Comparative Analysis of BER Performance in UAV-assisted THz Communication Systems with Different Modulation Schemes

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***Abstract*—This paper presents a detailed comparison of bit error rate (BER) performance for three modulation schemes—Pulse Amplitude Modulation (PAM), Quadrature Amplitude Modulation (QAM), and Chirp Spread Spectrum Modulation (CSSM)—in the context of UAV-assisted terahertz (THz) communication systems. As THz communication gains traction for its potential to support ultra-high data rates, understanding the error performance of various modulation techniques is essential for optimizing system design. This study simulates and analyzes the BER performance of PAM, QAM, and CSSM under various signal-to-noise ratio (SNR) conditions, aiming to identify the trade-offs in reliability and efficiency for each scheme. The results indicate that CSSM exhibits superior resilience under noisy and fluctuating conditions, making it the most robust choice for UAV-assisted THz communication. In contrast, QAM performs moderately well at high SNR levels but is less effective in low-SNR environments, while PAM requires high SNR for reliable performance. These findings offer valuable guidance for selecting suitable modulation schemes in THz communication systems, especially for UAV applications.**

***Index Terms*—THz communication, BER, PAM, QAM, Chirp Spread Spectrum Modulation (CSSM)**

I. Introduction

The growing demand for ultra-high data rates and bandwidth efficiency has positioned terahertz (THz) communication as a promising solution for future wireless technologies, including 6G and the Internet of Things (IoT) [1], [2]. The integration of Unmanned Aerial Vehicles (UAVs) in communication systems enhances network flexibility and coverage, particularly when combined with THz communication, enabling UAVs to serve as mobile base stations and relay nodes [3], [4].

While several studies have explored UAV-assisted communications using a variety of technologies [5]–[17], fewer have focused on the comparative performance of modulation schemes in UAV-assisted THz systems. For instance, [6] demonstrated that THz and visible light communication (VLC) systems outperform Free-Space Optics (FSO) and Radio-Frequency (RF) communication under certain conditions, highlighting the potential of hybrid systems in UAV-assisted networks.

In addition, research has shown that UAV networks can be optimized using advanced technologies, such as machine learning and innovative network architectures [8]. These advancements are crucial for enhancing data throughput and reducing bit error rate (BER), particularly in dynamic THz communication environments.

This paper compares the BER performance of three modulation schemes—Pulse Amplitude Modulation (PAM), Quadrature Amplitude Modulation (QAM), and Chirp Spread Spectrum Modulation (CSSM)—in UAV-assisted THz systems. Unlike prior studies on UAV-assisted THz-VLC systems, this work addresses the gap in literature regarding a comprehensive analysis of modulation schemes. By evaluating BER under varying SNR conditions, we aim to offer valuable insights into the trade-offs between reliability and efficiency in THz communication, following a similar approach to [18].

II. System Model

The proposed system model as illustrated by Fig. 1, consists of a UAV equipped with a camera for surveillance, hovering stationary above a house to transmit high-resolution video footage using THz communication. This configuration facilitates a consistent line-of-sight (LOS) communication link between the UAV and the receiving unit in the house, allowing for real-time video streaming with minimal latency. Although the UAV remains stationary, potential misalignment effects due to environmental factors may still impact the communication quality.

A. Channel Model

The gain of the THz channel is modeled as:

$$G_{THz} = g_p \cdot g_a \cdot g_m, \tag{1}$$

where g_p, g_a, and g_m represent the free-space path loss, molecular absorption loss, and misalignment loss, respectively. The free-space path loss g_p is based on the Friis equation, while molecular absorption loss g_a is modeled using an

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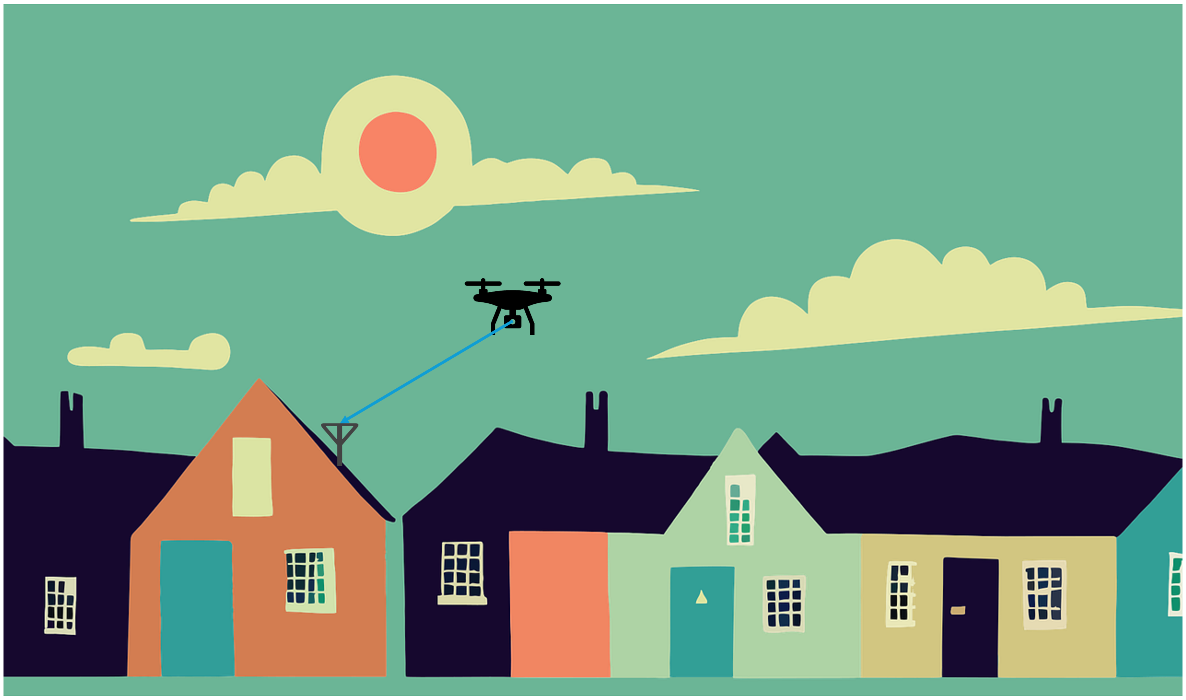

Fig. 1. The System Model.

absorption coefficient $\kappa_a(f)$. Misalignment loss g_m is derived from beam misalignment and approximated using $g_m(s)$ with its PDF expressed as:

$$f_{g_m}(y) = \frac{\eta^2}{B_0^{\eta^2}} y^{\eta^2 - 1}, \quad 0 \le y \le B_0, \tag{2}$$

where η relates the beam width to the pointing error.

III. Simulation Results

The simulation is conducted across a range of signal-to-noise ratio (SNR) values, specifically from 0 dB to 50 dB in increments of 5 dB, to observe the BER performance across low to high SNR conditions. The primary noise considered is thermal noise, which is prevalent in THz communication systems due to the high-frequency band utilized. Additional environmental factors affecting the THz channel include molecular absorption and potential misalignment loss caused by UAV movement and atmospheric disturbances. The UAV, equipped with THz communication modules, is simulated to hover at a fixed altitude, ensuring a consistent line-of-sight (LOS) link with the ground receiver. This setup aims to replicate a realistic scenario where the UAV provides stable THz communication under varying SNR conditions, taking into account the environmental challenges intrinsic to THz frequencies.

Fig. 2 illustrates the BER performance as a function of SNR for three modulation schemes: QAM, CSSM, and PAM.

QAM, represented by the red curve, shows moderate performance with the BER decreasing as the SNR increases, achieving a BER below 10^{-5} at around 40 dB. While it offers a balance between spectral efficiency and BER, it struggles under low SNR conditions, making it more suitable for short-distance or stable line-of-sight communication in UAV-assisted THz systems.

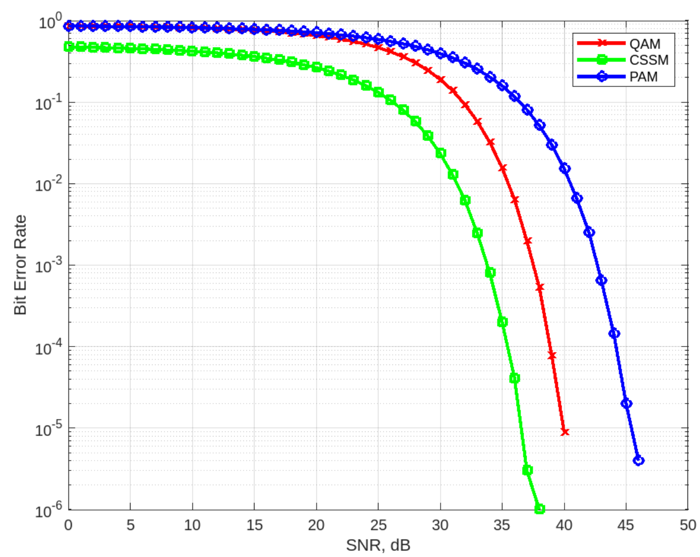

Fig. 2. Comparison of BER performance for QAM, CSSM and PAM modulation schemes

CSSM, shown by the green curve, delivers the best overall performance, achieving a BER below 10^{-5} at 37 dB. Its resilience to noise and adaptability in dynamic environments make it ideal for UAV-assisted THz communication, especially in varying SNR conditions and mobile scenarios.

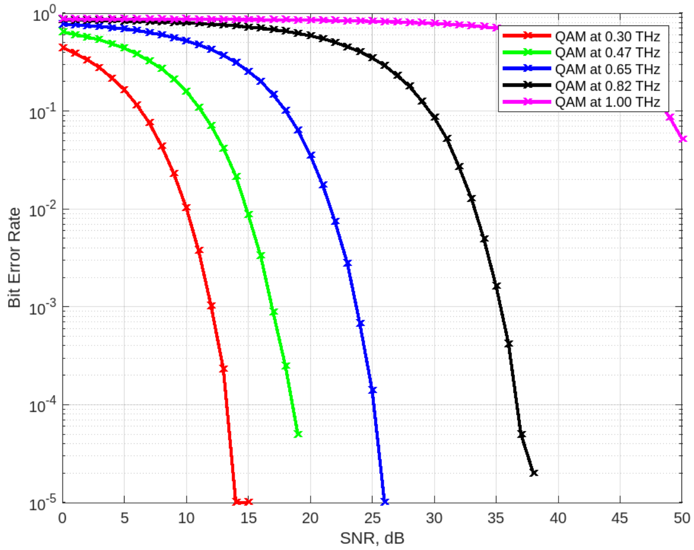

Fig. 3. Comparison of BER performance for QAM under varying frequencies

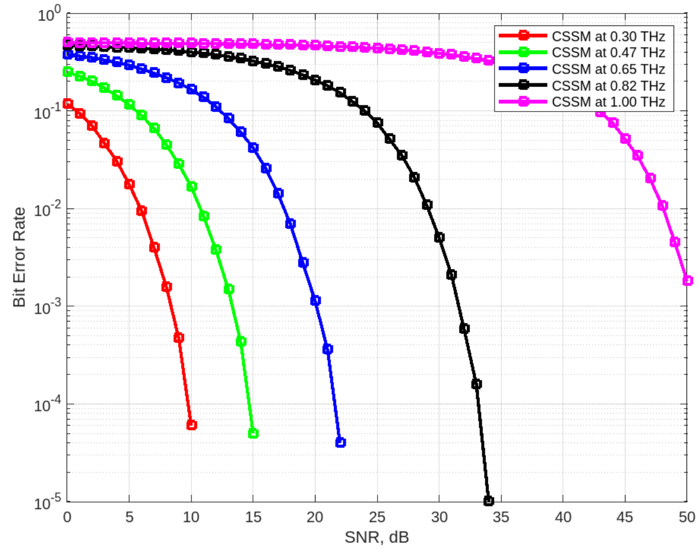

Fig. 5. Comparison of BER performance for CSSM under varying frequencies

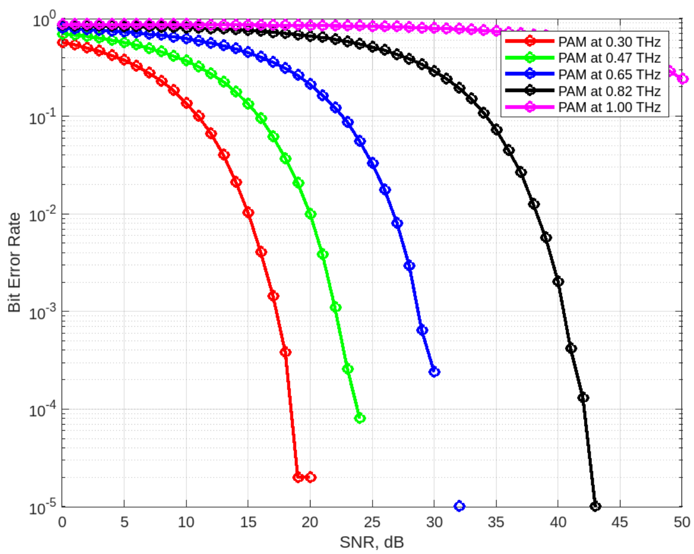

Fig. 4. Comparison of BER performance for PAM under varying frequencies

PAM, represented by the blue curve, provides the poorest performance, requiring an SNR of 45 dB to reach a BER below 10^{-5}. Due to its high susceptibility to noise, PAM is less viable for THz communication unless restricted by system constraints such as short-range, high-SNR applications.

The performance differences among these schemes stem from the THz band's susceptibility to free-space path loss and atmospheric absorption. CSSM's spread-spectrum technique mitigates these issues, excelling in fluctuating UAV channels, while QAM offers high spectral efficiency but is more prone to noise, and PAM lacks error-correction capabilities.

The BER performance comparison for QAM, CSSM, and PAM modulation schemes across different THz frequencies are illustrated in Fig. 3, Fig. 5, and Fig. 4. QAM, as observed, performs well at lower frequencies (0.30 THz to 0.65 THz), achieving a BER below 10^{-5} at moderate SNR levels. However, as the frequency increases (above 0.82 THz), its performance degrades, requiring significantly higher SNR values to maintain acceptable BER levels. This indicates QAM's sensitivity to high-frequency THz channels, making it suitable mainly for short-range or stable link conditions.

CSSM, on the other hand, demonstrates superior performance across the entire frequency range, with notably low BER values even at higher frequencies (up to 1.00 THz) and lower SNR. This highlights CSSM's robustness in challenging environments, such as UAV-assisted communication systems, where the channel conditions may fluctuate due to mobility and environmental factors.

PAM consistently shows the poorest performance across all frequencies, requiring significantly higher SNR values to achieve acceptable BER levels. Its vulnerability to amplitude-related noise and distortions makes it unsuitable for THz communication, particularly in dynamic environments.

While QAM balances spectral efficiency and performance, it demonstrates higher susceptibility to noise, especially in low-SNR scenarios. This susceptibility arises from the modulation's sensitivity to amplitude and phase errors, which are magnified in the THz band where free-space path loss and atmospheric attenuation are significant. Consequently, QAM is most suitable for stable, high-SNR conditions and shorter-range applications in UAV-assisted systems. CSSM outperforms the other schemes in robustness, achieving the lowest BER across varying SNR conditions. This resilience is attributed to its spread-spectrum approach, which enhances noise immunity and adaptability in dynamic environments. The THz band's vulnerability to absorption and misalignment loss is mitigated by CSSM's wide bandwidth usage, making it ideal for UAV applications in mobile or noisy environments. PAM's performance is the lowest among the schemes, as it requires a significantly higher SNR to achieve acceptable

BER levels. Its high susceptibility to amplitude noise makes PAM less viable in THz communication, especially where the environment is prone to rapid changes in signal conditions. Although simpler in design, PAM's lack of spread-spectrum benefits limits its application to short-range or high-SNR scenarios within UAV-assisted systems.

CSSM emerges as the most resilient and efficient modulation scheme for UAV-assisted THz communication, especially in dynamic and noise-prone conditions. QAM can be considered under favorable, stable conditions, while PAM is not recommended unless in short-range, high-SNR scenarios.

IV. Conclusion

This study provides an in-depth analysis of the BER performance of modulation schemes, including PAM, QAM, and CSSM, in UAV-assisted THz communication systems. The results indicate that while QAM strikes a balance between spectral efficiency and performance, it falters at low SNR. CSSM proves to be the most robust, showing strong resistance to noise and misalignment, making it ideal for dynamic UAV environments. PAM, though simpler, underperforms in noisy conditions, limiting its broader applicability. The findings highlight the critical role of choosing modulation schemes based on specific environmental conditions, offering valuable insights for improving UAV-assisted THz communication systems in various applications.

References

[1] D. Serghiou, M. Khalily, T. W. Brown, and R. Tafazolli, "Terahertz channel propagation phenomena, measurement techniques and modeling for 6g wireless communication applications: A survey, open challenges and future research directions," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 1957–1996, 2022.

[2] I. F. Akyildiz, A. Kak, and S. Nie, "6g and beyond: The future of wireless communications systems," *IEEE access*, vol. 8, pp. 133 995–134 030, 2020.

[3] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Communications magazine*, vol. 54, no. 5, pp. 36–42, 2016.

[4] A. Masaracchia, Y. Li, K. K. Nguyen, C. Yin, S. R. Khosravirad, D. B. Da Costa, and T. Q. Duong, "Uav-enabled ultra-reliable low-latency communications for 6g: A comprehensive survey," *IEEE access*, vol. 9, pp. 137 338–137 352, 2021.

[5] A. Patil, M. P, and D. N. K. Jayakody, "Performance of uav networks over the ocean: A perspective towards connected ocean," *Wireless Personal Communications*, pp. 1–20, 2024.

[6] H. Rajahrajasingh and D. N. K. Jayakody, "Unmanned aerial vehicle-assisted terahertz–visible light communication systems: An in-depth performance analysis," *Sensors*, vol. 24, no. 13, p. 4080, 2024.

[7] V. Sharma, D. N. K. Jayakody, and K. Srinivasan, "On the positioning likelihood of uavs in 5g networks," *Physical Communication*, vol. 31, pp. 1–9, 2018.

[8] A. Sharma, P. Vanjani, N. Paliwal, C. M. W. Basnayaka, D. N. K. Jayakody, H.-C. Wang, and P. Muthuchidambaranathan, "Communication and networking technologies for uavs: A survey," *Journal of Network and Computer Applications*, vol. 168, p. 102739, 2020.

[9] H. Rajahrajasingh, D. N. K. Jayakody, P. Muthuchidambaranathan, and R. Dinis, "Hybrid vlc systems with terahertz communication: A performance analysis," in *2024 IEEE 100th Vehicular Technology Conference (VTC2024-Fall)*, 2024.

[10] D. N. K. Jayakody, T. D. P. Perera, A. Ghrayeb, and M. O. Hasna, "Self-energized uav-assisted scheme for cooperative wireless relay networks," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 578–592, 2019.

[11] M. F. Ali, D. N. K. Jayakody, and P. Muthuchidambaranathan, "Revolutionizing firefighting: Uav-based optical communication systems for wildfires," in *Photonics*, vol. 11, no. 7. MDPI, 2024, p. 656.

[12] C. M. W. Basnayaka, D. N. K. Jayakody, and M. Beko, "Freshness-in-air: An aoi-inspired uav-assisted wireless sensor networks," *ICT Express*, 2024.

[13] A. Jeganathan, B. Dhayabaran, D. N. K. Jayakody, S. A. R. Don, and P. Muthuchidambaranathan, "An intelligent age of information based self-energized uav-assisted wireless communication system," *IET Communications*, vol. 17, no. 19, pp. 2141–2151, 2023.

[14] A. Gunasekar, L. B. Kumar, P. Krishnan, R. Natarajan, and D. N. K. Jayakody, "All-optical uav-based triple-hop fso-fso-vlc cooperative system for high-speed broadband internet access in high-speed trains," *IEEE Access*, 2023.

[15] H. Hydher, D. N. K. Jayakody, K. T. Hemachandra, and T. Samarasinghe, "Uav deployment for data collection in energy constrained wsn system," in *IEEE INFOCOM 2022-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 2022, pp. 1–6.

[16] H. Hydher, D. N. K. Jayakody, and S. Panic, "Maximizing the latency fairness in uav-assisted mec system," *IET Intelligent Transport Systems*, vol. 16, no. 4, pp. 434–444, 2022.

[17] T. D. P. Perera and D. N. K. Jayakody, "Aoi-driven swipt-enabled uav trajectory optimization for two-way relaying," *Transactions on Emerging Telecommunications Technologies*, vol. 35, no. 1, p. e4910, 2024.

[18] S. S. Morapitiya, T. Leelarathna, and D. N. K. Jayakody, "Ber analysis in ps-slipt architecture using different modulation schemes," 2023.