2026 5th International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE) | 979-8-3315-6135-2/26/$31.00 ©2026 IEEE | DOI: 10.1109/ICECTE69292.2026.11429420

AFDM-based PD-NOMA for Terahertz Channels

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***Abstract*— The growing demand for highly reliable, high-throughput wireless communication in next-generation networks has spurred the exploration of advanced modulation and multiple access techniques. Affine Frequency Division Multiplexing (AFDM) offers strong robustness against time–frequency dispersion, ensuring reliable transmission over doubly dispersive channels (DDCs), while Power-Domain Non-Orthogonal Multiple Access (PD-NOMA) enhances spectral efficiency by enabling multiple users to share the same frequency resources with different power levels. This paper investigates a unified AFDM-based PD-NOMA framework that combines AFDM's resilience to multipath and Doppler effects with PD-NOMA's efficient spectrum utilization for Terahertz (THz) communication. Performance analysis over THz channels—characterized by ultra-wide bandwidth and support for extremely high data rates—demonstrates that the proposed system can provide massive connectivity along with improved Bit Error Rate (BER) performance and enhanced spectral efficiency, making it a strong candidate for future 6G wireless networks.**

Keywords—AFDM, PD-NOMA, Terahertz channel, 6G

I. INTRODUCTION

The evolution toward sixth generation (6G) wireless communication systems has driven a fundamental shift in modulation and multiple access strategies to achieve higher spectral efficiency, improved bit error rate (BER), and massive connectivity. Traditional orthogonal multiple access (OMA) schemes are inadequate for meeting next-generation communication requirements [1]. Consequently, advanced technologies capable of overcoming time–frequency dispersion, enhancing user multiplexing, and operating efficiently at higher frequency bands have become essential.

Affine Frequency Division Multiplexing (AFDM) has attracted significant attention as a promising modulation technique due to its strong capability to manage high-speed doubly dispersive channels [2]. By employing the discrete affine Fourier transform (DAFT) on the time–frequency lattice [3], AFDM offers improved signal resilience to Doppler effects and multipath delay spreads compared to OFDM, making it well-suited for high-mobility applications where conventional modulation schemes suffer from severe inter-carrier interference (ICI) [4].

In parallel, Power-Domain Non-Orthogonal Multiple Access (PD-NOMA) has emerged as a key enabler of enhanced spectral efficiency and massive connectivity [5]. PD-NOMA allows multiple users to share identical time–frequency resources through power-domain separation supported by successive interference cancellation (SIC), resulting in significantly higher system capacity than traditional OMA. However, its performance deteriorates in environments characterized by severe multipath fading or high time–frequency selectivity [6].

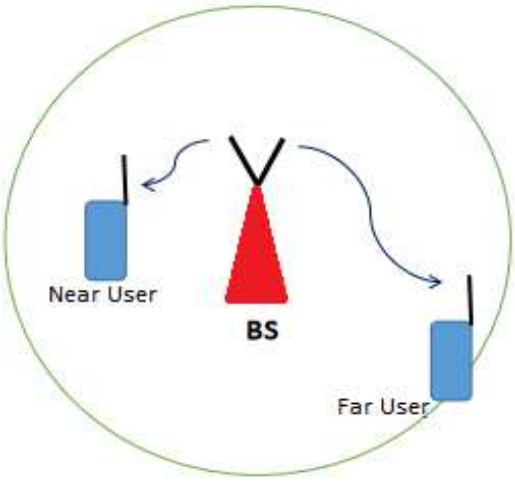


Fig. 1. Single cell with two user scenarios

Integrating AFDM with PD-NOMA creates a powerful architecture for next-generation systems by combining the robustness of AFDM under time–frequency selective channels with the improved spectral efficiency, BER performance, and user multiplexing enabled by PD-NOMA. In this direction, Peng Xu et al. [7] introduced a CSI-based NOMA-integrated AFDM framework for uplink transmission in doubly dispersive channels, demonstrating notable improvements in signal separation, channel estimation accuracy, and data detection through a sparse pilot–aided sensing scheme and iterative estimation algorithm. Their results show enhanced communication reliability and spectral efficiency.

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Additionally, the terahertz (THz) band has been recognized as a promising spectrum for 6G communications due to its exceptionally wide unused bandwidth [8], enabling ultra–high data rates and low-latency transmission. Although it faces challenges such as severe path loss and molecular absorption, the THz channel remains highly suitable for short-range, high-capacity communication links [9], making it an attractive candidate for evaluating AFDM-based PD-NOMA integration.

In this paper, we examine the performance of an AFDM-based PD-NOMA system designed for THz channels, emphasizing its potential to deliver high data rates, improved BER, and enhanced spectral efficiency. Simulation results confirm that the proposed framework efficiently mitigates Doppler and multipath dispersion effects while maintaining high throughput compared to conventional benchmark systems, positioning AFDM-based PD-NOMA as a compelling solution for future 6G networks.

The key contributions of this work are summarized as follows:

a) An AFDM-aided PD-NOMA scheme is developed for THz channels, combining AFDM's resilience to doubly dispersive THz environments with the superior spectral efficiency of multiuser PD-NOMA.

b) The proposed system demonstrates improved BER performance across varying SNR levels, validating the reliability and effectiveness of AFDM-based PD-NOMA for next-generation THz communication.

The rest of the paper is organized as follows. The system model is described in Section II. The performance of the proposed scheme is investigated using numerical simulations in Section III. The limitations and the potential future research directions are outlined in Section IV, while the paper is concluded in Section VI.

II. SYSTEM MODEL

This section presents the system design and mathematical formulation of the proposed AFDM-based PD-NOMA for the Terahertz (THz) channel. The model integrates the time–frequency dispersion strength of AFDM with the high spectral efficiency of PD-NOMA to achieve reliable and high-capacity communication for 6G wireless systems. The design flow of the proposed AFDM-based PD-NOMA for the Terahertz channel is shown in Fig. 2.

A. AFDM Signal Representation

AFDM was introduced to handle the problems that OFDM faces in fast-moving environments, where channels change quickly over time and frequency. Its chirp-based signals are more flexible to Doppler shifts and interference, making communication more reliable. This robustness also makes AFDM suitable for combining sensing and communication in high-mobility scenarios.

Information symbols are transmitted over an affine time–frequency lattice, which provides improved robustness against doubly dispersive channels in AFDM. [10]. Let the input data vector be represented as follows:

$$x = [x_0, x_1, \ldots, x_{N-1}]^T \quad (1)$$

where x denotes the modulated symbol corresponding to the k^{th} subcarrier. AFDM signal in the discrete domain is expressed as:

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x_k \; e^{j2\pi\left(\frac{ak^2}{2N} + \frac{bkn}{N}\right)}, \quad (2)$$

where $n=0,1,\ldots,(N-1)$ and $s[n]$ represents the transmitted AFDM signal sample at the n^{th} instant. k is the subcarrier index, which indicates the symbol position in the frequency domain. N is the total number of subcarriers or data symbols transmitted in one AFDM block. T represents the sampling period related to each discrete time sample, such that the total AFDM frame duration is $N \times T$.

AFDM maps data symbols onto a curved (affine) time–frequency grid, which results in improved performance for Doppler and delay spread [10]. On the other hand, OFDM uses a linear frequency grid. The exponential term in the AFDM expression acts as a discrete linear chirp, which allows the signal to remain approximately orthogonal even under severe channel dispersion. [11].

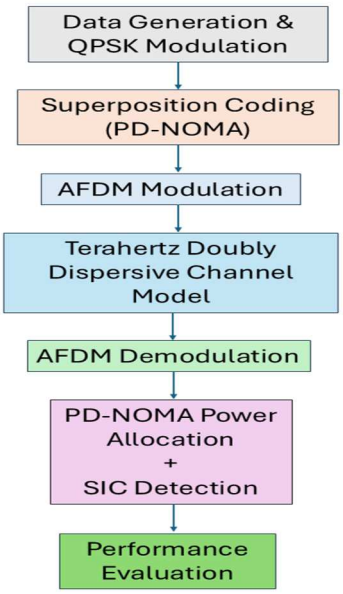


Fig. 2. Schematic Diagram of the Proposed System

B. PD-NOMA Transmission Scheme

Multiple users transmit simultaneously over the same AFDM subcarriers in Power-Domain Non-Orthogonal Multiple Access (PD-NOMA). The received signal at user U_i can be represented as

$$y_i = h_i x + w_i \quad (3)$$

where $x = \sum_{i=1}^{N} \sqrt{P_i} S_i$ indicates the superimposed signal transmitted by the BS, with S_i being the signal for user U_i, and w_i represents the additive white Gaussian noise (AWGN) of user U_i. Users with a weaker channel (far user) are assigned higher power [12].

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In PD-NOMA, the total transmit power P_{total} is divided using power allocation factors $\alpha_1$and $\alpha_2$for two users. That means, we have:

$$P_1=\alpha_1 P_{\text{total}}, \quad P_2=\alpha_2 P_{\text{total}}, \qquad \alpha_1+\alpha_2=1 \tag{4}$$

Typically, $\alpha_1 > \alpha_2$ for the far user [13].

C. Channel Models And Received Signal

The transmitted signal is affected by the wireless channel before reaching the receiver. The signal received over the time-selective channel given by

$$y(t) = h(t)x(t) + n(t) \tag{5}$$

where $y(t)$ is the received signal, $x(t)$ is the transmitted signal, $h(t)$ is the time-varying channel gain, and $n(t)$ represents additive noise [14].

Multipath propagation causes different frequency components of the signal to experience different gains in a frequency-selective channel. Hence, we can write

$$y(t) = \sum_{l=0}^{L-1} h_l x(t-\tau_l) + n(t) \tag{6}$$

where h_l and τ_l are the gain and delay of the l^{th} path, respectively [15].

A doubly dispersive channel (DDC) combines both time and frequency variations, which means it accounts for both Doppler shifts and multipath effects simultaneously. This may also be modeled similarly to (6). However, each multipath component $h_l(t)$ varies over time, and hence can be written as

$$y(t) = \sum_{l=0}^{L-1} h_l\,(t)x(t-\tau_l) + n(t) \tag{7}$$

Note further that each multipath component $h_l(t)$ varies over time. These models form the foundation for analyzing communication performance in dynamic wireless environments [16].

The THz channel is specified by a high path loss and frequency-selective fading [7, 17]. Its impulse response can be represented as:

$$h(t,\tau) = \sum_{p=1}^{P} \alpha_p\, e^{j2\pi v_p t \delta(\tau-\tau_p)} \tag{8}$$

where P indicates the number of multipath components, α_p the complex gain, τ_p the delay, and v_p the Doppler shift. The path loss is modeled as:

$$L_{THz}(f,d) = \left(\frac{4\pi f d}{c}\right)^2 e^{K_{abs}(f)d} \tag{9}$$

where f indicates the carrier frequency, d represents the distance, c is the speed of light, and $k_{\text{abs}}(f)$ denotes the molecular absorption coefficient.

D. Received Signal Processing

The received signal is expressed as

$$y[n] = \sum_{p=1}^{P} h_p\, s_{PD-NOMA}[n-\tau_p] e^{j2\pi v_p n T_s} + w[n] \tag{10}$$

where T_s denotes the sampling period and $w[n]$ is the additive white Gaussian noise (AWGN). At the receiver, AFDM de-chirping and inverse discrete affine Fourier transform (IDAFT) are applied to recover the transmitted symbols.

Successive interference cancellation (SIC) in this NOMA scenario works by decoding the strongest user's signal first, subtracting it from the combined received signal, and then decoding the weaker user. This allows multiple users to share the same frequency without major interference. It's the property of PD-NOMA that improves spectral efficiency and supports reliable communication for users with different channel conditions.

III. NUMERICAL RESULTS AND DISCUSSION

The performance of the proposed AFDM-based PD-NOMA system for the THz channel is evaluated using the parameter values listed in TABLE I.

TABLE I. Simulation Parameters of the Proposed AFDM-Based PD-NOMA for THz channel

Description	**Value**
AFDM block size	64
Number of AFDM frames	500
QPSK modulation order	4
Power allocation for the far user	0.75
Power allocation for the near user	0.25
Transmit SNR range	0:2:30 dB
Number of multipath components	4
Maximum delay spread	4 samples
Maximum Doppler shift	2×10^4 Hz
Carrier Frequency	0.3 THz
System Bandwidth	1 GHz

Specifically, the AFDM block size of 64 is chosen as a balance between complexity and performance, which is large enough to provide good frequency resolution. 500 AFDM frames ensure enough averaging for reliable simulation results without extra computation time. QPSK modulation (order 4) is selected for its simplicity and robustness in high-mobility channels, which ensures a good trade-off between spectral efficiency and error performance. For power allocation, the far user is given 0.75 of the total power and the near user 0.25. It's the PD-NOMA principles in which far users need more power to overcome path loss, while near users can achieve reliable performance with less power. The transmit SNR range of 0–30 dB covers both low and high SNR scenarios, which allows the evaluation of system performance under realistic conditions. The number of multipath components (4) represents a typical urban scattering environment, and the maximum delay spread of 4 samples ensures the channel

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captures frequency-selective behavior. The maximum Doppler shift of 2×10^4 Hz models a high-mobility scenario that tests the robustness of AFDM in doubly dispersive channels. A carrier frequency of 0.3 THz indicates operation in the terahertz band, which supports ultra-high data rates. The 1 GHz system bandwidth offers ample spectral resources for high-speed transmission and provides fine delay resolution, both of which are essential for dense user access and accurate sensing in THz systems.

We investigate the achievable BER and the spectral efficiency of the proposed AFDM-aided PD-NOMA in the THz setting using the simulation parameters shown in Table I.

A. Performance Evaluation: BER Analysis

The achievable BER of the proposed AFDM-based PD-NOMA for the Terahertz channel can be expressed as [13],[18]:

$$\mathrm{BER}_{\mathrm{k}} = Q\sqrt{\frac{2\alpha_k P|h_k|^2}{\sum_{j<k}\alpha_j P|h_k|^2 + N_0}} \tag{11}$$

where $Q(.)$ denotes the Gaussian Q-function, α_k represents the power allocation factor of the user k of the PD-NOMA, P indicates the total transmit power. h_k the effective AFDM channel gain in delay–Doppler (THz doubly dispersive channel). Additionally, N_0 represents noise power, $\sum_{j<k}$ represents residual multi-user interference (removed by SIC for near user).

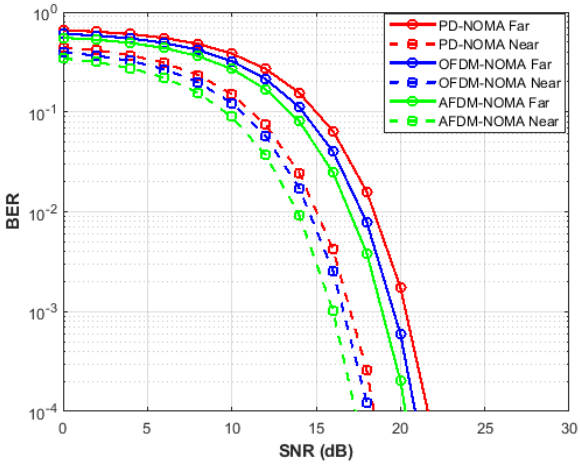


Fig. 3. Bit Error Rate performance of the proposed AFDM-based PD-NOMA for the Terahertz Channel

As shown in Fig. 3 and Fig. 4, the proposed AFDM-based NOMA exhibits improved BER performance compared to conventional PD-NOMA and OFDM-based PD-NOMA for the THz channel. The bit error rate (BER) performance of the proposed AFDM-based PD-NOMA for the THz Channel is shown in Fig. 3, and the bit error rate (BER) comparison of the proposed AFDM-based PD-NOMA with classical PD-NOMA and OFDM-based PD-NOMA for the THz channel is shown in Fig. 4.

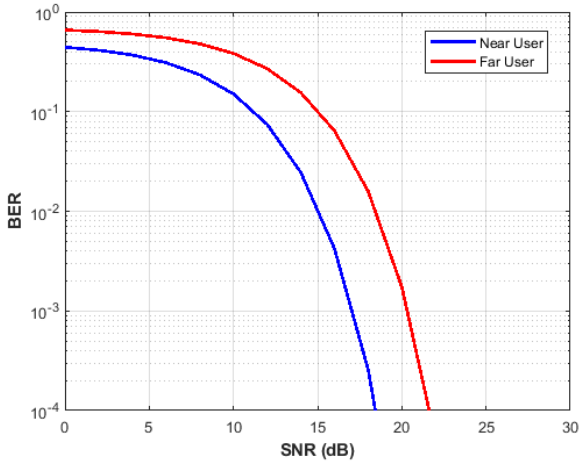


Fig. 4. Bit Error Rate comparison of the proposed AFDM-based PD-NOMA with classical PD-NOMA and OFDM-based PD-NOMA for the THz Channel

B. Performance Evaluation: Spectral Efficiency Analysis

The spectral efficiency (SE) of the proposed AFDM-based PD-NOMA for the Terahertz channel is given by [12], [13],[18]:

$$SE = \sum_{k=1}^{K}\log_2\left(1+\frac{P_k|h_k|^2}{\sum_{j<k}P_j|h_k|^2 + N_0 B}\right) \tag{12}$$

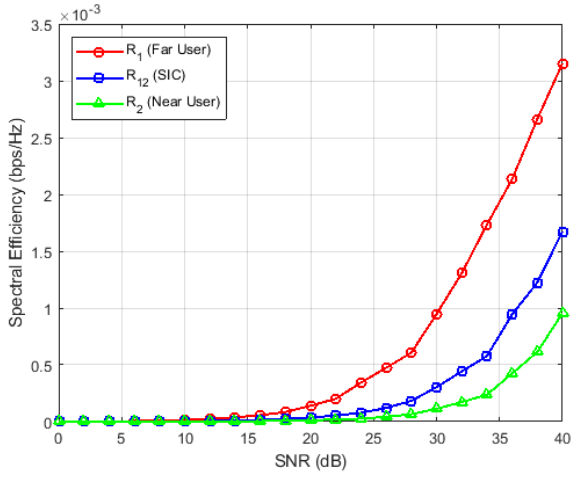


Fig. 5. Spectral Efficiency performance of the proposed AFDM-based PD-NOMA for the THz Channel

The total spectral efficiency performance of AFDM-based PD-NOMA, PD-NOMA, and OFDM-based NOMA systems is compared for a THz channel. As the SNR increases from 0 dB to 40 dB, AFDM-based PD-NOMA consistently achieves the highest total SE among the three models.

This is mainly due to AFDM's ability to effectively handle both delay and Doppler dispersion, which ensures more reliable data recovery in the THz band. On the other hand, PD-NOMA and OFDM-based PD-NOMA show lower SE growth. It's because their conventional modulation schemes are less effective under doubly selective THz channel

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conditions. Spectral Efficiency performance of the proposed AFDM-based PD-NOMA for the THz Channel is shown in Fig. 5, and the total Spectral Efficiency comparison of the proposed AFDM-based PD-NOMA with classical PD-NOMA and OFDM-based PD-NOMA for the THz channel is shown in Fig. 6.

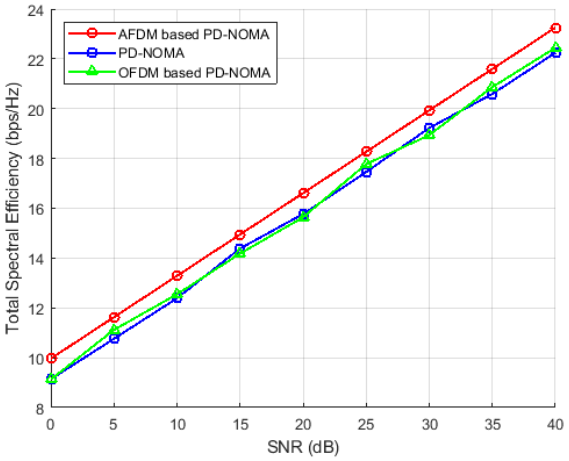


Fig. 6. Total Spectral Efficiency comparison of the proposed AFDM-based PD-NOMA with classical PD-NOMA and OFDM-based PD-NOMA for the THz Channel

At high SNR values, our proposed AFDM-based PD-NOMA achieves a sound performance of approximately 1–2 bps/Hz over PD-NOMA and OFDM-based PD-NOMA, which shows its superior spectral efficiency and suitability for a THz communication environment.

As mentioned previously, the THz band provides a considerably wide bandwidth, but faces severe path loss and molecular absorption [19]. Conventional PD-NOMA and OFDM-based PD-NOMA experience a significant downfall under these effects. However, AFDM-based PD-NOMA maintains better results due to AFDM's dispersion tolerance and PD-NOMA's optimized power allocation. Therefore, the proposed AFDM-based PD-NOMA ensures reliable and efficient transmission even under challenging THz propagation conditions.

IV. Limitations of this Study and Future Directions

This paper provides a rudimentary study on AFDM-based NOMA. A power-domain NOMA has been considered and is investigated for THz channels. However, a power-domain versus code-domain NOMA can be readily studied and compared. No sophisticated power allocation algorithm has been considered, which can obviously improve both the error performance and the achievable throughput. A simple, straightforward successive interference cancellation (SIC) strategy has been investigated, albeit an advanced interference mitigation mechanism can be adopted for the overall performance enhancement of the proposed scheme. More importantly, the THz-specific channel impairments and the THz-related hardware characteristics can be elaborately studied in the near future. In a nutshell, this study opens up the possibility of a range of relevant potential research works.

V. Conclusion

The paper presents a comparative performance analysis of conventional PD-NOMA, OFDM-based PD-NOMA, and the proposed AFDM-based PD-NOMA systems over THz communication channels. The results demonstrate that the AFDM-based PD-NOMA design delivers superior bit error rate (BER) and spectral efficiency (SE), primarily due to AFDM's strong resilience to Doppler and delay dispersion combined with the effective power-domain multiplexing of PD-NOMA. In contrast, both conventional and OFDM-based PD-NOMA systems exhibit higher error rates and reduced throughput under THz channel conditions. The proposed scheme maintains stable and reliable transmission even in highly doubly dispersive environments, enabling efficient utilization of the wide THz bandwidth. These findings position the AFDM-based PD-NOMA model as a promising candidate for short-range, ultra-high-speed 6G communication systems. Future work may investigate hardware implementation, adaptive power-allocation strategies, and the incorporation of MIMO techniques to further enhance overall system performance.

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