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Improving the Performance of Cell-Edge Users in 6G and Beyond Networks by Utilizing a Novel Precoding-based Hybrid CoMP Transmission Design

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The Matlab simulation codes used to generate the results in this paper can be found at <https://researcherstore.com>

ABSTRACT The rapid growth of mobile traffic is driving the development of cellular communication technologies to massively improve the high-end communication experiences such as high throughput, high reliability, and universal access. To accomplish these demands in a cellular environment is a huge challenge and it is more critical at the cell edges infected with interference. Moreover, if the users have poor channel conditions, they experience even more severe degradation due to inter-cell interference that creates a bottleneck in wireless systems. Besides, neither time/frequency division multiplexing nor power control has achieved the full promise of spectral efficiency. Due to differences in transmission power and channel gain in heterogeneous networks, interference cancellation-based transmission techniques have great opportunities to increase throughput. Therefore, to meet the quality of service (QoS) requirements, user equipment devices (UEs) must be assigned a significant amount of power. To address these requirements and challenges, we propose a novel hybrid coordinated multi-point (H-CoMP) design for cell-edge users to combat inter-cell interference (ICI), inter-user interference (IUI), and improve spectral efficiency. Specifically, channel-based precoders are designed to deal with ICI, remove channel effects and provide reliable communication to cell-edge users. Mathematical models and simulations highlight the inventiveness and efficiency of the proposed H-CoMP paradigm. The acquired results show the performance of the proposed solution and the ability to reduce system complexity leading to enhanced overall system performance.

INDEX TERMS Coordination multi-point (CoMP), cell edge, multi-user, reliability, spectral efficiency, precoding, wireless communication, physical layer security, 6G and beyond networks.

I. INTRODUCTION

The 2030th era will be governed by the emergence of never before seen applications with unprecedented performance requirements that will accelerate the uprise of 6G technology even earlier. The use cases of future 6G systems are extreme data rates, enhanced spectral efficiency and coverage, very wide bandwidths, enhanced energy efficiency, ultra-low latency, and extremely high reliability. However, it is highly unlikely that all of these use cases

will be available simultaneously but each will represent its own different key performance indicators (KPIs) [1].

These KPIs will govern the direction of wireless communication network design, increasing network requirements and introducing new challenges that need to be addressed. A few challenges are excessive inter-cell interference, network domain coverage, mobility handling, deterioration in data rates at the cell edges. To resolve these challenges a coordinated multi-point (CoMP) design was introduced where

multi-transmit points coordinate (joint transmission) with each other to reduce the interference and improve coverage [2]. However, conventional CoMP cannot mitigate interference and improve throughput at the cell edges. Especially the signal-to-interference-plus-noise ratio (SINR), which is extremely low at the cell edges, and there is no significant increase in the performance even with the several numbers of antennas [3].

Moreover, in the literature, several techniques were presented to cope with scenarios like handling of scattered interference in time division duplex (TDD) downlink multi-cell multiple-input multiple-output (MC-MIMO) systems [4], where a user is linked to a different clusters of different base stations (BSs). In [4], the total rate of the network is enhanced due to supervising the added interference at the BSs and the power used by them, at the BSs by designing clusters and precoding matrices. Authors in [5] propose a single codeword transmission design from different transmit points to align the signal to the better eigenmode to achieve higher capacity. However, there is no consideration for the performance at the cell edges.

A precoding scheme proposed in [6], based on Tomlinson-Harashima Precoding (THP), performs minimization of error probability of the system by nonlinear processing and combined channel decomposition. However, this technique doesn't focus on the performance at the cell edges. In [7], authors study the per-cell codebook designs to gauge the local channel state information (CSI) and update the intra-cell geographical relevancy. At the receiver, many components of spatial autocorrelation are derived, when implementing a differential equation to reconstruct itself at the transmitter, this increases the burden on the receiver, thereby increasing complexity.

In ultra-dense networks, users receive multiple signals from different BSs. To handle this scenario, CoMP scheme is utilized. However, due to power constraints posed by CoMP, authors in [8] propose a CoMP design drafted on cell load-aware (CLA-CoMP), which balances the cell load after this, the power allocation is considered. However, the proposed framework increases system complexity and latency. Concerning cell edge user throughput, in [9] authors design a new CoMP transmission technique by utilizing a quasi-orthogonal space-time block code (QO-STBC) to improve throughput performance. But this doesn't decrease the complexity on the user side.

A. INTER-CELL INTERFERENCE CANCELLATION (ICI) TECHNIQUES

Conventional CoMP techniques are classified into joint transmission (JT) and coordinated beamforming (CB) schemes. Precoding researches indicate that JT doesn't affect the average throughput. And the algorithms used in CB are designed on the iterative evaluation that leads to an increase in computational complexity. Therefore, to address these issues, in [10], authors propose an ICI coordination scheme with two stages; the first stage includes employing

JT and the second stage consists of CB linear precoders for reducing the processing complexity. In the study [11], authors present an algorithm for suppressing ICI by joint scheduling method and joint precoding scheme.

In [12], authors talk about a novel user scheduling procedure that includes ICI and intra-cell orthogonality. The reduction in ICI and channel gain at the time of the beamforming results in the improvement of the network's sum rate. The authors in [13] propose coordinated precoding and proactive interference cancellation scheme. In this scheme, known decoding order is used for precoding, focused on improving the sum rate of two users. In [14], a new transceiver design is presented that enables two schemes like pre-designing of time offset preamble and post designing of successive interference cancellation. The two schemes offer synchronization with channel estimation supervised by multi-base stations and eliminate interference from the other BSs while detecting data symbols related to them, respectively.

Authors propose a hybrid interference management framework in [15]. This case study introduces the dynamic enhanced inter-cell interference coordination (eICIC). During the network initialization, virtual cells are established that mimic ultra-dense Heterogeneous Networks (HetNets). The proposed joint dynamic eICIC scheme is employed with beamforming to mitigate ICI and improve throughput. In [16], authors design a precoding scheme based on signal superposition in non-orthogonal multiple access (NOMA) MIMO multi-cellular networks to improve sum throughput. Path following algorithms are generated to produce a simple convex problem instead of an inconsistent and irregular function that suffers from nonconvex constraints.

B. CELL EDGE RELATED PERFORMANCES

ICIC focuses on improving the throughput at the cell edges, which is entirely different from JT. However, in ICIC, the cell edge data rate is enhanced by stopping transmissions from adjacent cell BSs. But this prevention ultimately results in overall system performance degradation [17]. In [17], authors propose a muting/scheduling algorithm that works on the relation such that when muted, the obtained throughput is more enhanced than the non-muted total throughput.

Managing interference has been considered a very important aspect of designing new wireless systems. However, the interference available at the cell edges has been a nuisance for the users located there [18]. To surpass such a harsh interference environment, authors in [18] propose a novel dynamic interference avoidance scheme, which prevents ICI at the cell edges by utilizing inter-cell coordination (ICC). This design consists of two stages, the BS stage and the central controller that connects the other BSs.

C. NOVELTY OF THE PROPOSED DESIGN

- 1) Efficient usage of the network's resources for transmissions to all users at cell edges with improved throughput.

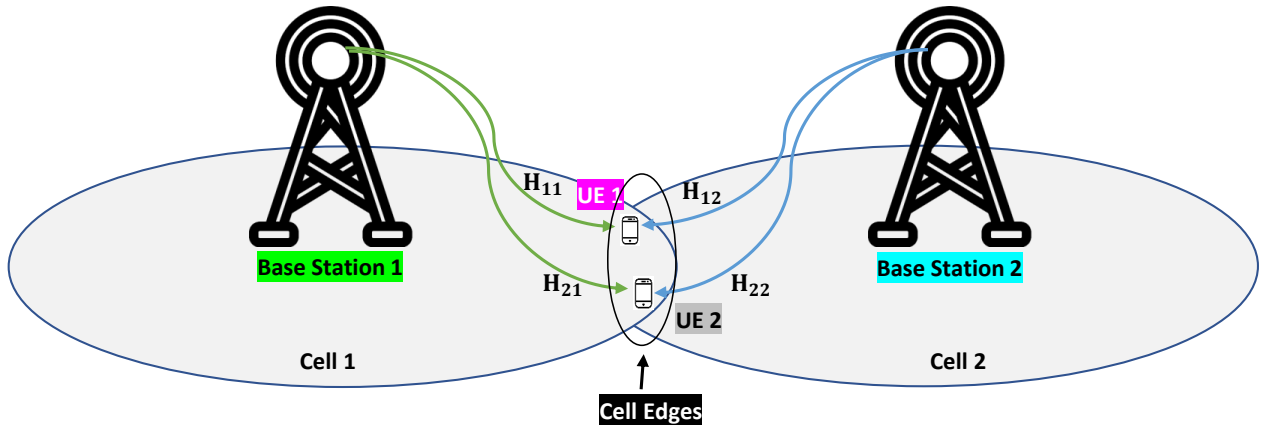


FIGURE 1. H-CoMP proposed description, illustrating two users located at the cell edges served by two BSs.

- 2) Specially designed precoder matrices ($\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3, \mathbf{A}_4$) transmission design for eliminating inter-cell interference at cell edges resulting in significantly reducing complexity at receiver side.
- 3) Joint transmission is employed to achieve multiplexing gain and reliability at cell edges.
- 4) The channel matrices are diagonal making the inverse procedure quite simple. As a result, the precoder matrices can be designed using simple mathematical process.

II. PROPOSED SYSTEM MODEL

The proposed novel H-CoMP scheme is designed for two users. The system consists of two BSs \mathbf{BS}_1 , and \mathbf{BS}_2 that have a single antenna. These BSs are geographically separated and located in two different cells 1 and 2. Fig. 1 presents the illustration of the proposed model, where the BSs in cells 1 and 2 transmit the superimposed [19]–[22] precoded signals that have the same user data for \mathbf{UE}_1 and \mathbf{UE}_2 . The user data symbols are multiplied by precoders $\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3$, and \mathbf{A}_4 [23]. \mathbf{UE}_1 and \mathbf{UE}_2 are located at the cell edges of each cell and attain coverage from both BSs. The BSs adopt JT approach [24], that improves users' reception quality by employing the same transceiver resources for UEs at the cell edges. \mathbf{H}_{km} is the channel frequency response (Diagonal) for the k_{th} user and m_{th} BS during transmission.

Time division duplexing (TDD) system is utilized to estimate the channels at the transmitters by determining the receiver to transmitter channels. The estimated channels are multipath Rayleigh fading channels.

III. PROPOSED ALGORITHM

This section illustrates the derivation of the mathematical algorithm of the proposed system model. This work ex-

plores the use of precoder matrices multiplied with the sum of user data to prevent inter-cell interference at the cell edges, resulting in enhanced performance and decreased complexity at the receiver. The proposed system employs JT from \mathbf{BS}_1 , and \mathbf{BS}_2 . During the transmission process, each BS transmits a signal that contains superimposed user data multiplied with precoder matrices ($\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3$, and \mathbf{A}_4). The downlink transmission from the two separate BSs in two different cells ensures different channels, allowing for the design of precoder matrices that provide reliable communication, mitigate inter-cell interference, and reduce system complexity.

The proposed mathematical framework is given below. As illustrated in Fig. 2, the multi-carrier downlink system has two cells, and each cell has one BS. Furthermore, the system model has two UEs, each with its antenna. BSs transmit superimposed signals to \mathbf{UE}_1 , and \mathbf{UE}_2 , located at the cell edge.

N_f is the number of modulated symbols in a single OFDM block. As a result, each OFDM symbol's frequency response for \mathbf{UE}_1 , and \mathbf{UE}_2 is denoted by $\mathbf{x}_1 = [\mathbf{x}_0, \mathbf{x}_1, \dots, \mathbf{x}_{N_f-1}] \in C^{[N_f \times 1]}$ and $\mathbf{x}_2 = [\mathbf{x}_0, \mathbf{x}_1, \dots, \mathbf{x}_{N_f-1}] \in C^{[N_f \times 1]}$, respectively. The precoder matrices at both BSs are unique for each transmission. The expressions such as $\mathbf{y}_{km} \in C^{[N_f \times 1]}$, $\mathbf{h}_{km} \in C^{[N_f \times N_f]}$, and $\mathbf{z}_{km} \in C^{[N_f \times 1]}$ depict the captured signal, the channel frequency response matrix, and the additive white Gaussian noise (AWGN) between user k and transmit antenna m , respectively. \mathbf{x}_1 and \mathbf{x}_2 are added together after being modified from serial to parallel. Furthermore, before transmitting the intended precoder matrices are multiplied to the corresponding user data symbols.

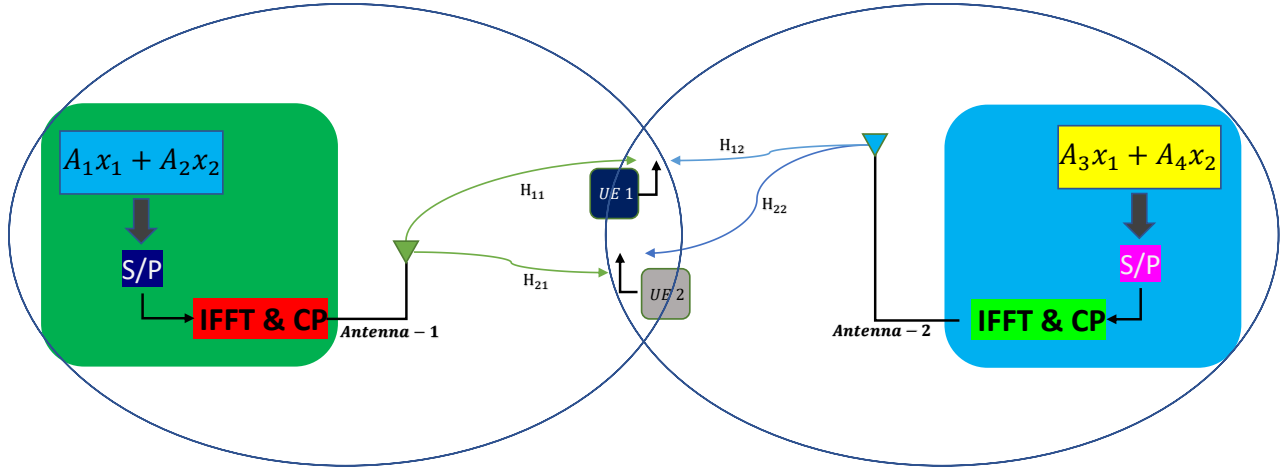


FIGURE 2. Proposed framework utilising precoder matrices with superimposed user data transmitted simultaneously to both UEs.

A. MATHEMATICAL DERIVATION

BS₁ transmits the superimposed signal s_1 as:

$$s_1 = A_1x_1 + A_2x_2, \quad (1)$$

Furthermore, s_2 is transmitted from BS₂ as:

$$s_2 = A_3x_1 + A_4x_2, \quad (2)$$

where x_1 and x_2 are frequency domain data vectors designed for UE₁ and UE₂. Moreover, the precoder matrices such as A_1 , A_2 , A_3 , and A_4 are particularly designed based on the intended receiver's channel. These matrices will make sure that the UE₁ and UE₂ get high quality signals that are free from interference even at the cell edges. The received signals at UE₁ and UE₂ are discussed in the subsequent subsections as well as the precoder matrices.

1) Reception at UE₁

The signal received at UE₁ transmitted from BS₁ is given as:

$$y_{11} = H_{11}s_1, \quad (3)$$

where H_{11} indicates the channel's frequency response between UE₁ and BS₁. Similarly, the signal received at UE₁ from BS₂ is given as:

$$y_{12} = H_{12}s_2, \quad (4)$$

where H_{12} is the channel's frequency response between UE₁ and BS₂. The signals received at UE₁ transmitted from BS₁ and BS₂ are combined together and given as follows:

$$\hat{y}_{r1} = y_{11} + y_{12} + w_1, \quad (5)$$

After putting the values of y_{11} and y_{12} , (5) can be expressed as:

$$\hat{y}_{r1} = H_{11}s_1 + H_{12}s_2 + w_1, \quad (6)$$

where u_1 and u_2 are the transmitted superimposed signals and w_1 is the additive white Gaussian noise (AWGN). By putting the values of u_1 and u_2 in (6), we get (7) as:

$$\hat{y}_{r1} = H_{11}(A_1x_1 + A_2x_2) + H_{12}(A_3x_1 + A_4x_2) + w_1, \quad (7)$$

(7) can be rearranged and combined in a certain way to give the similar terms as:

$$\hat{y}_{r1} = (H_{11}A_1 + H_{12}A_3)x_1 + (H_{11}A_2 + H_{12}A_4)x_2 + w_1. \quad (8)$$

The desired term concerning UE₁ is the first term in (8), whereas the remaining expressions are unwanted. The undesirable terms, channel effects, and inter-cell interference are mitigated and canceled at UE₁ due to precoder matrices.

2) Reception at UE₂

The UE₂ receives the signal y_{21} from BS₁ and is given as:

$$y_{21} = H_{21}s_1, \quad (9)$$

where H_{21} is the channel's frequency response between UE₂ and BS₁. Similarly, the signal received at UE₂ via BS₂ is represented as:

$$y_{22} = H_{22}s_2, \quad (10)$$

where H_{22} is the channel's frequency response between UE₂ and BS₂. The received signals at UE₂ from BS₁ and BS₂ can be represented as:

$$\hat{y}_{r2} = y_{21} + y_{22} + w_2, \quad (11)$$

where \mathbf{y}_{21} is the signal received by UE_2 from BS_1 , and \mathbf{y}_{22} denotes the received signal at UE_2 from BS_2 . By inserting the values of \mathbf{y}_{21} and \mathbf{y}_{22} into the Eq. (11) with \mathbf{u}_1 and \mathbf{u}_2 , the signal $\hat{\mathbf{y}}_{r_2}$ can be written as follows:

$$\hat{\mathbf{y}}_{r_2} = \mathbf{H}_{21}(\mathbf{A}_1\mathbf{x}_1 + \mathbf{A}_2\mathbf{x}_2) + \mathbf{H}_{22}(\mathbf{A}_3\mathbf{x}_1 + \mathbf{A}_4\mathbf{x}_2) + \mathbf{w}_2, \quad (12)$$

Eq. (12) can be further simplified as indicated below.

$$\begin{aligned} \hat{\mathbf{y}}_{r_2} = & (\mathbf{H}_{21}\mathbf{A}_1 + \mathbf{H}_{22}\mathbf{A}_3)\mathbf{x}_1 \\ & + (\mathbf{H}_{21}\mathbf{A}_2 + \mathbf{H}_{22}\mathbf{A}_4)\mathbf{x}_2 + \mathbf{w}_2. \end{aligned} \quad (13)$$

The term related to UE_2 is the second term in the Eq. (14), which is the desired one, whereas the remaining components are undesirable. Likewise, the additional supporting signals will guarantee that undesirable terms, channel effects, and inter-cell interference are eliminated and canceled at UE_2 .

3) Designing the Precoder Matrices

This section illustrates the design of precoder matrices \mathbf{A}_1 , \mathbf{A}_2 , \mathbf{A}_3 , and \mathbf{A}_4 . The design of precoder matrices is motivated by the work in [25]–[27]. The matrices function in such a way that when the transmitted signals are received at the intended UE, the UE doesn't have to do any additional processing and the received signal is free of interference due to the precoders. The precoders are designed based on wireless channel characteristics.

The desired term for UE_1 is the first component of the Eq. (8). To calculate, the precoder matrices \mathbf{A}_1 and \mathbf{A}_3 , the first term of the Eq. (8) should be equated to identity matrix \mathbf{I}_1 , as shown below:

$$\mathbf{H}_{11}\mathbf{A}_1 + \mathbf{H}_{12}\mathbf{A}_3 = \mathbf{I}_1, \quad (14)$$

Also, to remove the unwanted term in Eq. (13), it should be equal to null matrix \mathbf{O}_1 as:

$$\mathbf{H}_{21}\mathbf{A}_1 + \mathbf{H}_{22}\mathbf{A}_3 = \mathbf{O}_1. \quad (15)$$

Similarly, to design \mathbf{A}_2 and \mathbf{A}_4 . The identity matrix \mathbf{I}_2 will be equated to second term in the Eq. (13) which can be seen from (16), and the second term in (8) is equated to \mathbf{O}_2 as shown in (17).

$$\mathbf{H}_{21}\mathbf{A}_2 + \mathbf{H}_{22}\mathbf{A}_4 = \mathbf{I}_2, \quad (16)$$

$$\mathbf{H}_{11}\mathbf{A}_2 + \mathbf{H}_{12}\mathbf{A}_4 = \mathbf{O}_2. \quad (17)$$

By jointly solving the Eqs. (14) and (15) and Eqs. (16) and (17), we can calculate the values of precoder matrices \mathbf{A}_1 , \mathbf{A}_3 and \mathbf{A}_2 , \mathbf{A}_4 respectively, as shown below.

$$\mathbf{A}_1 = \frac{-\mathbf{H}_{22}}{\mathbf{H}_{12}\mathbf{H}_{21} - \mathbf{H}_{11}\mathbf{H}_{22}}, \quad (18)$$

$$\mathbf{A}_2 = \frac{-\mathbf{H}_{12}}{\mathbf{H}_{11}\mathbf{H}_{22} - \mathbf{H}_{12}\mathbf{H}_{21}}, \quad (19)$$

$$\mathbf{A}_3 = \frac{\mathbf{H}_{21}}{\mathbf{H}_{12}\mathbf{H}_{21} - \mathbf{H}_{11}\mathbf{H}_{22}}, \quad (20)$$

$$\mathbf{A}_4 = \frac{\mathbf{H}_{11}}{\mathbf{H}_{11}\mathbf{H}_{22} - \mathbf{H}_{12}\mathbf{H}_{21}}. \quad (21)$$

The Eqs. (18), (19), (20), and (21) represent the precoder matrices value. These precoders will ensure the cell edge users receive reliable signals with fewer complexities and are free from ICI.

IV. EVALUATION OF THE PROPOSED MODEL

This section details the evaluation of the performance of the proposed model.

A. ANALYSING THE PERFORMANCE OF THE UE_1

For the analysis, numerical data fitting method will be used [28]. For each UE, the instantaneous signal-to-noise ratio (SNR) γ_b is calculated. Authors in [28], also mention that to determine the γ_b by numerical fitting approach, power distribution of sub-channels related to each UE has to be calculated. Power distributions of sub-channels are depicted in Figs. 3 and 4.

Firstly, the effective γ_b is calculated than the probability density function of the SNR is determined as:

$$\begin{cases} P_{\gamma_b}(\gamma_b) = D\sqrt{\gamma_b}^{(-1)} \exp\left(-\left(\frac{\Omega}{2\sigma^2\gamma_b} - \frac{\mu^2}{2\sigma^2\gamma_b}\right)\gamma_b\right) \\ D = \frac{1}{4\sigma\sqrt{\frac{2\pi\gamma_b}{\Omega}}} \end{cases} \quad (22)$$

where Ω is the mean square of channel fading amplitude and $\bar{\gamma}_b$ is the average SNR.

By using $P_{\gamma_b}(\gamma_b)$, the value BER can be calculated.

$$BER_{UE_s} = \frac{1}{2} \int_0^\infty \text{erfc}(\sqrt{\gamma_b}) P_{\gamma_b}(\gamma_b) d\gamma_b \quad (23)$$

Now, putting $P_{\gamma_b}(\gamma_b)$ in (22), we get:

$$BER_{\gamma_b} \approx \frac{G}{2\sqrt{\pi}} \left(\frac{\arctan(\sqrt{\xi})}{(\xi)^{3/2}} - \frac{1}{\xi(1+\xi)} \right) \quad (24)$$

where $\arctan(\cdot)$ denotes the inverse tangent function. Eq. (24), denotes the possible BER analysis for UE_1 and UE_2 according to the Figs. 3 and 4.

TABLE 1. Simulation Metrics

Channel	Multipath Rayleigh Fading Channel
Channel Length	9
Cyclic Prefix (CP)	9
FFT Size	64
Modulation Type	BPSK
Guard Interval	16

V. SIMULATION WORKS

In this section, bit error rate (BER), throughput error rate (TER), and peak to average power ratio (PAPR) metrics are explained. Table 1 includes the parameters used in the simulation.

For the simulation, OFDM transmission scheme is utilized which contains $N_f=64$ subcarriers, BPSK modulation, and cyclic prefix (CP) of size L required to cancel inter-symbol interference (ISI). As shown in Table 1, the transmitter and receiving nodes share the same multi-path Rayleigh fading channel that has an equal number of taps $L=9$.

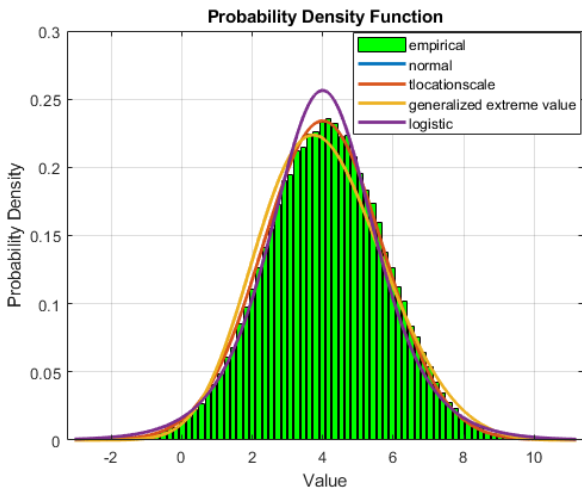


FIGURE 3. Distribution related to power of sub-channels concerning UE₁

Fig. 5 illustrates the BER plots for the system model, theoretical CoMP, supporting signal and theoretical MIMO system with two inputs and two outputs. As seen in Fig. 5, the BER outputs of UE₁ and UE₂ (depicted as proposed User1-BER and proposed User2-BER respectively) perform better than the theoretical CoMP, supporting signals and theoretical MIMO system, By utilizing the precoder matrices ICI can be removed at cell edge, indicating that the new technique can provide efficient and reliable communication.

Fig. 6 illustrates the TER graphs such as the proposed user1 and user2 TERs, proposed total sum TER, theoretical sum TER, and supporting signals TERs and their sum. The proposed TER graphs show that the throughput did not decrease at the cell edges due to eliminating ICI after utilizing the proposed precoders. In Fig. 6, the sum throughput of

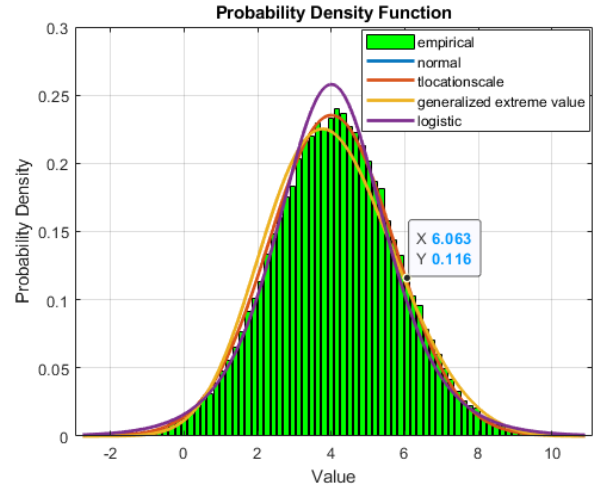


FIGURE 4. Power distribution of sub-channels related to UE₂

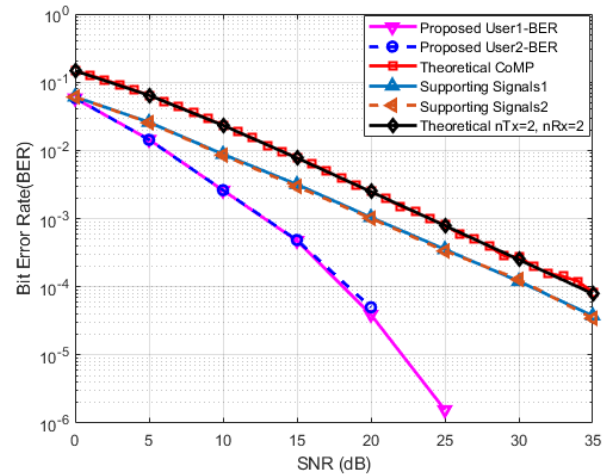


FIGURE 5. BER Vs SNR performance measure for the proposed algorithm

the proposed model is illustrated, which is double the sum throughput of theoretical sum TER. The comparison clearly describes the benefits of the proposed H-CoMP model over conventional system model.

The peak-to-average-power-ratio (PAPR) graphs for proposed Tx₁ and Tx₂, ideal Tx₁ and Tx₂ and supporting signals Tx₁ and Tx₂ are shown in the Fig. 7. At high SNR levels, the PAPR performance of the proposed system beats the ideal system as well as supporting signals, as shown in Fig. 7. The PAPR of the proposed method is less due to specially designed precoder matrices. In conclusion, it tackles one of the most significant issues with the OFDM systems as in [29] by lowering the PAPR, which is highly desirable for low complexity devices and applications.

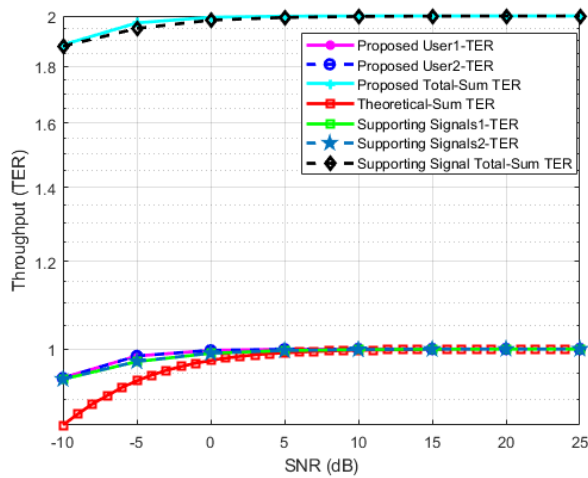


FIGURE 6. TER graphs showing throughputs of different schemes.

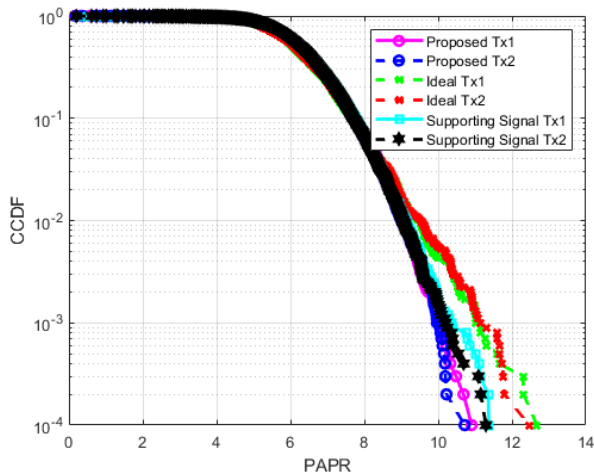


FIGURE 7. PAPR graph showing the effectiveness of the proposed H-CoMP.

VI. CONCLUSION OF THE PROPOSED STUDY

A new H-CoMP communication technique is proposed aimed to disintegrate ICI and enhance throughput at the cell edges while conserving the network's resources. The proposed model consists of two cells with two BS that have two UEs UE_1 and UE_2 at the boundaries of each cell. The precoder matrices are designed based on the user's channels. The proposed model is analyzed and approved mathematical. According to the obtained simulation results, the proposed system provides users at the cell edges with ICI-free communication that has high spectral efficiency. When comparing the proposed model to conventional cell-edge interference reduction techniques, this technology utilizes the least power while providing better reliability with a low degree of complexity and efficient throughput at the cell edges. As a result, the suggested paradigm is well-suited

to IoT applications that need little complexity and power. We intend to improve this communication technology in the future to allow for more than two users.

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