Energy Efficient Hybrid Precoding in Terahertz MIMO Systems

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Abstract—**Terahertz (THz) spectrum communication is currently widely used to satisfy the need for ultra-high bandwidth in the future. The Multi-Input Multi-Output (MIMO) technique enhances network capacity by accommodating more users and enabling multiplexing. This study addresses the challenge of optimizing Energy Efficiency (EE) in THz-MIMO systems. Leveraging channel correlation properties, we introduce a THz-MIMO framework that considers both power consumption and implementation complexity. A hybrid precoding strategy based on a sub-connection architecture is adopted to improve system performance. Additionally, this paper thoroughly evaluates key THz precoding algorithms for next-generation 6G networks, highlighting critical challenges and future opportunities. Differences between millimeter-wave and THz channels are explored, alongside challenges unique to THz precoding, such as distance-dependent direction loss, beam split effects, and high-power consumption. To address these issues, three distinct THz precoding systems, including hybrid precoding, are proposed, and their performance is compared to existing methods. Simulation results reveal that the proposed approach enhances energy efficiency, reduces power consumption, and achieves an improved sum rate in THz cache-enabled networks.**

Keywords—**precoding, Terahertz (THz), antenna, energy efficiency**

I. Introduction

Terahertz (THz) communication is emerging as a key technology for future 6G wireless networks, offering the potential to support ultra-high data rate applications due to its vast bandwidth capacity. The shorter wavelength in THz signals allows for high-speed data transfer and exceptional spatial resolution, making it ideal for applications such as wireless backhaul in dense network deployments, real-time VR/AR experiences, and Ultra High Definition (UHD) video streaming. Compared to the present wireless communication spectrum usually seen in smartphones, which can offer enormous transmission capacity, the THz band is three to four orders a magnitude higher [1]. The benefits of THz communication include high capacity, robust confidentiality, and strong anti-interference capabilities. As a result, THz waves enable short-range broadband wireless communication with extremely high data rates. THz communication can achieve wireless transmission rates of tens of gigabits per second in terrestrial wireless communication, which is a major improvement over the state-of-the-art ultra-wideband technology [2].

However, hybrid precoding in THz communications leads to very high energy consumption. To implement analog beamforming in mm Wave communication, phased array-based hybrid precoding requires numerous analog phase shifters. In THz communication, the number of phase shifters increases significantly due to the need for a larger number of antennas to overcome the greater attenuation of THz signals compared to mmWave signals. For instance, mmWave systems typically employ 128 or 256 antennas, whereas THz systems may require 1024 or even 2048 antennas.

Moreover, Multi-Input Multi-Output (MIMO) system precoding has been widely proposed in the low-frequency range as an essential technology to enhance wireless communication capacity. In THz networks, precoding requires a larger antenna array while maintaining lower

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complexity. It is necessary to explore hybrid precoding applied to Terahertz (THz) Non-Orthogonal Multiple Access (NOMA) systems since pure digital precoding is frequently impractical in practice due to the higher baseband processing capability required. In THz, a number of precoding techniques have been suggested.

Numerous data services will be provided by the THz network's wide band, which will result in high transmission costs as well as other expenses. One efficient way to reduce the transmission burden is to cache on the BS side [3]. For cached-enabled systems, numerous precoding techniques have also been put forth. Jeyakumar *et al.* [4] highlighted the importance of caching for low-power, efficient backhaul link networks. In Ref. [5], the precoding challenge in MIMO wireless access networks with cache support was explored. However, there remains a need for further investigation into caching in THz-NOMA networks. The complexity of the system is increased by factors such as the capacity limitations of the fronthaul link, given that the communication capacity of THz networks is substantially higher than that of current wireless access networks.

Although a NOMA caching system based on the THz band can significantly boost data rates, challenges remain in user clustering, precoding, and power optimization. Additionally, THz waves differ from traditional frequency band-based wireless networks due to the high attenuation of the THz band and the limited transmit power of THz transmitters. To overcome the issue of low, transmit power, it is crucial to explore power optimization techniques for THz networks. To meet users' Quality of Service (QoS) requirements, a downlink THz-NOMA system was proposed in Chang and Chiueh [6], addressing related beamforming and resource optimization challenges.

II. Related Work

The frequency range of the THz spectrum is 0.1 THz–10 THz, and it lies between the infrared and microwave spectrums. One of the most intriguing issues with THz is high-speed broadband wireless communication, which uses THz waves as carrier signals. Because of the significant air absorption and scattering of THz signals, the technique works well for short-range, line-of-sight communication. The constraints of the 5G millimeter-wave spectrum and the significance of THz precoding were presented in Ref. [7]. A high data rate cannot be supported by the 5G spectrum. At 0.6 THz, path loss is 120 dB/100 m, rendering THz transmissions challenging. Coverage is challenging because of this loss. This could be reduced with precoding without increasing transmit power.

THz precoding is therefore crucial for upcoming 6G networks [8]. The THz hybrid precoding technology is a flexible and cost-effective system that balances power consumption and performance by combining digital and analog precoding [9]. At THz bands, a method called mMIMO-ISAC (Integrated sensing and massive multiple-input multiple-output, or MIMO) communication. The method uses the sparse nature of THz channels to connect channel and target characteristics across the angular, delay, and Doppler domains.

THz communications can effectively replace Tbps communication in wireless communications due to the abilities of modern technology and signal processing. Sub-6 GHz spectrum scarcity: Jeyakumar *et al.* [10] discussed advanced transmission methods such as THz propagation channel characteristics, NOMA and MMIMO [11]. Massive frequencies above 100 GHz are needed for Tbps communications. Despite the broad range of visible light [12], UV frequencies and infrared, there are difficulties in the optical bands. In Ref. [13], the difficulties of implementing 6G and other mobile technologies—which provide very significant health concerns—were discussed.

Additionally, a system with a single antenna feeder was proposed in Ref. [14], where the antenna feeder directly transmits the modulated signals instead of reflecting them. In this setup, the receiver element is integrated with the transmitter at the Base Station (BS). Achieving analog beamforming with high array gains is difficult in these systems, as they use WF precoding to modulate the radio waves by simultaneously controlling all elements with the same control signals.

Research on resource optimization in THz-NOMA networks has been relatively scarce. This study explores the application of NOMA and THz band technology for user-to-small cell base station communications [15]. In a downlink heterogeneous THz-NOMA-MIMO network, we focus on the resource optimization challenge of hybrid precoding, coupled with power optimization, to enhance the network's energy efficiency.

III. System Model

The primary goal of this work is to maximize spectral efficiency using various matrix factorization techniques. Based on the proposed system and channel model, the achievable spectral efficiency of the hybrid precoding method is analysed. Precoding is a technique that uses broadcast diversity at the transmitter to send many data streams with independent and suitable weighting to the receiver. The distribution of the signals among these antennas and the amount of power that each antenna receives from the transmission are determined by the precoders. There are an equal number of information beams and users because the scenario is MIMO multiuser as illustrated in Fig. 1.

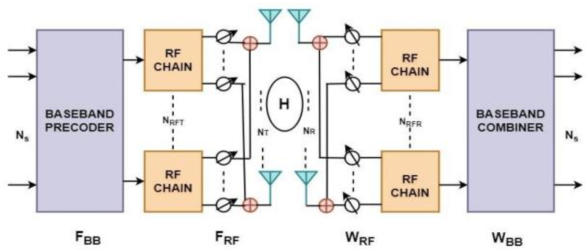


Fig. 1. Structure of proposed model – Hybrid precoding model.

A. Matched Filter (MF) Precoding

By ignoring multi-user disruption, MF boosts received Signal-to-Noise Ratio (SNR). MF precoding can perform effectively in noise-limited conditions (low SNR regimes or large-scale MIMO situations), but its effectiveness is significantly reduced in interference-limited conditions. The MF precoders are the conjugate transpose of the down-link channel matrix and is represented in Eq. (1).

$$W_{MF} = \sqrt{\alpha} H^* \tag{1}$$

The signal power is equalized using the scaling factor α. Next, the received signal vector is given in Eq. (2).

$$Y_{ZF} = \sqrt{\rho\alpha} H^T H^* s + n \tag{2}$$

Through MF, signal gain is enhanced at the intended user. However, when M and K are close, the asymptotic massive MIMO feature does not hold in a degraded massive MIMO scenario. In this case, there is a lot of intruder interference on the system, and the rate per user is low. MF maximizes the signal gain at the intended user. It is the downlink equivalent of the maximal-ratio combining receiver. However, the asymptotic big MIMO feature is broken due to the close values of M and K, leading to a degraded massive MIMO scenario. The system is now experiencing significant intruder interference, with a low rate per user. As the number of base station antennas rises, the channel vectors in H approach mutual orthogonality. As a result, the term $H^T H^*$ approaches a diagonal matrix, leading to the optimal solution [16]. The matched filter offers a low-complexity solution, its performance suffers in interference-rich environments. To address this limitation, we next examine the Zero Forcing technique, which aims to eliminate inter-user interference by inverting the channel matrix.

B. Zero Forcing (ZF) Precoding

Using the zero-forcing (also called null-steering) precoding approach, multiuser interference in a multi-user MIMO wireless communication system can be eliminated. When the transmitter is aware of the channel state information, the pseudo-inverse of the channel matrix offers the zero-forcing precoders. ZF precoding is one well-liked MIMO precoding method. Because of its modest complexity, it is often implemented without having any prior knowledge of noise statistics. Projecting each stream onto the orthogonal complement of the intra-user interference allows interference to be recovered for ZF MU interference.

To retrieve the ZF precoders, using Eq. (3).

$$W_{ZF} = \sqrt{\alpha} H^* (H^T H^*)^{-1} \tag{3}$$

As well as the matching received signal vector represented in Eq. (4).

$$Y_{ZF} = \sqrt{\rho\alpha} H^T H^* (H^T H^*)^{-1} s + n \tag{4}$$

The term $H^T H^*$ forms a matrix diagonal element among the channels, whereas mutual correlations between the channels are characterized by the off-diagonal elements. Highly coupled channels are decorrelated by ZF precoding at the cost of channel capacity [17]. It is the best pre-coding strategy since additive noise is not present. In the presence of additive noise, this precoding technique might make the noise impact worse. Although ZF effectively mitigates interference, it can significantly amplify noise, especially when the channel matrix is ill-conditioned. To overcome this trade-off, the Wiener Filters approach introduces a balance between noise suppression and interference cancellation, as discussed in the following section.

C. Wiener Filter (WF) Precoding

It is one method of precoding that seeks to lower Mean square error between the sending and receiving sequence. Using the huge MIMO-WF, which can also convey a multiple real-valued symbolic representation, two time periods are required to communicate a single complex-valued signal [18].

D. Hybrid Precoding Model

In this section, we first reformulate the hybrid precoding optimization problem. We then introduce the Hybrid precoding method to solve the reformulated problem is represented as flowchart in Fig. 2. Following that, we analyse the complexity of the proposed method. Finally, we discuss how the concept behind the method can be applied to other wireless communication challenges.

Digital precoding optimization as well as analog beamforming optimization are the two processes that can be used to solve the hybrid precoding optimization problem. The low-complexity ZF algorithm; Xie *et al.* [19] employed to optimize digital precoding based on the effective channel. Additionally, we propose the hybrid precoding method, leveraging the impressive performance of classification tasks, to solve the redefined sum-rate maximization problem with significantly reduced complexity and runtime [20]. This method aims to identify the binary pattern within the channel matrix for each diagonal element.

Here, n_n represents Additive White Gaussian Noise (AWGN) and is denoted as $n_u \in r \times 1$.

In this work, we evaluate the proposed hybrid precoding scheme using two key performance metrics: Spectral Efficiency (SE) and Energy Efficiency (EE). These metrics are critical for assessing the overall performance of Terahertz (THz) MIMO systems, where both high data rates and power-efficient operation are essential.

Spectral efficiency, measured in bits per second per Hertz (bps/Hz), quantifies the amount of data that can be transmitted over a given bandwidth. It serves as a fundamental indicator of how effectively the wireless channel is utilized. In the context of hybrid precoding, spectral efficiency is calculated using the Eq. (5).

$$SE = \log_2 \left| I_N + \frac{1}{\sigma^2} H_{eff} F F^H H_{eff}^H \right| \tag{5}$$

where:

I_N is the identity matrix of size N,

H_{eff} represents the effective channel matrix after analog and digital precoding,

F denotes the hybrid precoding matrix, and

σ^2 is the noise power.

This equation specifies the mutual information of the equivalent MIMO channel and reflects the achievable rate under Gaussian signalling.

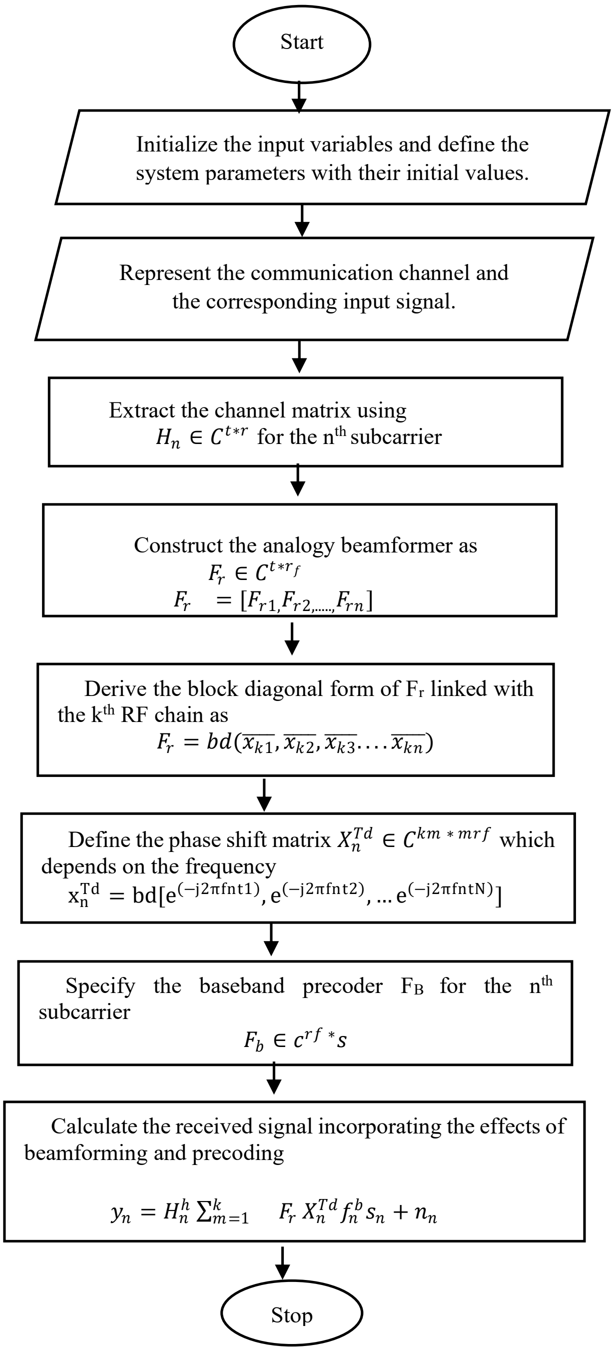


Fig. 2. Proposed hybrid precoding model.

By incorporating this metric into our analysis, we are able to evaluate how the proposed hybrid precoding approach balances spectral performance with power consumption, which is further discussed through the energy efficiency metric in the subsequent section.

Hybrid precoding combines analog beamforming and digital baseband processing to strike a balance between performance and hardware efficiency. The analog precoder, implemented using phase shifters, provides coarse beam steering, while the digital precoder fine-tunes the signal for multi-user or spatial multiplexing gains. This structure significantly reduces the number of required RF chains compared to full-digital precoding, making it cost- and power-efficient for mmWave and THz systems.

The main advantage of hybrid precoding lies in its ability to approach the performance of fully digital systems with far fewer RF chains, especially in terms of Spectral Efficiency (SE) and Sum Rate. Our results in Table I demonstrate that hybrid precoding offers a favorable trade-off between performance and complexity, achieving substantial gains in SE while keeping the hardware requirements realistic for practical implementations.

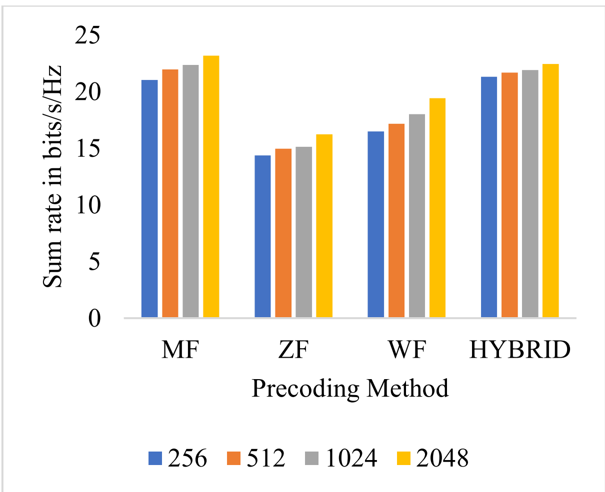
TABLE I. SIMULATION PARAMETERS

Parameters	Value
Number of transmitting antennas	128, 256, 512, 1024
Number of receiving antennas	8
Number of channels	1
Central frequency	140 GHz
Bandwidth B	5 GHz
Number of subcarriers	128
Number of RF chains	4
Number of Time Delay elements	8, 16, 32, 64
SNR	−20 db to 20 db

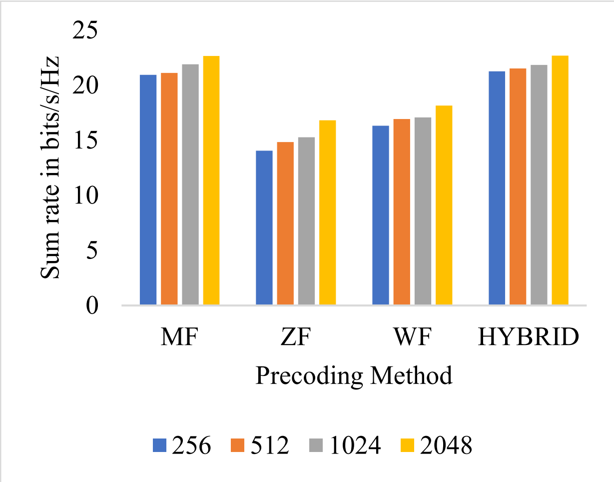
IV. RESULTS AND DISCUSSION

To compare the feasible sum rate of used. precoding methods, including the optimal fully-digital precoding simulation data are presented. The used THz system has a bandwidth of 5 GHz and a carrier frequency of 140 GHz

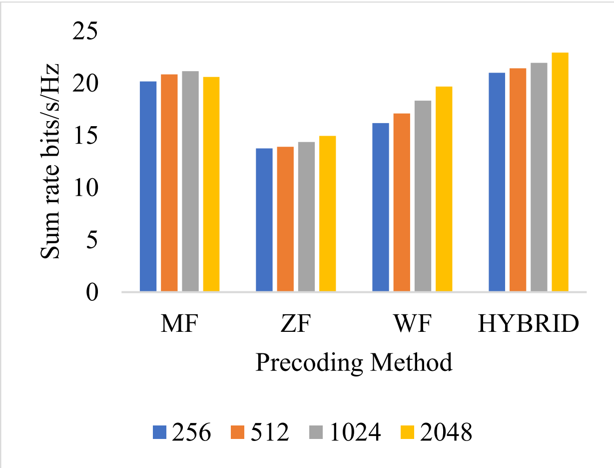
From Figs. 3 (a−d), the proposed method attainable sum rate, ZF, and MF-based precoding have been compared with different time delayers, K = 8, 16, 32 and 64. We conclude that this approach far exceeds earlier techniques, achieving 96% of the optimal precoding.



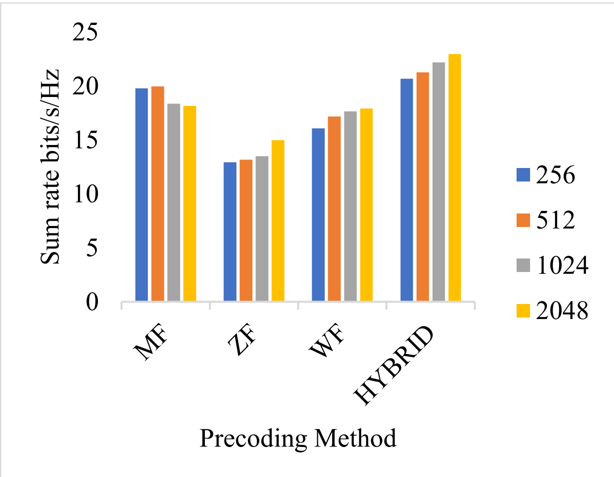
(a)



(b)



(c)



(d)

Fig. 3. Sum rate comparison (a) Matched filter, (b) Zero forcing, (c) Wiener filter, (d) Hybrid precoding.

For K= 8, the recommended method achieves a sum rate of 22.43 bits/s/Hz, which is close to MF precoding at 23.18 bits/s/Hz. For K= 16, the sum rate is 22.69 bits/s/Hz for hybrid, which is near MF precoding at 22.67 bits/Hz. For K=32, the DPP sum rate value is 22.92 bits/s/Hz, nearby MF precoding at 20.59 bits/s/Hz. For K=64, the proposed method accomplishes a sum rate of 22.96 bits/s/Hz, which is close to optimum precoding at 18.14 bits/s/Hz. The comparative analysis of various precoding techniques for 20 dB SNR is presented in Table II.

TABLE II. MAXIMUM ACHIEVABLE SUM RATE FOR PROPOSED METHOD WITH EXISTING METHOD

Precoding method	No of Delays	Number of Antennas			
		256	**512**	**1024**	**2048**
MF	**K = 8**	21.02	21.95	22.37	23.18
	K = 16	20.94	21.13	21.89	22.67
	K= 32	20.16	20.83	21.16	20.59
	K = 64	19.79	19.95	18.37	18.14
ZF	**K = 8**	14.38	14.95	15.13	16.22
	K = 16	14.06	14.83	15.27	16.81
	K = 32	13.75	13.92	14.38	14.94
	K = 64	12.92	13.16	13.49	14.98
WF	**K = 8**	16.48	17.16	18.01	19.43
	K = 16	16.31	16.94	17.09	18.16
	K = 32	16.18	17.09	18.34	19.68
	K = 64	16.07	17.16	17.64	17.92
Hybrid	**K = 8**	21.31	21.67	21.92	22.43
	K = 16	21.25	21.51	21.85	22.69
	K = 32	21.01	21.42	21.94	22.92
	K = 64	20.67	21.28	22.19	22.96

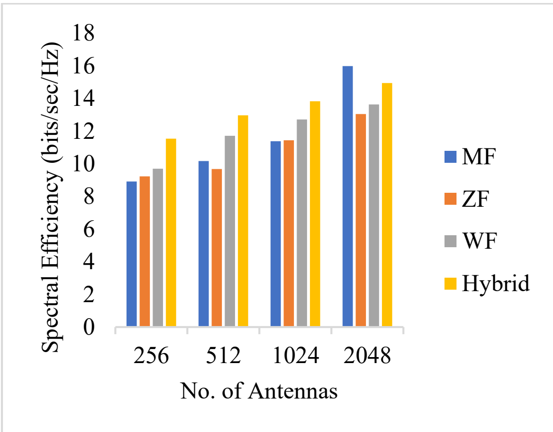


Fig. 4. Comparison of energy efficiency.

Table III compares the performance of different precoding methods — MF, ZF, WF, and Hybrid—across varying numbers of antennas (256, 512, 1024, and 2048). The numbers likely represent performance metrics such as spectral efficiency (bits/sec/Hz), energy efficiency, or another performance indicator. Hybrid Precoding method is the superior method for all antenna counts, combining robustness and scalability. The analysis reveals that Hybrid precoding consistently outperforms other methods across all antenna counts, making it the most robust and efficient choice, particularly for smaller antenna arrays. WF follows closely, offering steady and reliable performance, while MF and ZF lag behind, especially at lower antenna counts. As the number of antennas increases, the performance gap between the methods narrows, indicating diminishing returns for more advanced precoding techniques in massive MIMO systems. Therefore, Hybrid precoding is the optimal solution for achieving high performance, especially in scenarios with constrained antenna resources as illustrated in Fig. 4.

TABLE III. ENERGY EFFICIENCY OF VARIOUS PRECODING TECHNIQUES

Precoding Method	Number of Antennas			
	256	512	1024	2048
MF	8.90	10.15	11.36	15.97
ZF	9.21	9.67	11.42	13.04
WF	9.68	11.71	12.69	13.61
Hybrid	11.53	12.96	13.82	14.93

V. CONCLUSION

The current study developed the channel model and antenna characteristics, assessing user performance in the context of a 6G indoor office network deployment scenario. The feasibility of the proposed approach, which utilizes common frequency-independent phase shifters along with RIS and NF-based precoding to mitigate the beam split effect, was evaluated. The proposed method successfully eliminates the beam splitting phenomenon while achieving a significant performance for K = 8 with N=2048 antennas, according to both theoretical analysis and simulation results. Furthermore, the impact of time delays, the number of transmitting antennas, and carrier frequency of 140 GHz on the total rate effectiveness in a single-cell, multi-user setup was analysed. Future work will expand this study to include a multicellular structure.

CONFLICT OF INTEREST

The authors declare that they have no known com peting financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Radha Krishna Karne: Conceptualization, Methodology, Data Curation; Ashok Battula: Writing − Original Draft, Writing Review and Editing; Kallem Niranjan Reddy: Formal Analysis, Writing; Laxmi Kantha B.: Review and Editing; Kasapaka Rubenraju: Validation, Supervision, Resources, Writing – Review and Editing; Ashok Battula: Visualization, Project Administration; Krishnaveni B. V.: Methodology, Data Analysis; P. Sheker and Damodar S. Hotkar: Writing – Review and Editing; all authors had approved the final version.

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