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Performance Evaluation of Concatenated Rate Splitting Multiple Access for 6G Multiuser Communication System

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***Abstract*—Rate splitting multiple access (RSMA) technology successfully mitigates same-channel interference among users and enhances system performance through flexible control of rate distribution. This study presents an integration of 6G concatenated code with RSMA to offer an improved ultra-reliable communication for a 6G multi-cell communication system. In current wireless communication networks, having imperfect channel state information (CSI) is unavoidable, which leads to significant multi-user interference in multi-antenna broadcast channels, which reduces the data rate, system reliability, reducing the overall quality of service (QoS). This study, breaks this limitation and propose a novel scheme, denoted as Concatenated Rate Splitting Multiple Access (C-RSMA), that relies on the 6G coding technique to encode the private parts of RSMA data blocks. The study demonstrate that the rate region of C-RSMA in a multiple input single output (MISO) system with partial CSI is expanded beyond that of traditional coded RSMA, where C-RSMA achieves higher data rate of 10^3 Tbps, and 99.95% reliability.**

I. Introduction

A. Motivation and Background

Recently, rate-splitting multiple access (RSMA) has been suggested for multi-antenna networks, where it is acknowledged as a promising physical-layer non-orthogonal multiple access transmission method, as well as an effective interference management technique, and a potential multiple-access solution for the upcoming generation 6G [1]. RSMA facilitates flexible interference management by partitioning user messages into common and private segments, encoding the common segments into shared streams for decoding by multiple users, and encoding the private segments into individual streams for exclusive decoding by the respective users, thereby allowing for partial decoding of interference and treating the remainder as noise [2]. Previous studies have demonstrated that RSMA surpasses other multiple access methods, such as space division multiple access (SDMA), power-domain non-orthogonal multiple access (NOMA), orthogonal multiple access (OMA), and multicasting, in terms of spectral efficiency, energy efficiency, max-min fairness, and resilience to inaccuracies in channel state information at the transmitter [3].

RSMA transmitters employs rate-splitting (RS), while the receivers implement successive interference cancellation (SIC) mechanisms [4]. RSMA represents a variant of NOMA in which a user signal is partitioned into two separate components: common and private. The base station (BS) broadcasts two types of messages to users: common messages and private messages. All users receive the common message, whereas an individual user receives only the private message. Users are required to interpret the interference from other users to comprehend the shared message [5]–[8]. In order for the users to receive their private messages, users must account for the interference caused by messages from other users, which may manifest as random noise. This approach results in increased computational time and inter-user interference, lower reliability and lower data rates. To minimise the impact of noise from private streams, the concept of coded RSMA is first introduced in [9], demonstrating an ability to achieve higher data rates. Coded RSMA has been examined and analysed in various studies, however the role and benefits of 6G codes integration for coded RSMA have not been thoroughly investigated and remain an unresolved issue.

B. Literature Summary

The significance of coded RSMA and it is importance in communication system is extensively explored in the literature. The study in [10] presented a linear coding strategy based on weighted minimum mean square error (WMMSE), additionally, in [11] coded RSMA was introduced to solve the constraint on the minimum rate, which is derived from the generalised power iteration (GPI) technique. The coded RSMA suggested in [12] exclusively addresses uniformly distributed digital-to-analogue converter bits, to enhance system relatability. In [13], a data-oriented strategy was implemented in downlink RSMA systems, examining two distinct coded

RSMA architectures to maximise the data rate. The simulation findings demonstrate that employing a data-oriented strategy in downlink RSMA systems yields superior performance regarding packet delivery time and transmitted power for individual transmissions however failed to achieve higher data rates. Accordingly, [14] implemented a data-oriented strategy for uplink RSMA. [15] introduces a device-to-device aided coded RSMA scheme that encodes the messages from both devices into a unified common data stream within each cell or group. However, this deployment strategy may pose challenges in complex resource allocation and the selection of transmission modes. In a downlink multi-user millimetre wave (mmWave) RSMA system, the authors [16] offer an energy-efficient one-layer coded RSMA design for K users with quality of service limitations, where analogue and digital coders architecture are decoupled. Coded RSMA is developed in [17] to concurrently optimise the average weighted sum rate for users while adhering to QoS constraints across varying levels of CSI inaccuracies.

The design of coded RSMA utilising practical finite-alphabet constellations, as opposed to Gaussian inputs, has been discussed in [18]. [19] proposes the integration of finite block length with rate splitting techniques to facilitate massive transmissions. In [20], the authors propose and enhance the coded RSMA framework for multi-antenna receivers, optimising the encoder to maximise Weighted Ergodic Sum-Rate (WESR). [21] proposes a novel successive null space (SNS) coded RSMA for private messages in MIMO-RSMA. The proposed SNS coder employs linear combinations of the null-space basis vectors derived from users' successively augmented MIMO channel matrices as coding vectors. This approach aims to mitigate inter-user interference at the receivers, improving performance and robustness. [22] the authors integrated rateless codes (RC) into the system, which demonstrate enhancing system throughput. The authors in [23], presented methods for stream combining and regularised block diagonalisation coding for RSMA in MIMO broadcast channels, focussing on a single shared stream.

Even the above mentioned studies provided seminal important contributions to the development of coded RSMA in communication systems, none of the aforementioned studies and the other studies in the literature those cannot be all referred here considered the application of 6G performance expected measuers neither 6G approved coding techniques.

C. Content and Contributions

This study introduces an efficient coded RSMA that incorporates 6G coding and RSMA to maximise data throughput and increase reliability. The proposed structure is formulated as a concatenated coding technique using Polar Convolutional Serial Code (PCSC) approach. 6G communication expected measures are addressed through applying the coded RSMA. Although the aforementioned studies provided seminal contributions to the existing knowledge on the use of coded RSMA, none of them have provided a comprehensive analysis combining 6G coding techniques to consider the dependability, reliability, and data rate together with 6G operating frequency range. The contributions of this proposed concept are twofold:

- Introduces a novel Concatenated Rate Splitting Multiple Access (C-RSMA) scheme over Rayleigh channel to improve the performance of RSMA by employing advanced 6G coding technique to encode private messages. Here, instead of the predefined coded RSMA, a concatenated approach is considered to obtain higher reliability and data rate.
- Both robustness to interference and enhances data transmission efficiency are taken into account, thereby improving user experience. It facilitates dynamic resource allocation that adapts to fluctuating user demands and channel conditions, optimising bandwidth utilisation.

D. Paper Organisation

The rest of the paper will be organized as follows. In section II the mathematical modelling of the proposed structure will be given. Performance analysis calculation of the implementation of the proposed C-RSMA to the communication network will be provided in Section III. Expected results and discussion will be shown in IV. Conclusion and further studies will be given in Section V.

II. SYSTEM MODEL

The proposed system is a downlink multiuser communication framework that serves K users through a single base station antenna. Users are classified into far users (FUs) and near users (NUs) according to the power gain from the BS. Assume that FU and BS are positioned at the network communication edges. NUs are assigned lower gain and positioned near the BS, while FUs are assigned higher gain, with their edge cell locations denoted by the numbers nu_k and fu_k, respectively.

A. Transmission Protocol

In this study, rate splitting occurs at the BS, where the messages of two users are divided into private and common components. NUs and FUs utilise an identical message format concatenated and encoded into a singular stream. Private messages are encrypted as a distinct stream for each user. Consider the following scenario involving two users. Where U_1 and U_2 are the messages sent to user1 and user2, respectively. User messages are divided into two parts: common part u_c^1, u_c^2 and private part u_p^1, u_p^2. The common parts are encoded together to produce a common stream; the private parts, on the other hand, are encoded as a private stream using, PCSC to form concatenated RSMA (C-RSMA), The C-RSMA architecture is illustrated in Fig.1 and operating with 6G 300GHz frequency.

The BS divides the k^{th} user message U_k, (i.e.$k = 1, 2, \dots, K$), into two sub messages known as private $U_{(p,k)}$ and common messages $U_{(c,k)}$. The common parts are grouped from all users into a single data stream X_c, which can be decoded by all users. After that, each user's private message is encoded separately into one data stream as X_p^k, which is only decoded by the k^{th} user. The final data vector at the BS

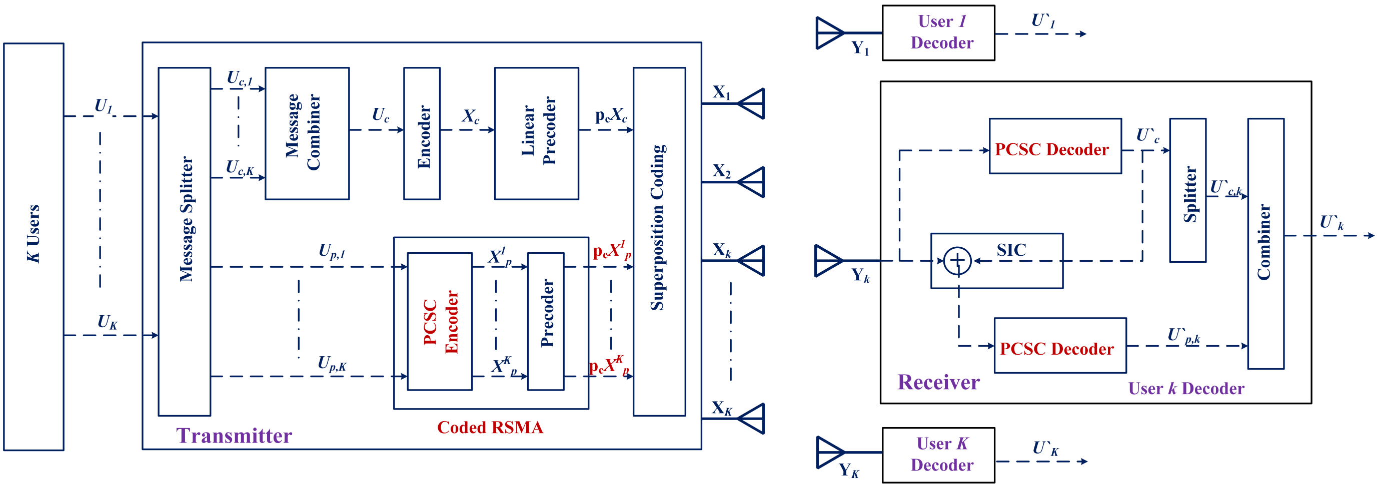

Fig. 1. Transceiver architecture for C-RSMA.

is $X = [X_c, X_1, \ldots, X_K]^T$, which is the total data vector at the BS.

The total transmission power at the BS is identified as P. α_p and α_c are the power allocation factors for private and common data streams. The factors α_p and α_c are chosen such that $0 \leq \alpha_c, \alpha_k \leq 1$ and $\alpha_c + \sum_{k=1}^{K} \alpha_k = 1$. The combined data stream transmitted is obtained as follows:

$$U = \sum_{k=1}^{K} \sqrt{\alpha_p P} X_p^k + \sqrt{\alpha_c P} X_c. \tag{1}$$

Thus, the transmitted signal from the BS at the NU_K is written as

$$Y_{nu_k} = h_{nu_k} U + e_{nu_k}. \tag{2}$$

where, h_{nu_k} is the Additive White Gaussian Noise (AWGN) with mean and variance (μ, σ), $\mu = 0$ and σ is the average channel power, e_{nu_k} denotes the noise at the NU_{k_1} with μ mean and σ^2.

B. PCSC Encoder and Decoder

The private message part is encoded using PCSC code, as shown in Fig.2.

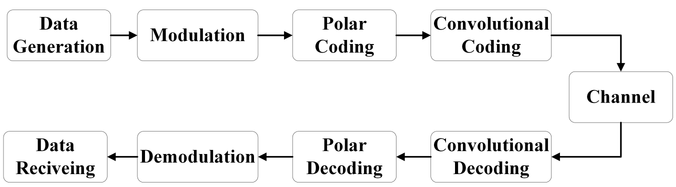

Fig. 2. Polar convolutional Serial Code Structure.

Polar code parameters are defined as N, k which represents the codeword and message length respectively. In here, polar code is used as the outer encoder with the following parameters: $N = 2048$, $k = 528$, the output of the polar encoder is fed into a convolutional encoder as the inner code, which takes advantage of low complexity shift registers D, the coding parameters used for convolutional code are $N = 9, k = 3, D = 9$, the resultant codeword then transmitted over the channel, where the modulation used is 64QAM.

Polar encoder is performed as $x = mG$, where x is the codeword, m is the message, and G is polar code generator matrix. Polar decoder use the likelihood ratios (LRs) butterfly digram to implement the successive cancellation decoding (SCD) recursive decoding.

In convolutional encoder, the codeword is obtained by applying the message sequence of length k into several finite shift registers equals D. Viterbi algorithm is used for convolutional decoding, readers are referred to [24] for PCSC detailed description.

C. C-RSMA Encoding

The NUs and FUs are grouped into two groups named the near group and far group, indexed by $g_{n,f}$, and each group contains K users. Each user splits their message U_k into two sub-messages, namely one common message $U_{c,k}$ and one private message $U_{p,k}$. The near group common sub-messages $\{U_{c,k}^n | k \in K\}$ are encapsulated into one common message $U_{c,K}$, which is encoded into a common stream X_c^n using a codebook shared by all users and is decoded by all users. The near group user's private messages $\{U_{p,k}^n | k \in K\}$ are independently encoded with PCSC coding into K private streams $\{X_{p,1}^n, \ldots, X_{p,K}^n\}$, which are decoded by the corresponding users. The overall encoded streams $[X = X_1, X_2, \ldots, X_K]^T$ are linearly precoded with $[\rho = \rho_c, \rho_1, \ldots, \rho_K]$, then the signal sent from the transmitter for the NUs is given as follows:

$$U^n = \alpha_c P \rho_c X_c + \sum_{k \in K} \alpha_p P \rho_k X_k. \tag{3}$$

The received signal at each NUs is given as in (4).

$$Y_{nu_k} = h_{nu_k} U^n + e_{nu_k}. \tag{4}$$

The sent signal for FUs is as follows:

$$U^f = \alpha_c^f P\rho_c X_c^f + \alpha_c P\rho_c X_c + \sum_{k\in K} \alpha_p P\rho_k X_k. \quad (5)$$

The term $\{\alpha_c^f P\rho_c X_c^f\}$ in (5) represents the FUs common part, while $\{\alpha_c P\rho_c X_c\}$ is the NUs common part which is decoded and eliminated through PCSC decoder as in Fig.2. As a result, the received signal at the FUs is written as follows:

$$Y_{fu_k} = h_{fu_k} X^f + e_{fu_k} + S_{nu}. \quad (6)$$

where the term $\{S_{nu}\}$ refers to the signal of the NUs, which has a small amount of power and fades through transmission.

D. C-RSMA Decoding

The decoding process occurs independently for each user; NUs and FUs follow the same process. Each user k decodes the common stream X_c by the PCSC decoder into $\tilde{U_c}$ by treating all the private stream interference as noise. The resultant $\tilde{U_c}$ is then applied to SIC block, which is re-encoded, preceded, and subtracted from the received signal. The resultant stream is applied through a PCSC decoder such that each user can decode its private stream X_k into $\tilde{U_{p,k}}$ by treating the remaining private parts from the other private streams as noise. User k reconstructs the original message by extracting $\tilde{U_{c,k}}$ from $\tilde{U_c}$, and combining $\tilde{U_{c,k}}$ with $\tilde{U_{p,k}}$ into $\tilde{U_k}$.

E. Signal to Noise Ratio (SNR) Analysis

In the described system model, the BS sends the signal to the NUs and FUs via Rayleigh distribution. All users decode the common message at first and treat the interference from all private messages as noise, the SNR at NUs for common and private signals are given, respectively by:

$$SNR_{nu,c} = \frac{\alpha_c \left|h_{nu}\rho_c\right|^2}{\sum\limits_{k=1}^{K} \alpha_k \left|h_{nu}\rho_c\right|^2 + \frac{\sigma^2}{P}}. \quad (7)$$

$$SNR_{nu,p} = \frac{\alpha_{nu} \left|h_{nu}\rho_j\right|^2}{\sum\limits_{j=1\, j\neq k}^{K} \alpha_k \left|h_{nu}\rho_j\right|^2 + \frac{\sigma^2}{P}}. \quad (8)$$

After successfully decoding the common signal, the common signal is removed from the received signals. The private messages are then decoded by assuming all other private signals as noise. The SNR at FUs for common and private signals are given by:

$$SNR_{fu,c} = \frac{\alpha_c \left|h_{fu}\rho_c\right|^2}{\sum\limits_{k=1}^{K} \alpha_k \left|h_{fu}\rho_c\right|^2 + \frac{\sigma^2}{P}}. \quad (9)$$

$$SNR_{fu,p} = \frac{\alpha_{fu} \left|h_{fu}\rho_j\right|^2}{\sum\limits_{j=1\, j\neq k}^{K} \alpha_k \left|h_{fu}\rho_j\right|^2 + \frac{\sigma^2}{P}}. \quad (10)$$

Assuming the presence of Gaussian signalling and infinite block length, the instantaneous rates for decoding the common and private streams at each k user are given as follows:

$$\Re_{nu,k} = \log_2\left(1 + \frac{\left|h_k^H \rho_k\right|^2}{\sum_{j\in K} \left|h_k^H \rho_j\right|^2 + \sigma_{n,k}^2}\right). \quad (11)$$

$$\Re_{fu,k} = \log_2\left(1 + \frac{\left|h_k^H \rho_k\right|^2}{\sum_{j\in K, j\neq k} \left|h_k^H \rho_j\right|^2 + \sigma_{n,k}^2}\right). \quad (12)$$

III. PERFORMANCE ANALYSIS

A. Outage Analysis for FUs

A FU will not experience an outage if the SNR values for both common and private messages exceed their respective threshold SNRs, corresponding to the planned QoS. The outage probability at FU is defined as

$$P_{fu_k}^{\text{out}} = 1 - P_\Xi \left\{SNR_{fu,c} > \Xi_c, SNR_{fu,p} > \Xi_p\right\}. \quad (13)$$

where Ξ_c and Ξ_p are SNR thresholds for common and private messages, respectively, with $\Xi_c = 2^{\Re_c} - 1$ and $\Xi_p = 2^{\Re_p} - 1$. $\Re_c$ and $\Re_p$ are the expected data rates for common and private messages.

B. C-RSMA Rayleigh Fading Channel Analysis

This section looks into the outage probability for the users of the system within the context of a Rayleigh fading channel.

1) NU Common Message: Using (7), the outage scenario at NU's common message may be expressed as follows.

$$\Re_{nu,c} = BW * \log_2\left(1 + \frac{\alpha_c |h_{nu,k}|^2}{\sum\limits_{k=1}^{K} \alpha_k |h_{nu,k}|^2 + \frac{\sigma^2}{P}}\right) < \Xi_c. \quad (14)$$

The user's outage is the achievable rate, which should be lower than the desired value (threshold value); the following equation gives the outage probability of the NU.

$$P_{nu_k}^{\text{out}} = 1 - P_\Xi \left\{SNR_{nu,c} > \Xi_c, SNR_{nu,p} > \Xi_p\right\}. \quad (15)$$

having the probability density function (PDF) of Rayleigh Fading channel F given by.

$$F_{B_1}\left(SNR_{nu,c}\right) = \frac{1}{\delta_1^2} e^{-\frac{SNR_{nu,c}}{\delta_1^2}}. \quad (16)$$

To obtain the closed form expression, integrate (17) with regard to SNR of NU common message as in (18).

$$\beta < \frac{\Re_{nu,c}}{\alpha_{nu,c} - \Re_{nu,c}\ \rho B \sum\limits_{k=1}^{K} \alpha_{nu,p}}. \quad (17)$$

$$P_{out} = \int_{0}^{\Re_{nu,c} / \alpha_{nu,c} - \Re_{nu,c}\rho B \sum_{k=1}^{K} \alpha_{nu,p}} F_{B_1} d\left(SNR_{nu,c}\right). \tag{18}$$

The outage of the near user is expressed as in (19) :

$$P_{out,nu,c} = 1 - \exp\left(-\frac{\Re_{nu,c}}{\alpha_{nu,c} - \Re_{nu,c}\,\rho_c B \sum\limits_{k=1}^{K} \alpha_{nu,p}}\right). \tag{19}$$

2) NU Private Message: The calculation of the outage for the NU private part is analogous to that of the NU common part. The outage impacting the nearby user is quantified as follows using (8):

$$\Re_{nu,p} = BW * \log_2\left(1 + \frac{\alpha_p |h_{nu,k}|^2}{\sum\limits_{j=1\, j\neq k}^{K} \alpha_k |h_{nu,k}|^2 + \frac{\sigma^2}{P}}\right) < \Xi_p. \tag{20}$$

The outage expression of the NU private message can be simplified as.

$$P_{out,nu,p} = 1 - \exp\left(-\frac{\Re_{nu,p}}{\alpha_{nu,p} - \Re_{nu,p}\,\rho_j B \sum\limits_{j=1\, j\neq k}^{K} \alpha_{nu,p}}\right). \tag{21}$$

The NU overall outage probability is determined by adding the common and private outage parts.

$$P_{out,nu} = P_{out,nu,p} + P_{out,nu,c}. \tag{22}$$

3) FU Common Message: A FU will experience an outage only if, the SNR values for both common and private symbols are above the relevant threshold SNRs. Therefore, the outage condition for the user at the cell edge can be expressed based on (9).

$$\Re_{fu,c} = BW * \log_2\left(1 + \frac{\alpha_c |h_{fu}\rho_c|^2}{\sum\limits_{k=1}^{K} \alpha_k |h_{fu}\rho_c|^2 + \frac{\sigma^2}{P}}\right) < \Xi_c. \tag{23}$$

$\Re_{fu,c}$ represents the achievable rate for the common users, where it should be less than the targeted threshold value Ξ_c, as in (23). Having the PDF value for FUs given in (24). To obtain the closed form expression, integrate (24) with regard to SNR of FU common message as in (25). The outage of the FU is expressed as in (26).

$$F_{B_1}\left(SNR_{fu,c}\right) = \frac{1}{\delta_1^2} e^{-\frac{SNR_{fu,c}}{\delta_1^2}}. \tag{24}$$

$$P_{out} = \int_{0}^{\Re_{fu,c} / \alpha_{fu,c} - \Re_{fu,c}\rho_c B \sum_{j=1 j\neq k}^{K} \alpha_{fu,p}} F_{B_1} d\left(SNR_{fu,c}\right). \tag{25}$$

$$P_{out,fu,c} = 1 - \exp\left(-\frac{\Re_{fu,c}}{\alpha_{fu,c} - \Re_{fu,c}\,\rho_c B \sum\limits_{k=1}^{K} \alpha_{fu,p}}\right). \tag{26}$$

4) FU Private Message: The outage probability of the FU private message is calculated using (10) as in.

$$\Re_{fu,p} = BW * \log_2\left(1 + \frac{\alpha_p |h_{fu}\rho_j|^2}{\sum\limits_{j=1 j\neq k}^{K} \alpha_k |h_{fu}\rho_j|^2 + \frac{\sigma^2}{P}}\right) < \Xi_p. \tag{27}$$

In which $\Re_{fu,p}$ should be less than the targeted threshold, (27) can be further simplified. The simplified outage expression of the FU private message as in (28) and (29).

$$P_{out} = \int_{0}^{\Re_{fu,p} / \alpha_{fu,p} - \Re_{fu,p}\rho_j B \sum_{j=1 j\neq k}^{K} \alpha_{fu,p}} F_{B_1} d\left(SNR_{fu,p}\right). \tag{28}$$

$$P_{out,fu,p} = 1 - \exp\left(-\frac{\Re_{fu,p}}{\alpha_{fu,p} - \Re_{fu,p}\,\rho_j B \sum\limits_{j=1 j\neq k}^{K} \alpha_{fu,p}}\right). \tag{29}$$

Adding (26) and (29) will produce the overall outage of FU in the system.

IV. RESULTS AND DISCUSSION

This section evaluates the performance of C-RSMA in 6G compared to other coded RSMA techniques. The system supports 50 users, comprising 30 FUs and 20 NUs. We analyze key performance parameters, including outage probability, achievable data rates, and reliability across various SNR values. The results provide a comparative analysis of the C-RSMA assisted system, demonstrating its superior reliability, and improved data rates, positioning it as a strong multiple access candidate for future 6G networks.

Fig.3 demonstrate that C-RSMA is the most dependable scheme for both NUs and FUs, which achieves the lowest outage probability and rapidly decreases as SNR increase.

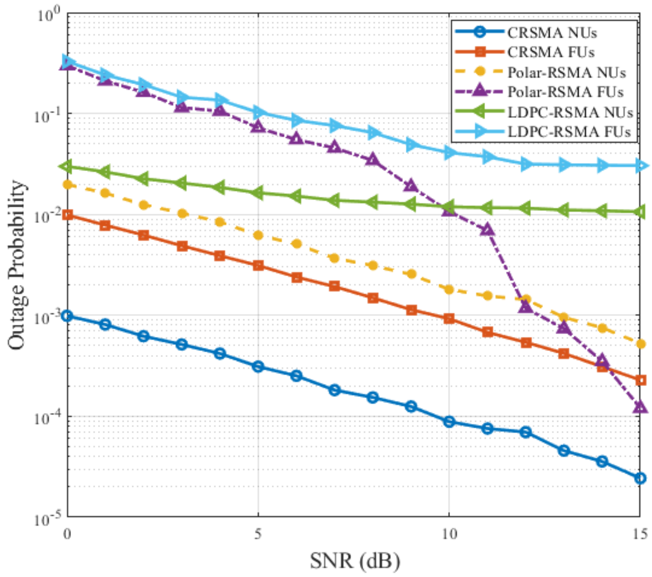

Fig. 3. Outage Probability Comparison.

Specifically, adapting C-RSMA in the communication system indicates that the likelihood of a communication link to fail meeting a specified performance criterion is less than other used techniques, in which C-RSMA meets the 10^{-3} at SNR=0 for NUs and SNR=10 for FUs. On the other hand, Polar-RSMA meets the specified threshold at SNR=13 for NUs and SNR=12 for FUs, in case of using LDPC code the threshold is never achieved. The findings highlight the efficacy of combining 6G concatenated code and RSMA to form C-RSMA to establish a strong and dependable communication framework, ensuring high-quality service for near and far users.

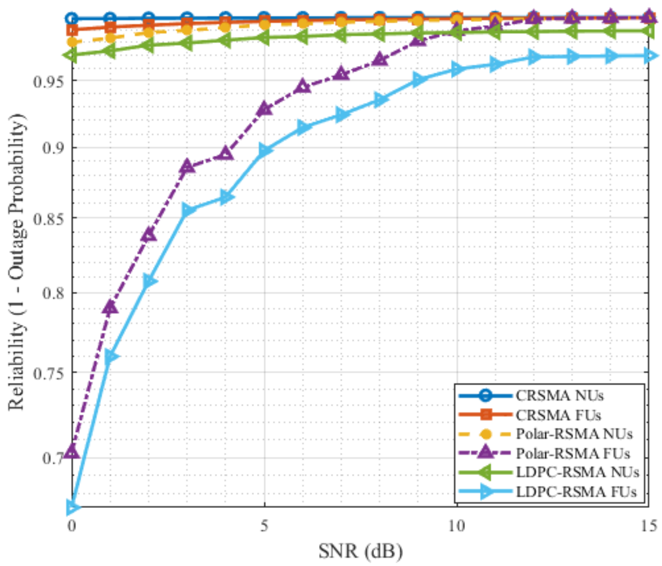

Fig. 4. Reliability Comparison.

In accordance to the results shown in Fig.3, Fig.4 indicates the reliability performance. Reliability is quantified as $1-P_{out}$, with a higher value signifying enhanced system dependability. The findings indicate that the C-RSMA system attains near-perfect reliability, exceeding 99.95% even at low SNR levels, with reliability enhancing as SNR rises. The nearly similar performance of both FUs and NUs highlights the efficacy of the C-RSMA method in maintaining uniform service quality, which ensures that all users experience the same level of service across varied user groups. Polar and LDPC RSMA shows better performance serving NUs group rather than FUs with much lower reliability that does not exceeds 70.5%.

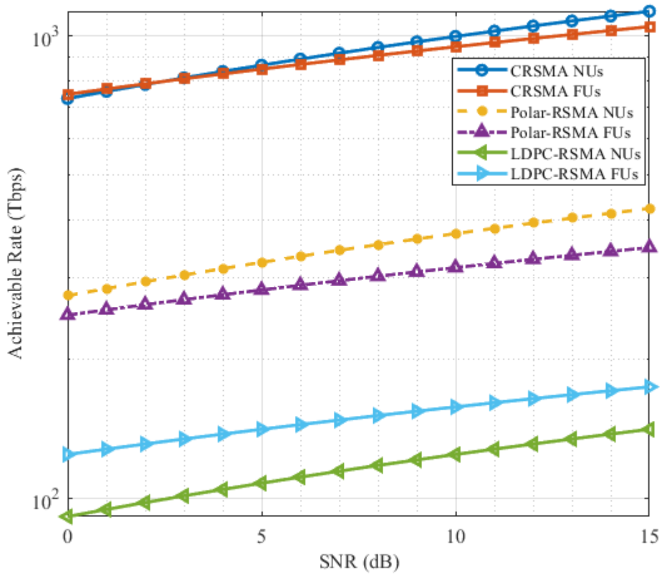

Fig. 5. Throughput Comparison.

Fig.5 demonstrates the significant performance enhancements of C-RSMA over Polar and LDPC RSMA in terms of achievable rates for FUs and NUs. The pivotal role C-RSMA is evident, consistently improving performance and enabling FUs to achieve notably higher rates than NUs. The total achievable rate for C-RSMA surpasses 10^3 Tbps at high SNRs, marking a substantial improvement over the other coded RSMA. In contrast, Polar-RSMA, while capable of achieving higher rates for NUs, shows lower rate for FUs. This underscores the advantages of C-RSMA in delivering dependable high-throughput communication across diverse channel conditions, making it a compelling choice for 6G requirements, particularly in dense areas. LDPC-RSMA on the other hand, shows the lowest performance in which C-RSMA achieves 6 times higher data rates for both FUs and NUs.

V. Conclusion

In order to improve the dependability, reliability and throughput in a 6G communication system, this study introduces coded RSMA approach focusing on the integration of 6G concatenated code PCSC with RSMA. The simulation results highlight the special benefits of the suggested C-RSMA system, which outperforms other 6G current suggested coded

RSMA and traditional configurations in terms of dependability, reliability, and throughput. Unquestionably, the results showed significant performance improvements. With a considerable 98% decrease in the likelihood of the outage probability for users who were fully and partially decoded, the integration of C-RSMA greatly increased system reliability. These findings underscore the critical impact of effectively employing coded multiple access technique in 6G communication network.

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