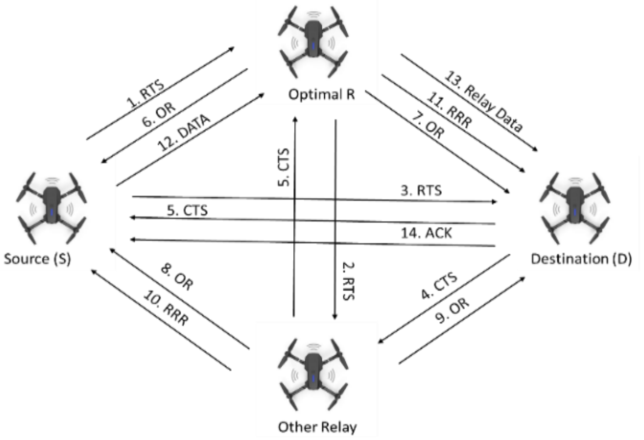


Fig 2a: CT-MAC protocol of CT mode.

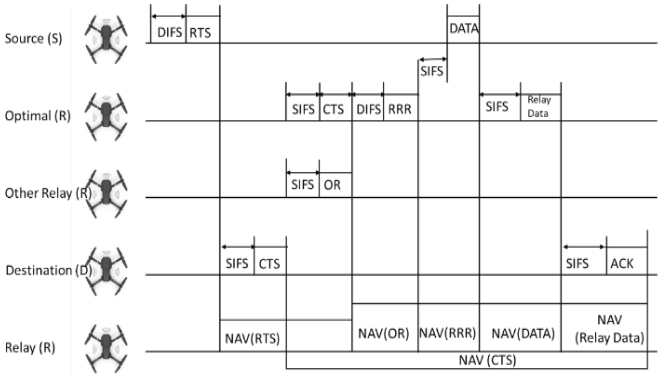


Fig 2b: Time period of the control packet exchange.

For efficient data transmission, choosing the appropriate transmission mode between DT and CT is essential, along with selecting a suitable relay when required. The effectiveness of cooperative communication is influenced by the number of available relays, as increasing the relay count enhances communication reliability and diversity gain. Certain parameters must be considered when selecting a relay node. The chosen relay should be idle and possess a high KH SNR value. Additionally, the current channel status serves as a crucial factor in the selection process. Since cooperative communication relies on all links from the source to the destination, selecting a relay depends on the real-time SNR of control messages. Through RTS and CTS transmissions, neighboring nodes can determine the SNR of both the sender and the receiver. These control packets also contain additional SNR information, allowing nodes K and H to assess the data transmission rate. Idle nodes with high SNR values send OR to both K and H, facilitating the selection of the most efficient relay paths. As a result, a group of high-quality relay nodes, denoted as Ur, is identified. Data transmission typically succeeds due to the RTS-CTS exchange, which provides real-time SNR details. By analyzing this information, the optimal relay (R) is selected based on the shortest path between K and H. Relay nodes are categorized into "good relays" and "optimal relays." The process begins with identifying a set of good relays, which are idle, have high data rates, minimal transmission delays, and stable channel conditions. From this group, the optimal relay is chosen using a shortest-path algorithm. Unlike regular good relays, the optimal relay not only meets all these criteria but also ensures the shortest transmission route. This mechanism allows nodes with lower data rates to successfully transmit data at higher speeds by utilizing relay assistance.

3. Throughput Analysis:

In a communication network, the successful data delivery is defined as the throughput. In an UAV based FANET, throughput depends on the successful data transmission, collision and blockage probabilities and also data transmission rate, transmission duration and error probability. This section provides the provides the mathematical analysis of throughput based on all the required probabilities.

a. Path Loss in the THz Band: Path loss in the THz band refers to the reduction in signal strength as a THz wave propagates through the medium. It occurs due to factors like spreading loss, molecular absorption, and scattering in the atmosphere. In mathematical terms, path loss (P_L) in the THz band is given by:

$$P_L = \frac{1}{G_T G_R (H(f))^2} \quad (1)$$

Where G_T and G_R are the antenna gains and H(f) is the system response and is given as

$$H(f) = \frac{c}{4\pi f d} e^{\left(-\frac{k_a f d}{2}\right)} \quad (2)$$

b. Transmission Probability (τ): Transmission probability (τ) represents the chance that a UAV node attempts to send data in a given time slot. It is an important factor in cooperative MAC protocols for THz-based UAV networks, helping to balance network efficiency and avoid collisions, which is given as:

$$\tau = \frac{2}{1+CW+m_r CW/2} \quad (3)$$

c. Probability of Collision (Pc): Probability of collision (Pc) represents the likelihood that a data packet transmission from a UAV node collides with another transmission in the network. In THz-based UAV communication, where multiple UAVs share the same channel, collisions can lead to packet loss, retransmissions, and network delays. The formula for collision probability is given as:

$$P_c = 1 - (1 - \tau)^{N-1} \quad (4)$$

d. Busy Channel Probability (P_b): Busy channel probability (P_b) represents the likelihood that at least one UAV in the network is transmitting at a given time. It helps measure how often the communication channel is occupied, which impacts network congestion, delay, and efficiency. The formula is given as :

$$P_b = 1 - (1 - \tau)^N \qquad (5)$$

e. Successful Transmission Probability (P_s): Successful transmission probability (P_s) is the probability of a UAV successfully transmitting a packet without collision. It depends on N, τ, and P_b. Higher N or τ increases collisions and reduces Ps. Optimizing Ps in THz-based UAV networks improves data reliability and reduces failures in 6G FANETs. The formula for P_s is given as:

$$P_s = \frac{N\tau(1-\tau)^{N-1}}{P_b} \qquad (6)$$

f. Unsuccessful Transmission Probability (P_{us}): Unsuccessful Transmission Probability (P_{us}) is the probability of transmission failure due to collisions (P_c) or frame errors (P_{ef}) due to fading or noise. Higher P_c or P_{ef} increases P_{us}, leading to more retransmissions. The P_{us} is given as:

$$P_{us} = 1 - (1 - P_c)(1 - P_{ef}) \qquad (7)$$

g. Time Durations for Transmission: It represents the total transmission time, including control packet exchanges and data transmission. Optimizing time reduces latency and improves 6G UAV network efficiency in THz communication. T_c and T_s are the collision and successful data transmission time durations, are given as:

$$T_c = T_{DIFS} + T_{SIFS} + T_{RTS} + T_{delay} \qquad (8)$$

$$T_s = 2T_{DIFS} + 5T_{SIFS} + T_{RTS} + T_{CTS} + T_{OTR} + T_{RRR} + T_{ACK} + \frac{2L}{R_d} \qquad (9)$$

where T_{DIFS}, T_{SIFS}, T_{ACK}, T_{Delay}, T_{RTS}, T_{CTS} , T_{OR}, and T_{RRR} are the time durations of DIFS, SIFS, ACK, delay, RTS, CTS, OR, and RRR, respectively. L and R_d represent the packet size and data transmission rate, respectively.

h. Optimal Relay Selection Probability (P_{or}): Optimal Relay Selection Probability (P_{or}) is the probability of selecting the best relay for transmission. N represents total relays, R_{no} is optimal relays chosen. Higher R_{no} increases P_{or}, improving transmission reliability in 6G THz UAV networks. The probability of selecting an optimal relay increases with the increase of relays, which is given as:

$$P_{or} = 1 - \frac{N - R_{no}}{N},\ 0 \leq R_{no} \leq N - 2 \qquad (10)$$

i. Outage Probability (P_{out}): Outage Probability is the probability of SNR dropping below the threshold (γ_{th}), causing transmission failure, The P_{out} depends on average SNR ($\overline{\gamma}$), which is given as:

$$P_{out} = P(\gamma < \gamma_{th}) = 1 - e^{-\frac{\gamma_{th}}{\overline{\gamma}}} \qquad (11)$$

j. Throughput Analysis: This equation calculates the throughput (S) of a UAV network by considering successful transmissions, channel conditions, and errors. It factors in data rate, transmission time, and relay selection to determine effective data transfer. The goal is to optimize network performance by reducing errors and improving efficiency.

$$S = P_s P_b (1 - P_{ef}) \frac{R_d T_d}{T_e(1 - P_{or})} \qquad (12)$$

Hence, eq (12) is used to estimate the throughput of a UAV network.

4. Results and Discussions:

In this section, the simulation results of path loss, outage probability, probability of successful transmission, and throughput are estimated for variable frequencies, transmission distances, SNR, and number of UAVs. We considered a THz frequency range of 1 - 5THz, SNR of 0-30dB, and number of UAVs is 50. Initially we estimated the path loss with path difference and THz frequency. Figure 3. illustrates how path loss varies with frequency in the THz spectrum for different distances (d = 5m, 10m, 20m). As the frequency increases, path loss grows substantially, with greater distances experiencing more significant losses. The relationship is non-linear, indicating that higher frequencies lead to exponentially increasing path loss. This emphasizes the difficulties in using THz frequencies for long-distance communication.

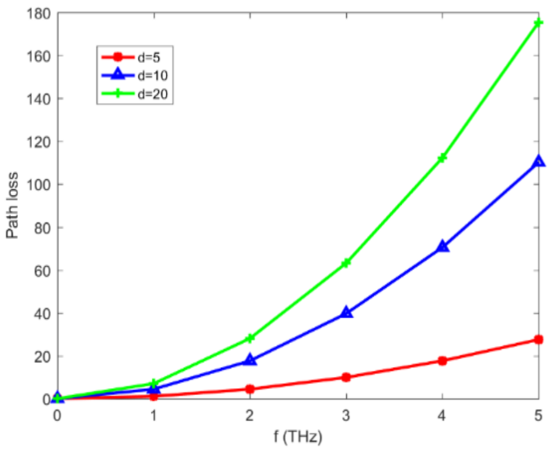


Fig 3. Path Loss with THz frequencies

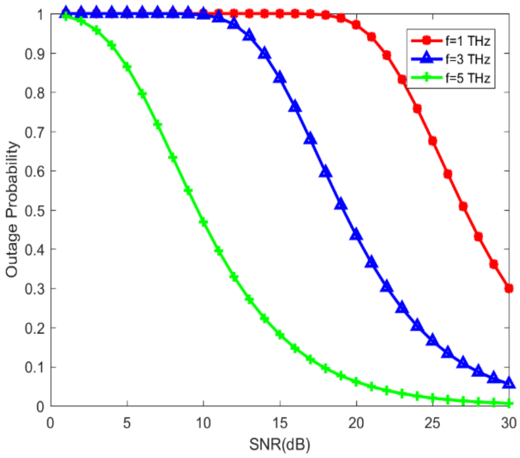
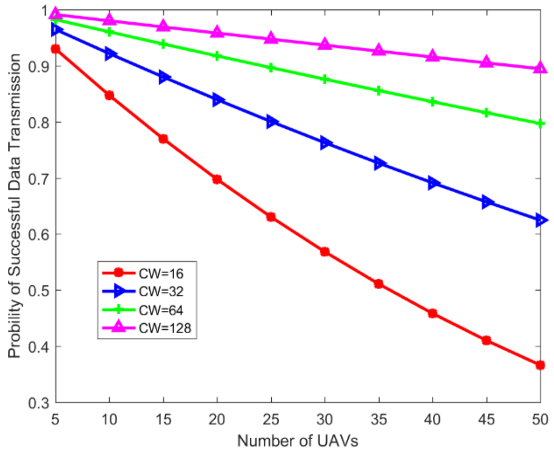


Fig 4. Outage Probability

The Figure 4. shows outage probability vs. SNR (dB) for frequencies 1 THz, 3 THz, and 5 THz. Higher frequencies have lower outage probabilities, meaning better reliability. As SNR increases, outage probability decreases, with 5 THz performing best and 1 THz worst. This highlights the advantage of higher frequencies in improving communication reliability.



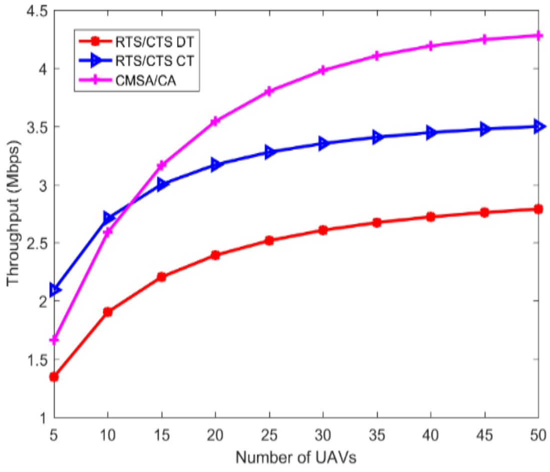


Fig 5. Success Probability with CW

Fig 6. Throughput RTS/CTS CT, DT and CSMA

In Figure 5 represents the successful data transmission probability in relation to the number of UAVs for various contention window (CW) sizes. As UAV density increases, the probability of successful transmission declines across all CW values. Larger CW sizes (e.g., 128) ensure better performance, sustaining higher success rates, whereas smaller CW sizes (e.g., 16) experience a sharper drop. From this figure it is observed that CW size of 32 is considered as an optimal value as it gives the successful data transmission probability of 0.63 to 0.97, which means the minimum probability is more than 60% for less CW size. As the CW size increases the probability also increases but it increases transmission delay, which impacts the system efficiency. This emphasizes the significance of selecting an optimal CW size to improve transmission efficiency in UAV networks.

Figure 6 represents the throughput as a function of the number of UAVs for three different communication protocols: RTS/CTS DT, RTS/CTS CT, and CSMA/CA. As the number of UAVs increases, all protocols experience a rise in throughput, but at varying rates. CSMA/CA demonstrates the highest efficiency, followed by RTS/CTS CT, whereas RTS/CTS DT shows the lowest throughput. This suggests that cooperative transmission and CSMA/CA offer better performance compared to direct transmission. The RTS/CTS provides the better throughput in the CT mode compared to DT mode. Hence, the optimal transmission method is RTS/CTS in CT mode and an optimal CW size is 32.

5. Conclusion:

A cooperative THz communication system for UAV-based FANETs in 6G and beyond is considered and analyzed using the CMSA/CA and RTS/CTS access mechanisms. Outage probability, successful transmission probability and throughput are estimated for variable number of UAVs, SNR and CW size and from the results identified the optimal CW size and access mechanism. From the results, it is observed that the path loss is increases and outage probability decreases with the increased THz frequency. The successful data transmission probability increases with the increased CW size but the network efficiency decreases due to its increase of propagation delay. Cooperative communication has demonstrated superior performance compared to direct transmission. Leveraging collaborative THz communication can significantly enhance the capacity of 6G networks and improve the efficiency of data transmission. Hence, a CW size of 32, maximum number of UAVs as 35 and RTS/CTS-CT mechanism are considered as an optimal values and methods to enhance the throughput and network efficiency. This advancement plays a crucial role in the evolution of wireless communication technologies, benefiting areas such as artificial intelligence, big data, industrial applications, and telecommunications. Further research can focus on optimizing cooperative communication protocols, considering the impact of UAV mobility in dynamic environments, and integrating AI-driven adaptive strategies to improve real-time communication efficiency. These enhancements will be essential for meeting the demands of next-generation wireless networks and advanced applications.

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Data Availability: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflict of interest: The authors declare that there is **no conflict of interest.**

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