Soft Computing
https://doi.org/10.1007/s00500-023-08464-7

FOCUS

Spectral efficiency enhancement by hybrid pre-coding technique for reconfigurable intelligent surfaces-based massive MIMO systems under variable CSI

A. Helen Victoria[1] · N. Manikanda Devarajan[2] · R. Saravanakumar[3] · Kripa Sekaran[4] · Charanjeet Singh[5] · Vemuri Suneetha[6]

Accepted: 6 May 2023

Abstract

In this paper, we propose a hybrid relay-reflecting intelligent surface (HR-RIS)-assisted cell-free (CF) massive multiple-input multiple-output (mMIMO) network to achieve consistent spectral efficiency (SE). The HR-RIS technique manipulates the propagation environment by reflecting and enhancing radio signals in desired locations, providing a symbiotic integration with CF mMIMO for future wireless communication systems. We first model uplink and downlink channels, obtaining minimum-mean-square-error estimations for efficient transmission paths. We then analyze the SE performance of the proposed system. To enhance sum spectral efficiency in downlink multi-antenna, multi-user, and millimeter-wave massive MIMO networks, we introduce a low-complexity hybrid precoding approach. The optimal analog equalizer is determined by converting the analog precoding matrix dimensions into square matrices and selecting a few discrete Fourier transforms to maximize the amplitude of corresponding wideband channel matrices. We employ the equal gain transmission technique to combine channel gains efficiently and ensure spectral efficiency. To mitigate inter-user interference, we propose an enhanced block diagonalization method for designing the digital precoder and combiner. Our study demonstrates that the proposed HR-RIS-assisted CF mMIMO system offers significant improvements in SE performance, paving the way for advanced wireless communication systems.

Keywords Spectral efficiency · MIMO systems · Discrete fourier transform (DFT) · Reconfigurable intelligent surfaces (RIS)

✉ A. Helen Victoria
helenvia@srmist.edu.in

N. Manikanda Devarajan
nmdeva@gmail.com

R. Saravanakumar
saravanakumarr.sse@saveetha.com

Kripa Sekaran
kripasekaran23@gmail.com

Charanjeet Singh
charanjeet.research@gmail.com

Vemuri Suneetha
suneetha.vemuri@aec.edu.in

[1] Department of Networking and Communications, Faculty of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu, India

[2] Department of Electronics and Communication Engineering, Malla Reddy Engineering College, Medchal-Malkajgiri District, Telangana 500100, India

[3] Department of Wireless Communication, Institute of ECE, Saveetha School of Engineering, Savertha Institute of Medical and Technical Science, Chennai 602105, India

[4] Department of Information Technology, St Joseph's College of Engineering, Chennai, Tamil Nadu, India

[5] Electronics and Communication Department, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, India

[6] Aditya Engineering College, Surampalem, India

Published online: 23 May 2023

1 Introduction

Two notable techniques that will fulfill the demanding range with large connection requests within the sixth generation (6G), as well as upcoming cellular telecommunication networks, seem to be cell-free huge MIMO with reconfigurable intelligence surfaces (RIS) (Shi et al. 2022; Matthaiou et al. 2021). Cell-free huge MIMO technology uses several accessing points (APs) that support a lower number of customers as a workable and sustainable deployment of such dispersed antenna routers (Liu et al. 2020; Chen et al. 2021). Also, all APs have been connected to one central processing unit (CPU) enabling data exchange via broadband cables. The cell-free huge MIMO technology outperforms dispersed methods and networking MIMO setups with regards to 95%-likely networking throughput (Wang et al. 2020).

Upcoming innovations like RIS enable electromagnetic radiation to be transmitted without the use of power amplification or electronic signal computing methods. RISs are customizable meta-surfaces having a large number of inactive reflective parts that may be individually constructed to change the phasing changes of an electromagnetic pulse that twist the reflected wave's stream in a variety of directions (Björnson et al. 2020; Lin et al. 2022a; Wu and Zhang 2020). Subsequent studies have shown the appealing advantages of using RISs for many forms of existent telecommunication, including RIS-aided NOMA networks, RIS-aided mmWave interaction, RIS-aided secured transmitting structures, including RIS-aided huge MIMO structures (Li et al. 2021; Du et al. 2021; Hong et al. 2020; Björnson and Sanguinetti 2020).

The findings of such investigations demonstrated that RIS introduction can enhance effectiveness by predicting better effectiveness and cheaper costs than conventional solutions. The two aforementioned approaches will be combined to form a cell-free huge MIMO network with the help of RIS (Khalil et al. 2021). (Al-Nahhas et al. 2021) have considered and examined the efficiency evaluation of the downstream RIS-aided cell-free huge MIMO employing a randomized beamforming technique. Moreover, the researchers in Zhang et al. (2021) used a cell-free huge MIMO network with numerous RISs to achieve a clear efficiency improvement. In addition, the sum rates optimizing issue was stated and the hybrid beamforming (HBF) method was created in our article. Moreover, in Chien et al. (2022), wherein numerous effect variables upon that network efficiency have been evaluated in depth, the upstream as well as downstream efficiency of RIS-aided cell-free huge MIMO networks under the existence of spatially correlated networks have been taken into consideration. Subsequently, in Zhou et al. (2021), a novel situation known as aerial IRS- (AIRS-) assisted cell-free huge MIMO has been investigated.

The point-to-point mmWave MIMO network was the subject of groundbreaking research on hybrid pre-coding with mmWave networks. The spectrum effectiveness maximization issue for mmWave MIMO networks has been demonstrated to be somewhat solvable by tackling a matrices estimation or reconstructing issue, i.e., reducing the Frobenius standard of such variance among the best FD controller as well as the hybrids combiner. The matrices estimation issue is reinterpreted as a compressive-sensing-like issue by making use of the sparseness of mmWave lines, and this issue is then handled via revised orthogonal matches pursue (OMP) approach. While hundreds of antennae have been utilized at the transceiver's input and output, or if the quantity of RF chains was more than the number of broadcast flows, the OMP approach will function well. The suggested hybrid multiplexing technique still performs much worse than the best FD precoding technique, particularly when the amount of RF networks equals the number of datasets. Thus, several efforts have been done to close this disparity. To estimate the answer to the matrices approximating issue, the researchers suggested utilizing oscillating minimization.

Manifold optimizing has been used to overcome the challenge posed by the unit-modulus limitations and to provide a stable digitized precoder solution for the analogous (or RF) precoder architecture issue. You will find further articles which use matrix estimation. However, as none of the aforementioned techniques explicitly account for such energy limitation during the optimizing process, they all suffer certain efficiency penalties in comparison with hybrids precoding efficiency which is considered to be ideal. This paper suggested a unique hybridization precoding approach, which will roughly handle the spectrum performance maximization issue with mmWave MIMO networks, in contrast to the matrices approximating techniques. Initially, the analog precoding gets separately built by reducing the interaction between the hybrids controller with decoders (or couplers) utilizing various assumptions with massive antenna arrangement. The analog precoder, digitized precoder, analog coupler, then digitized coupler have been then consecutively constructed using electromagnetic precoding. Although it remains a probabilistic approach, experiments show that using the hybrids precoder technique will obtain efficiency which is quite near to such FD precoder capability.

2 Literature review

Telecommunication safety for safeguarding secret signal transfer becomes significantly necessary in prospective Wi-Fi communicating systems because of the growing intricacy of such interaction contexts as well as the necessity of personal data safety (Feng and Wang 2021; Yerrapragada et al. 2021). Physical level safety could offer strong safety achievement by utilizing the features of Wi-Fi connectivity pathways in contrast to its conventional cryptographic encrypting and decrypting stable methodology (Li et al. 2020). This is done without the need for private key dispersion, safety, or monitoring. As a result, research on external-level safety in cellular networking settings is increasingly popular in both academics and enterprises. Multiple antenna Wi-Fi networking technologies in general could increase their physical level concealment by widening the message level gap between the intended client and the listener (Lin et al. 2022b). Thus, secrecy-improving methods such as secret beam formation, fake noisy propagation, collaborative jamming, and energy regulation have also been thoroughly studied in previous times. Massive MIMO may take full advantage of both the benefits of traditional MIMO because it is a programmable MIMO technology. Moreover, several sent antennae could be employed to increase confidentiality. Hence, it may be possible to use physical-level safety in huge MIMO systems. Most of the safety research for massive MIMO often pays close attention to co-located vast MIMO. Subsequently, the multi-cell, vast MIMO devices' safe transmission was investigated. The safety of vast MIMO communication in conjunction with multiple antennas and proactive eavesdroppers has also been thoroughly investigated. In addition, the investigation of safe massive MIMO precoding, energy regulation, relaying networks, and proactive threat identification, including device limitations, another viable large MIMO implementation involves using a so-called dispersed antennae structure that could outperform a co-located huge MIMO device in such a definite way. Moreover, (Zhang et al. 2020a) examined the safety efficiency study in multiple-user large MIMO with great depth. In other similar papers, the safe interaction in cell-free, huge MIMO systems has been investigated. The researchers' main concern was reliable interaction in such a huge MIMO system devoid of cells. Multi-group multipath routing over cell-free huge MIMO has taken safety into account (Zhang et al. 2019). The researchers in Zhang et al. 2020b were engaged in the issue of encrypted transmission within cell-free, vast MIMO systems while taking the effect of equipment limitations into account.

3 System model

To increase the total spectrum efficiency and minimize network cost in such a downstream multi-user, numerous antenna, and huge MIMO network, we present a spectral-efficient hybrid precoding approach. We divided the precoding architecture further into RF precoding and digitized precoding architecture to decrease the application's repetitive procedure while maintaining efficiency. To increase the corresponding frequency stream matrices' amplitude during RF precoding, we double the size of such analog precoding matrices and then choose the best analog multiplexer by choosing a few discrete Fourier transformation bases. Tenth, we immediately combine the network value using the identical amplitude transmitting technique to guarantee the execution of the transfer rate.

In this section, we describe the system model for the proposed HR-RIS-assisted cell-free massive MIMO network.

Network Architecture: Consider a network with a single central processing unit (CPU), M distributed access points (APs) equipped with N antennas each, and K single-antenna user equipment (UEs). Each AP serves all UEs in its coverage area. The HR-RIS is an L-element intelligent surface that reflects and enhances radio signals, aiding in the communication between the APs and UEs.

Channel Model: The wireless channel is modeled as the sum of three components—direct link, AP-to-HR-RIS link, and HR-RIS-to-UE link. The direct link represents the traditional MIMO channel between the APs and UEs, while the other two links represent the channels associated with the HR-RIS reflections. Each component is subject to path loss, shadowing, and small-scale fading.

HR-RIS Model: The HR-RIS is characterized by an $L \times L$ diagonal matrix, where each diagonal element represents the complex reflection coefficient of an individual HR-RIS element. The matrix can be configured to manipulate the phase and amplitude of the reflected signals, optimizing the overall communication performance.

Hybrid Precoding: We adopt a hybrid precoding approach that consists of an analog precoding matrix and a digital precoding matrix. The analog precoding matrix is implemented using phase shifters, while the digital precoding matrix is computed using an enhanced block diagonalization method. This approach reduces hardware complexity and power consumption while maintaining high spectral efficiency.

Signal Model: The received signals at the UEs are the superposition of the signals transmitted from the APs through the direct and HR-RIS-assisted channels. The transmitted signals are pre-processed using the hybrid precoding matrices, and the received signals are post-processed using a combiner at the UEs.

Performance Metrics: The key performance metrics for the proposed system are spectral efficiency (SE) and sum spectral efficiency (SSE), which quantify the network's capacity and overall data rate, respectively.

This system model provides a comprehensive framework for the HR-RIS-assisted cell-free massive MIMO network, incorporating the essential aspects of the network architecture, channel model, HR-RIS configuration, hybrid precoding, signal processing, and performance evaluation.

4 Multi-user massive MIMO system model

Figure 1 shows a downstream communication of such a TDD-dependent multi-antenna huge MU-MIMO network. To interact among K autonomous customers, the base stations (BS) get outfitted using N_t transmitting antennae as well as N_{RF}^t links. To handle N_s transmission flows, every client has $N_{RF}^r RF$ links with N_r receptive antennae. The quantity of transferred streams is capped at $KN_s \leq N_{RF}^t \leq N_t$ for such BS as well as $N_s \leq N_{RF}^r \leq N_r$ for every customer to guarantee that communication becomes effective.

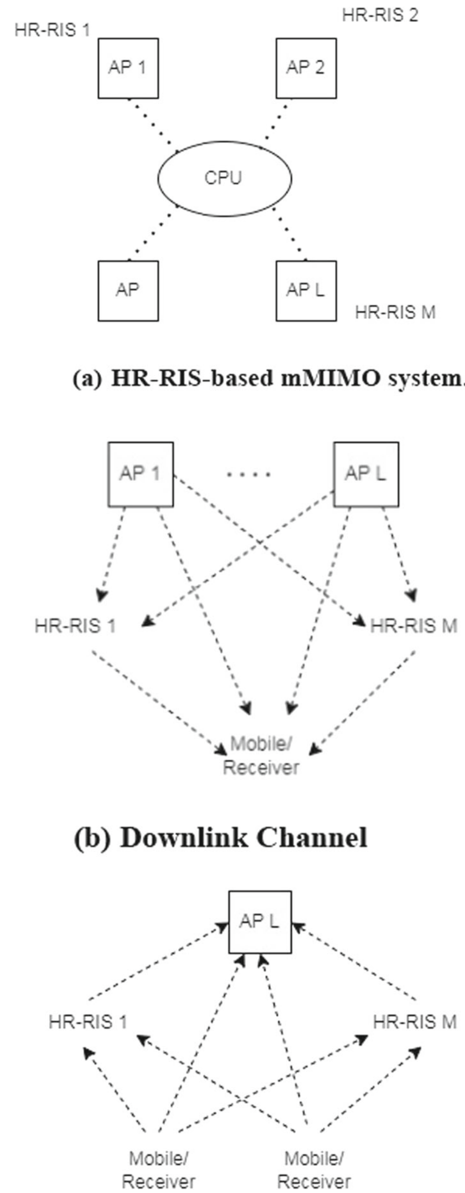
A $N_{RF}^t \times KN_s$ electronic precoder F_{BBk} processes the transferred signals then maps them onto $N_{RF}^t RF$ networks. A $N_t \times N_{RF}^t$ analog precoder F_{RF} processes the signals after number ten. The analog controller will only alter the phasing of the data because it is made up of analog switching devices, while every input of such F_{RF} gets normalized to fulfill $\left|F_{i,j} = \frac{1}{\sqrt{N_t}}\right|$, wherein $|F_{i,j}|$ stands for the intensity of such (i,j)-th component of such F_{RF}. Frequency and phasing adjustments are possible using the electronic precoder F_{BBk}.

We consider $H_k \in C^{N_t \times N_r}$ to be the k th customer's downstream stream matrices. The k th customer's transmitted message will be stated as

$$y_k = H_k F_{RF} F_{BBk} s_k + n_k, k = 1, 2, \ldots, K, \tag{1}$$

which $S \in C^{KN_s \times 1}$ appeases $E[SS^H] = \frac{P}{KN_s} I_{KN_s}$, P denotes the mean transmission energy of such BS, as well as I_{KN_s} seems to be an authenticity matrix. $S = \left[s_1^T, s_2^T, \ldots s_K^T\right]^T$ seems to be the frequency variable of K customers. The matrix of such additional white Gaussian noise (AWGN) with i.i.d. $\mathcal{CN}(0,1)$ is called $n_k \in C^{N_r \times 1}$. The transmitted stream y_k just after merging at k-th customer will be written as

$$\hat{y}_k = W_k^H W_{RFk}^H H_k F_{RF} F_{BBk} s_k + W_{BBk}^H W_{RFk}^H n_k, k = 1, 2, \ldots, K,$$



(a) HR-RIS-based mMIMO system.

(b) Downlink Channel

(c) Uplink Channel

Fig. 1 mMIMO system's HR-RIS, Uplink, and Downlink Channel

wherein W_{RFk} will be $N_r \times N_{RF}^r$ broadband compensator for the such k-th customer as well as W_{BBk} has been the $N_{RF}^t \times N_s$ analog compensator vector.

(2) will be re-expressed that $\widetilde{H}_k = W_{RFk}^H H_k F_{RF}, k = 1, 2, \ldots, K$ if that represents the appropriate broadband stream vector.

$$\hat{y}_k = W_{BBk}^H \tilde{H}_k F_{BBk} s_k + \sum_{i=1, i \neq k}^{K} W_{BBk}^H \tilde{H}_k F_{BBi} s_i + W_{BBk}^H W_{RFk}^H n_k, k = 1, 2, \ldots, K.$$

Hence, the total spectral efficiency of K customers will be written as.

$$R = \sum_{k=1}^{K} \log_2\left(\left| I_{N_s} + \frac{P}{KN_s} R_i^{-1} W_{BBk}^H \tilde{H}_k F_{BBk} F_{BBk}^H \tilde{H}_k^H W_{BBk} \right|\right)$$

while $R_i = \frac{P}{KN_s} \sum_{i=1, i\neq k}^{K} W_{BBk}^H \tilde{H}_k W_{BBk} + \sigma^2 W_{BBk}^H W_{RFk}^H W_{RF} W_{BBk}$ seems to be the correlation matrices of interfering and noises.

5 Channel mode

Network H accepts the geometry network paradigm having L propagating routes [35] also which is described as:

$$H = \sqrt{n_T n_R} \sum_{l=1}^{L} \psi_l a_R(\theta_l) a_T(\emptyset_l)^+ \quad (2)$$

$$= \sqrt{n_T n_R} A_R \psi A_T^+$$

wherein ψ_l stands for the lth propagating map's complicated network conditions. As a result, the l -th route's angle of arriving as well as the angle of leaving become θ_l as well as $\varnothing_l$, respectively. The indices $a_R(\theta_l)$ as well as $a_T(\varnothing_l)$, which represent the antennae matrix replies at the recipient and emitter, correspondingly. $\psi = diag(\psi_1, \ldots, \psi_l)$ represents a lateral array given (2), as well as the arrays $A_R = [a_R(\theta_1), \ldots, a_R(\theta_L)]$ and $A_T = a_T(\varnothing_1), \ldots, a_T(\varnothing_L)$ make up its l -th lateral element, which represents ψ_l.

As separate complicated Gaussian unpredictable factors $\psi \sim \mathcal{CN}(0, R)$, whereby $R = \mathbb{E}[\psi\psi^+]$, the complicated network gains $\psi = [\psi_1, \ldots, \psi_L]^T$ have been described as. Thus, r_l stands for the percentage of the mean absorbed energy that the l-th propagating route provided, where the normalization of $\{r_1\}_{11L}$ is $\sum_{l=1}^{L} r_l = 1$. Without sacrificing flexibility, $\{r_1\}_{11L}$ have been organized to be sorted: $r_1 \geq \ldots \geq r_L$.

Throughout the intervals, both angle-of-arrivals $\{\theta_1\}_{11L}$ as well as the angle-of-departures $\{\varnothing_1\}_{11L}$ seem to be separately and equally dispersed $[-\pi, \pi)$. The antennae element's shape affects how the matrix responds. We focus upon that Universal Linear Arrays (ULAs), as well as the matrix, replies for these, are provided by

$$a_R(\theta_l) = \frac{1}{\sqrt{n_R}} \left[1, e^{i\theta_l}, \ldots, e^{i(n_R-1)\theta_l}\right]^T,$$

$$a_T(\emptyset_l) = \frac{1}{\sqrt{n_T}} \left[1, e^{i\emptyset_l}, \ldots, e^{i(n_T-1)\emptyset_l}\right]^T.$$

It should be noted that now the matrix A_T, as well as A_R, represent the rectangle Vandermonde matrix [36]. When normalized, stream H becomes $\mathbb{E}[Tr(HH^+)] = n_T n_R$.

6 Computational complexity analysis

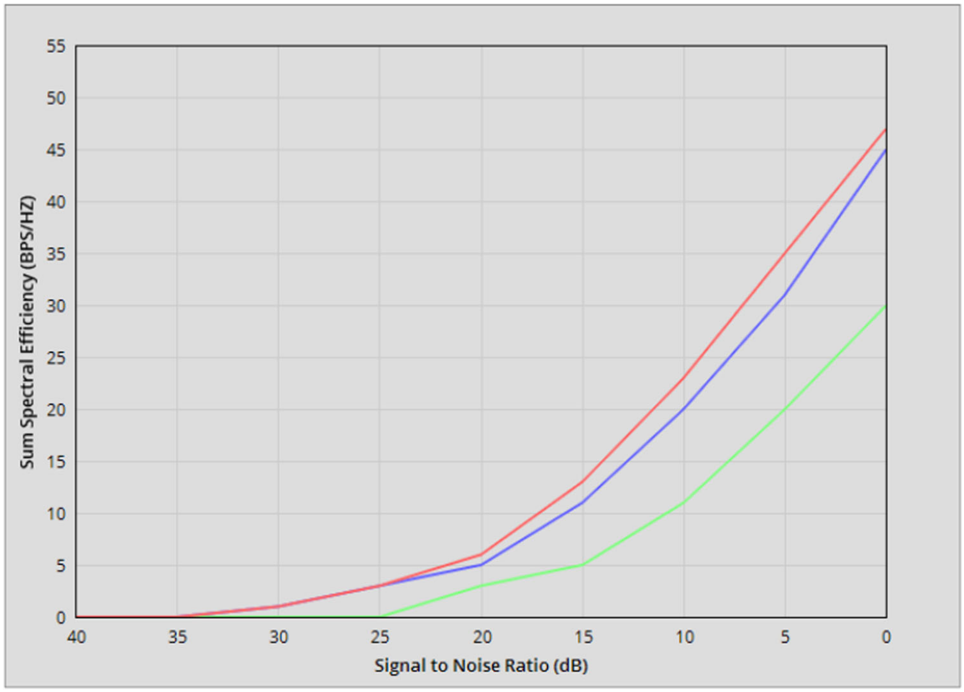
The suggested hybrid precoder method's computing cost gets explained in this part. The allocation of analog precoding as well as the computation of digitized precoding are what add difficulty to the suggested approach. The suggested hybrids precoding gets compared to various existing methods in terms of cost. The most complicated computing approach is this full-digital BD precoders method. We will see that the cost of such suggested BD precoder method is about 67,108,864 opcodes, which is just roughly 0.45% as complicated as the full-digital BD precoding method when we take into account the usual mmWave MIMO network having $N_t = 256$, $N_t = 16$, $K = 8$, Nr = 16, K = 8, $N_{RF}^t = 8$, $N_{RF}^r = 1$.

Our approach will be utilized in multiple antenna multi-user networks having low-cost and good spectrum efficiency, as opposed to the previous hybrid precoder methods depending upon the singular network as well as the single-antenna multi-user networks. The suggested precoder as well as merging approaches will be using a two-stage architecture to prevent high computing costs brought about by non-convex blended numeric enhancement of collaborative enhancement. The suggested methodology accomplishes a tradeoff between scheme effectiveness and difficulty contrasted to the two hybridized precoder methodologies since the multi-user comparable channel grid made possible by suggested analog precoding could effectively collate the stream progress in huge MIMO systems. DFT base is also created to significantly lower the computing cost when contrasted to the conventional EGT methods. Also, the suggested technique will ensure a greater spectrum efficiency capability by fully utilizing the multi-antenna matrix yield that produces larger summation rates. The suggested technique does have the best spectrum efficiency and BER efficiency with the least amount of computing cost when contrasted to as well as the traditional BD precoder methods.

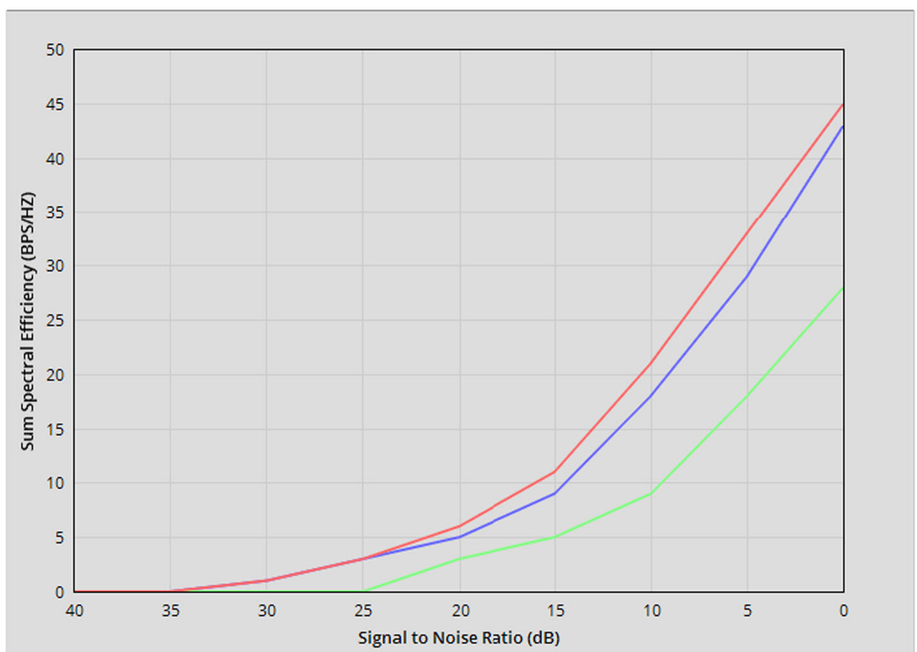
7 Result and discussion

In this part, we contrast the efficiency of the suggested method compared to that of the classic MMSE multiblock hybrid precoding system, the restricted signal hybrid multiplexing strategy, the geographically dense hybrid multiplexing method, as well as the traditional BD

Fig. 2 Sum spectral Efficiency in (**a**) mmWavw channel, (**b**) Rayleigh channel



(a)



(b)

precoding system. The Rayleigh faltering circuit will effectively define the wireless ecosystem with hurdles that will disperse several impulses, so we furthermore offer modeling findings of such spatial efficiency to assess the effectiveness of a suggested hybrid multiplexing system in Rayleigh shrinking stream to confirm the viability of such an automated system in different streams. The clustering mmWave network concept has been used to describe the restricted dispersion property of such mmWave networks in this context.

Figure 2 shows an efficiency distinction of such sum spectroscopy efficiency against this same SNR throughout mmWave broadcaster as well as Rayleigh stream, of Nt = 128 as well as Nr = 16, to confirm the spectroscopic

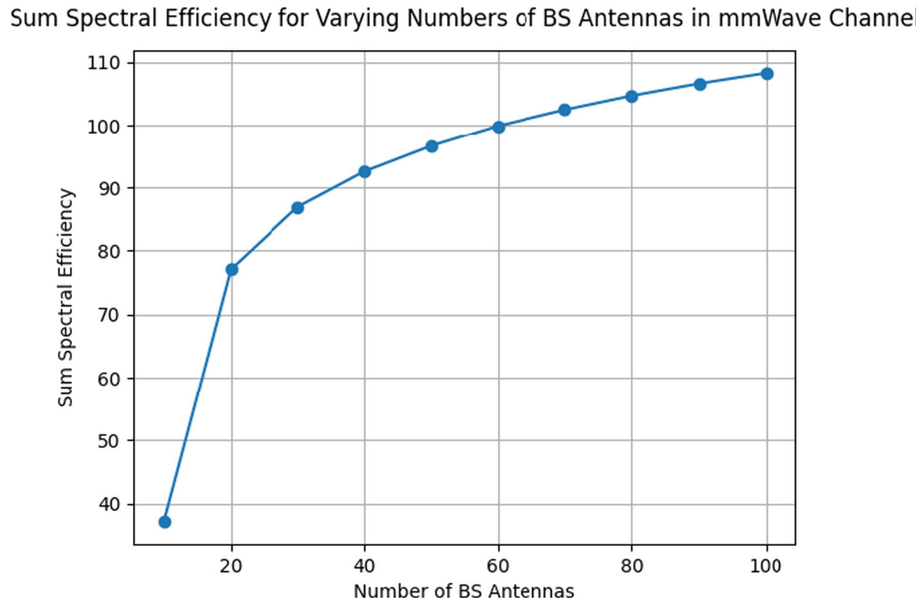


Fig. 3 Sum spectral efficiency for varying numbers of bs antennas in mmWave channel

efficiency results of the suggested method. This is clear that the suggested plan significantly outperforms the alternatives in both streams. This RF precoder's Exhaust gas temperature will effectively combine the network benefits, guaranteeing spectrum efficiency capability. The suggested system's total spectrum efficiency within the mmWave network equals 47.7 bits/s/Hz, whereas, through the Rayleigh network, it will be 47.26 bits/s/Hz for SNR = 0 dB. While we compare Figure. 2a and b, we discover that the suggested methodology performs poorer throughout the Rayleigh stream as compared to the mmWave stream since there are 128 BS towers. This is probably because the suggested system's DFT basis classification substantially catches the mmWave streams' dominating pathways.

For K = 8, 16 client transmitters, with SNR = 0 dB, Fig. 3 contrasts the total spectrum efficiency with the quantity of BS transmitters in both streams. The Rayleigh stream is complicated having many dispersed groups, as well as the mmWave network, is limited since there are 8 dispersion groups but every group contains 10 pathways. As with all blended designs, we discover that efficiency increases as the quantity of BS antennae increases. Furthermore, it seems very difficult to collect the precise network condition values in mmWave patchy networks since the important data only occurs in a small number of routes. Since the suggested technique in this instance has more spectrum efficiency than the conventional BD approach, it will operate superior when applied in huge MIMO networks with various network configurations.

The sum spectral efficiency (SSE) for varying numbers of base station (BS) antennas in a millimeter-wave (mmWave) channel can provide insights into the performance of a multi-user massive MIMO system as the number of antennas increases. In general, as the number of antennas at the BS increases, the sum of spectral efficiency also increases due to the increased spatial diversity and improved channel conditions.

In mmWave channels, the propagation characteristics are different from those in sub-6 GHz bands. The mmWave channels exhibit high path loss, increased penetration loss, and more significant shadowing effects. Despite these challenges, mmWave massive MIMO systems can still benefit from the increased spatial diversity and beamforming capabilities provided by a large number of antennas. Beamforming, in particular, helps to focus the transmission energy toward the desired users, compensating for the high path loss and improving the link quality.

The sum of spectral efficiency typically increases as the number of BS antennas grows, but the rate of improvement may gradually decrease due to diminishing returns. In other words, after a certain point, adding more antennas will have less impact on the overall performance improvement. This is mainly because inter-user interference and noise become less significant as the number of antennas increases, and the system performance becomes more limited by other factors such as hardware impairments or channel estimation errors.

8 Conclusion

For downstream multiple users mmWave huge MIMO devices, we suggest a minimal complexity blended precoding approach in our study having great spectrum efficiency. To enhance the amplitude of the comparable frequency stream matrices, we square the size of such analog precoding lattice and then identify the best analog multiplexer. To remove inter-client interference, a blocking diagonal (BD) precoding is carried out depending on the corresponding stream observed from the baseline. Having less design and computing cost, the suggested technique delivers throughput efficiency which is comparable to, and occasionally even better than, the level of traditional BD analysis. The modeling findings show, for all Rayleigh fade networks as well as the mmWave network, the suggested technique will outperform conventional precoding methods in terms of spectrum efficiency and bit-error-rate (BER) efficiency.

Funding This work has no funding resources.

Data availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent of publication Not applicable.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Al-Nahhas MO, Chaaban A, and Hossain MJ (2021) RIS-aided cell-free massive MIMO: performance analysis and competitiveness. In: proceding ieee international conference on communications workshops (ICC Workshops), pp 1–6, Montreal, QC, Canada

Björnson E, Sanguinetti L (2020) Power scaling laws and near-field behaviors of massive MIMO and intelligent reflecting surfaces. IEEE Open J Commun Soc 1:1306–1324

Björnson E, Özdogan O, Larsson EG (2020) Reconfigurable intelligent surfaces: three myths and two critical questions. IEEE Commun Mag 58(12):90–96

Chen S, Zhang J, Björnson E, Zhang J, Ai B (2021) Structured massive access for scalable cell-free massive MIMO systems. IEEE J Sel Areas Commun 39(4):1086–1100

Du H, Zhang J, Cheng J, Ai B (2021) Millimeter wave communications with reconfigurable intelligent surfaces: performance analysis and optimization. IEEE Trans Commun 69(4):2752–2768

Feng C, Wang H-M (2021) Secure short-packet communications at the physical layer for 5G and beyond. IEEE Commun Stand Mag 5(3):96–102

Hong S, Pan C, Ren H, Wang K, Chai KK, Nallanathan A (2020) Robust transmission design for intelligent reflecting surface-aided secure communication systems with imperfect cascaded CSI. IEEE Trans Wireless Commun 20(4):2487–2501

A. Khalil, M. Y. Selim, and M. A. Rahman (2021) CURE: enabling RF energy harvesting using cell-free massive MIMO UAVs assisted by RIS. In: proceding 46th IEEE conference local computer Network (LCN), pp 533–540, Edmonton, AB, Canada

Li B, Fei Z, Zhou C, Zhang Y (2020) Physical-layer security in space information networks: a survey. IEEE Internet Things J 7(1):33–52

Li Y, Jiang M, Zhang Q, Qin J (2021) Joint beamforming design in multi-cluster MISO NOMA reconfigurable intelligent surface-aided downlink communication networks. IEEE Trans Commun 69(1):664–674

Lin Z, Niu H, An K et al (2022a) Refracting RIS-aided hybrid satellite-terrestrial relay networks: joint beamforming design and optimization. IEEE Trans Aerosp Electron Syst 58(4):3717–3724

Lin Z, An K, Niu H et al (2022) SLNR-based secure energy efficient beamforming in multibeam satellite systems. IEEE Trans Aerospace Electron Syst 12:1–4

Liu P, Luo K, Chen D, Jiang T (2020) Spectral efficiency analysis of cell-free massive MIMO systems with zero-forcing detector. IEEE Trans Wireless Commun 19(2):795–807

Matthaiou M, Yurduseven O, Ngo HQ, Morales-Jimenez D, Cotton SL, Fusco VF (2021) The road to 6G: ten physical layer challenges for communications engineers. IEEE Commun Mag 59(1):64–69

Shi E, Zhang J, Chen S et al (2022) Wireless energy transfer in RIS-aided cell-free massive MIMO systems: opportunities and challenges. IEEE Commun Mag 60(3):26–32

Van Chien T, Ngo HQ, Chatzinotas S, Di Renzo M, Ottersten B (2022) Reconfigurable intelligent surface-assisted cellfree massive MIMO systems over spatially-correlated channels. IEEE Trans Wireless Commun 21(7):5106–5128

Wang D, Wang M, Zhu P, Li J, Wang J, You X (2020) Performance of network-assisted full-duplex for cell-free massive MIMO. IEEE Trans Commun 68(3):1464–1478

Wu Q, Zhang R (2020) Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network. IEEE Commun Mag 58(1):106–112

Yerrapragada AK, Eisman T, Kelley B (2021) Physical layer security for beyond 5G: ultra secure low latency communications. IEEE Open J Commun Soc 2:2232–2242

Zhang X, Guo D, An K, Ding Z, Zhang B (2019) Secrecy analysis and active pilot spoofing attack detection for multigroup multicasting cell-free massive MIMO systems. IEEE Access 7:57332–57340

Zhang X, Guo D, An K, Ma W, Guo K (2020a) Secure transmission and power allocation in multiuser distributed massive MIMO systems. Wireless Netw 26(2):941–954

Zhang X, Guo D, An K, Zhang B (2020b) Secure communications over cell-free massive MIMO networks with hardware impairments. IEEE Syst J 14(2):1909–1920

Zhang Y, Di B, Zhang H, Lin J, Li Y, Song L (2021) Reconfigurable intelligent surface aided cell-free MIMO communications. IEEE Wireless Commun Lett 10(4):775–779

Zhou T, Xu K, Xia X, Xie W, Xu J (2021) Achievable rate optimization for aerial intelligent reflecting surface-aided cell-free massive MIMO system. IEEE Access 9:3828–3837