Joint RSMA and IDMA-Based NOMA System for Downlink Communication in 5G and Beyond Networks

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Abstract—**Future communication networks may encounter various issues in order to facilitate heavy heterogeneous data traffic and large number of users, therefore more advanced multiple access (MA) schemes is required to meet the changing requirements. Recently, a promising physical-layer MA technique has been suggested for multi-antenna broadcast channels, namely Rate Splitting Multiple Access (RSMA). This new scheme has the ability to partially decode the interference and partially treat the remaining interference as noise which makes it to cope with wide range of user deployments and network loads. On the other hand, interleave division multiple access (IDMA) has already been recognized as a potential code domain NOMA (non-orthogonal multiple access) scheme, suitable for 5G and beyond communication network. Hence, in this paper, a new approach of multiple access scheme is proposed to get the grip on new challenges in future communication (6G). The proposed framework consists the joint processing of RSMA and IDMA (code domain NOMA), in which the transmitter involves an IDMA as encoder and allows rate splitting to split the message in two parts i.e. common part and private part, before the actual transmission. The mathematical modeling of proposed system is elaborated in the paper and for simulation purpose the downlink communication scenario has been considered where users faced diverse channel conditions. The weighted sum rate (WSR) performance is evaluated for the proposed scheme which validate the quality of service (QoS) of the joint RS-IDMA system.**

Index Terms- **IDMA, NOMA, rate splitting, SDMA, 5G.**

I. INTRODUCTION

WITH the continuous uptrend in the demand of devices in wireless communication networks, the underloaded or overloaded scenario arises, i.e. the number of devices become either smaller or larger than transmit antennas.

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Moreover, due to the heterogeneity in devices, massive connectivity requirements, the transmitter antennas have to serve different users simultaneously. Along with heterogeneity, massive connectivity, the channel state information (CSIT) and quality of service (QoS) are the qualitative parameters which forced researchers to re-access the design of multiple access scheme for 5G communication and beyond wireless network [1]. Further, opposite to orthogonal multiple access (OMA) in which users/ groups were scheduled in orthogonal dimensions; such as in frequency (FDMA) and time (TDMA), NOMA has recently spurred researchers to consider it as an efficient multiple access (MA) scheme. Power domain (PD) NOMA and code domain are two popular types of NOMA [2]. The PD-NOMA depends on superposition coding (SC) at the transmitter and successive interference cancellation (SIC) at the receiver. However, the urgent limitation of PD-NOMA is its complexity, which increases exponentially with the increase in number of users [3]. Recently, interleave division multiple access (IDMA) has been accepted as an efficient code domain non orthogonal multiple access (CD-NOMA) scheme in 5G communication standards. Code based NOMA schemes includes IGMA from Samsung, RDMA from Mediatek and IDMA from Nokia. These schemes are interleaving-based NOMA schemes, and originate from the fundamental concept of IDMA [6]. In Interleaving based NOMA (IDMA) scheme, interleaver patterns are utilizes to distinguish between different users. In the IDMA receiver, the low-complexity ESE algorithm is used and it provides log-likelihood ratio (LLR) estimates to decode the data. However, the code domain NOMA (IDMA) also decode the interference fully and so increase the complexity as well as suffers from rate loss [7].

Hence to address the issue of rate loss in IDMA, the concept of rate splitting can be utilized. In literature the rate splitting (RS) has been studied in early 1980s in [8] for the single-input single-output (SISO) system. The suitability of RS in mitigating the effect interference in SISO system has inspired the researchers to further investigate the benefits of RS in modern communication networks [2], [3]. On the basis of RS, a new

MA scheme is recently suggested in [4], named as rate splitting multiple access.

In RSMA, the main advantage is that the interference is partially decoded and partially treated as noise whereas the established power domain NOMA has extreme interference management scenario in which interference generated by the users is fully decoded even with weaker channel strengths. In this paper a joint RSMA and IDMA-based NOMA system is proposed to significantly increase the number of supported users and enhancements in rate performance for the next-generation wireless networks. The proposed NOMA system has better sum-rate performance as compared to the conventional IDMA- based NOMA systems.

To the best of the authors' knowledge, the proposed joint RSMA and IDMA-based NOMA is the first one to support massive connectivity for next-generation wireless networks. Further, the paper is organized as follows, section II explains the rate splitting, proposed system model is introduced in section III. Simulation results have been presented in section IV and section V concludes the paper.

II. Basics of Rate Splitting Approach

The Rate-Splitting (RS) approach is not a recently proposed concept. The idea of RS predates to Carleial's research on interference channel (IC) then behind time appears in the Han-kobayashi scheme, where it was proved mathematically that decoded part of interference improved the system performance. In Rate-Splitting scheme, the transmitting message is split in two parts; a common part and a private part. The common parts of all users are superimposed to make a super common message, encoded by the code drawn from a code book shared by all users. The private part is encoded by a secure code, known to corresponding user. For K- user system, the K+1 encoded data streams are simultaneously transmitted. At the receiver, the common message is decoded first and treating all private parts of message as noise and then private message is decoded by desired user through removing the common message via successive interference cancellation (SIC) [8].

It is interesting to note that the multi-user (MU) interference in multi-input single output (MISO) broadcast channel (BC) with imperfect CSIT draws a strong resemblance to the IC. In [xx], this is shown that RS improves the performance of sum degree of freedom (DoF) of MISO-BC channel under imperfect CSIT, where errors decay with increased SNR at a rate of $O(SNR^{-\alpha})$ for some constant $\alpha \in [0,1]$. In this context, it is proved in literature that RS outperforms the conventional transmission without rate splitting (NoRS) [8-9].

III. Proposed System Model

In this work, the downlink multi-antenna multiuser communication system has been considered, where one base station (BS) equipped with N_t transmit antennas transmits K messages simultaneously to K single-antenna users. Further, At the BS, the message for 'mth' user can be represented as; $\mathrm{w}_{m,\ell} = [\mathrm{b}_{m,1}\ \mathrm{b}_{m,2}\ ....\mathrm{b}_{m,\ell}]$, where ℓ is the data length. In RS scheme, each message can be split in two parts namely; private part ($w_{p,m}$) and common part ($w_{c,m}$). The private parts $[w_{p,1}w_{p,2}........w_{p,m}]$ are independently encoded into the private streams $[s_1 s_2.........s_m]$ and the common parts of all users $[w_{c,1}w_{c,2}........w_{c,m}]$ are combined into a common message $\mathrm{W_c}$ and then encoded into a common message stream s_c using a fixed spreading and interleaving logic. More-over the common interleaved and encoded message s_c and private streams $[s_1 s_2.........s_m]$ are grouped in the vector form $\mathrm{s}=[\mathrm{s_c},\ \mathrm{s_1},\mathrm{s_2}........\mathrm{s_m}]^{\mathrm{T}}$ such that $\mathrm{E}\{\mathrm{ss^H}\} = \mathbf{I}$. Before transmitting from the BS, the symbols are suitably mapped through a linear precoder, defined as; $\mathbf{P}=[\mathrm{p_c},\mathrm{p_1},..........\mathrm{p_m}]$. So the transmitting signal can be described as [10]:

$$\mathbf{x}=\mathbf{P}\mathrm{S} = \mathrm{p_c S_c} + \sum_{\mathrm{m}=1}^{\mathrm{m}} \mathrm{p_m S_m} \tag{1}$$

At the receiver, the signal received by m^{th} user can be written as

$$y_m = h_m^H \mathbf{x} + \eta_m \tag{2}$$

where, h_m is the channel vector from BS to m^{th} user, x is the transmit signal, $\mathbf{x} = [\ \mathrm{x_1}\ \mathrm{x_2}\ ....\mathrm{x}_m]$ and noise $\eta_m \sim \mathcal{N}(0, \sigma_{n,m}^2)$ is additive white gaussian noise (AWGN) at the receiver. The variances of all the users can also considered same, i.e., $\sigma_{n,m}^2 = \sigma_n^2$. Hence transmit SNR can be simply written as; $\mathrm{snr} = \mathrm{P}_t / \sigma_n^2$ and σ_n^2 is fixed for entire range of SNR, so the $\mathrm{snr} \to \infty$ is equivalent to $\mathrm{P}_t \to \infty$. Further, in RS the common message is superimposed on the top of the private message. The power constraint for this, can be expressed as; $\mathrm{tr}(\mathrm{PP^H}) \le \mathrm{P_t}$. The $\mathrm{m^{th}}$ user received average power can be written as [10-11]:

$$\mathrm{pow}_{\mathrm{avg,m}} = \overbrace{\left|\mathrm{h_m^H p_c}\right|^2}^{\mathrm{s_{c,m}}} + \overbrace{\left|\mathrm{h_m^H p}_m\right|^2}^{\mathrm{s_m}} + \overbrace{\sum_{i \ne m}\left|\mathrm{h_m^H p}_i\right|^2 + \sigma_n^2}^{\text{Interference}} \tag{3}$$

To recover the message, first common message is decoded treating all other messages as noise. Once the common message is successfully recovered then it is removed using SIC from y_m in order to improve the detectability of private message. The signal to interference noise ratio (SINR) of the common message and private message can be written as

$$\gamma_m^c = \frac{P_c\left|h_m^H w_c\right|^2}{\sum_{j=1}^{m} P_j\left|h_m^H w_j\right|^2+1},\ \gamma_m^p = \frac{P_m\left|h_m^H w_m\right|^2}{\sum_{j\neq m} P_j\left|h_m^H w_j\right|^2+1} \qquad (4)$$

The achievable rate of common message can be expressed as $R_c^{RS}=\log_2(1+\gamma^c)$, where $\gamma^c=\min(\gamma_m^c)$ for ensuring that common message is successfully decoded by each user [12]. The rate of the private message is given as $R_p^{RS}=\sum_{m=1}^{m}\log_2(1+\gamma_m^p)$. Then the net sum rate can be expressed as $R_{sum}^{RS}=R_c^{RS}+R_p^{RS}$. The maximization of sum rate can be seen as *max-min fairness optimization problem.* The actual rates are not taken as design matrices due to uncertainty in CSIT (channel state information). So, the pre-coders are optimized for worst case achievable rates. The worst-case achievable rates for m^{th} user can be expressed as

$$R'_{c,m}=\min R_{c,m}(h_m) \text{ and } R'_m=\min R_m(h_m) \qquad (5)$$

For the sake of simplicity, the m^{th} user's worst common rate can be denoted as C'_m where $\sum_{m=1}^{m}C'_m=R'_c$. Hence, total worst case achievable rate can be written as $\bar{R}_{tot,m}=R'_m+C'_m$.

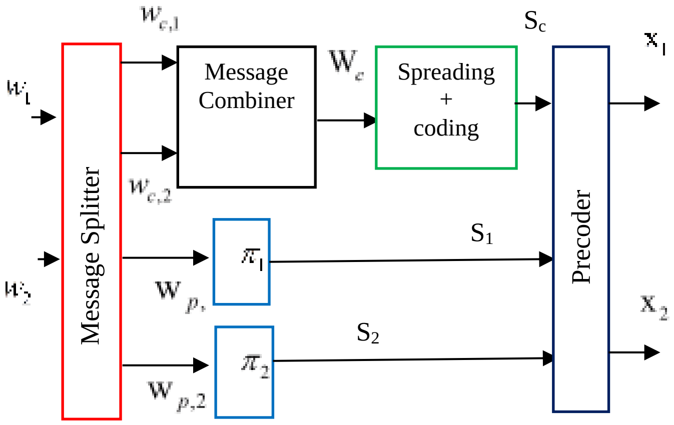

Fig. 1. Transmitter structure of RS-IDMA for two users

So, to maximize total rate, the optimization problem can be stated as [13-15]:

$$\begin{aligned} &\max R_{tot} \\ &\text{s.t.} \quad R'_m+C'_m \geq R_{tot} \\ &\qquad C'_m \geq 0 \\ &\text{tr}(PP^H)\leq P_t \end{aligned}$$

If the optimized rate is mentioned as $\mathbb{R}_{RS}$ and NoRS version of the optimization rate is $\mathbb{R}_{NoRS}$ then for the same transmit power, both the rates can be related as $\mathbb{R}_{RS} > \mathbb{R}_{NoRS}\mathbb{R}_{RS} > \mathbb{R}_{NoRS}$ (for proof see Appendix)

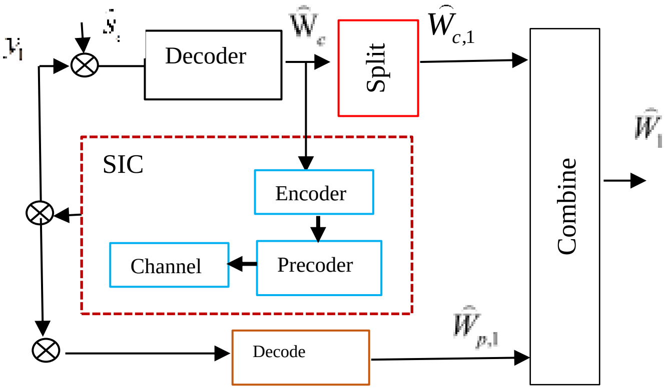

Fig. 2. RSMA receiver block for single user

Further, at receiver the message is detected and estimated with the help of SIC. In addition, with rate splitting, the SIC in IDMA also offers some more advantages, such as; in SIC based IDMA the convergence rate is faster in frequency domain analysis and ordering of users can be optimized according to SINR. Furthermore, the estimated message and the input to the decoder is represented as $\{\hat{s}_c\}$. The receiver carries following operations, (for simplicity, assumed BPSK modulation):

(*A*) Obtained the estimated original message i.e., $\{\hat{s}_c\}$ based on $\{y_1\}$ (obtained from SIC detector). This is assumed that all estimated $\{y_m\}$ are uncorrelated (which is approximately true due to interleaving).

(B) Further estimated message $\{\hat{s}_c\}$ is sent to decoder block to get the estimated super common part of the message $\hat{W}_c$. Moreover, this message is further split to get the common part of user1.

(*C*) Perform standard APP decoding using estimated private part of the message to get the estimated message $\hat{W}_{p,1}$. Here decoder also carries the de-interleaving operation. For simplicity, random interlver has been considered at transmitter (π_1 *and* π_2). LLRs (log likelihood ratios) can be generated to suitably decode the input bits [2].

(*D*) Finally, the common part and private part of the message should be properly combined to get the approximated outcome $\hat{W}_1$ (for user-1). For the successful reception of other user's message, the same process cane repeated.

IV. Performance Analysis

In this section, the performance of proposed system is presented in a wide range of network load. The performance of IDMA system without rate splitting is compared with the suggested RS-IDMA system. For performance realization the weighted sum rate (WSR) is calculated for both the system. Without rate splitting, the SINR of mth user of IDMA system can be written as

$$SINR_m^{NoRS} = \frac{P_m \left| h_m^H w_m \right|^2}{\sum_{j \neq m} P_j \left| h_m^H w_j \right|^2 + 1} \quad (8)$$

Further, the mutual information between transmitter and receiver can be lower bounded by

$$R^{NoRS} = \sum_{m=1}^{M} R_m^{NoRS} \quad (9)$$

where $R_m^{NoRS} = \log_2(1 + SINR_m^{NoRS})$

The Table-1 shows the simulation parameter and figure 1 shows the simulation result of the comparative analysis of the rate splitting based IDMA and conventional IDMA system. In the simulation experiment, four transmitter antennas $(N_t = 4)$ have been considered which serves three single antenna users. The SNR is considered in the range of 0 to 30 dB. Further the sum of weights allocated to three users is equal to one, such that; $w_1 + w_2 + w_3 = 1$.

TABLE I
SIMULATION PARAMETERS

S. no.	Simulation Parameter	Value
1	No. of transmitter Antenna	4
2	SNR range	0-30dB
3	No of users	3
4	Channel	Rayleigh fading
5	Interleaver	Random
6	Code rate	1/2

The simulation result shows that the sum rate of NoRS IDMA is monotonically increases with SNR. However, IDMA with rate splitting approach (RS-IDMA) has better sum rate performance at a particular value of SNR (dB).

In Fig 2, the weight vectors are considered as $w=[0.1\ 0.3\ 0.6]$ and $w'=[0.5\ 0.3\ 0.2]$ respectively. There should be sufficient channel gains differences among users. As per the simulation figure, it can be concluded that in all scenarios and SNR, the rate splitting IDMA (RS-IDMA) performs better. The WSR (weighted sum rate) improvement is clearly shown in the simulation result.

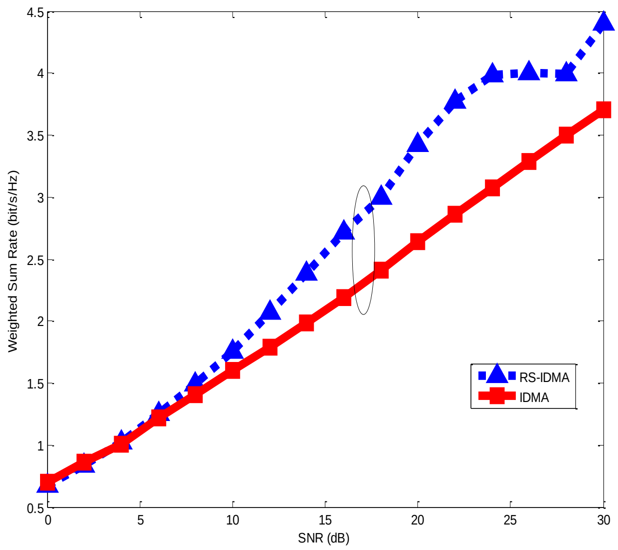

Fig. 3. Weighted Sum Rate Vs SNR comparison of IDMA and RS-IDMA

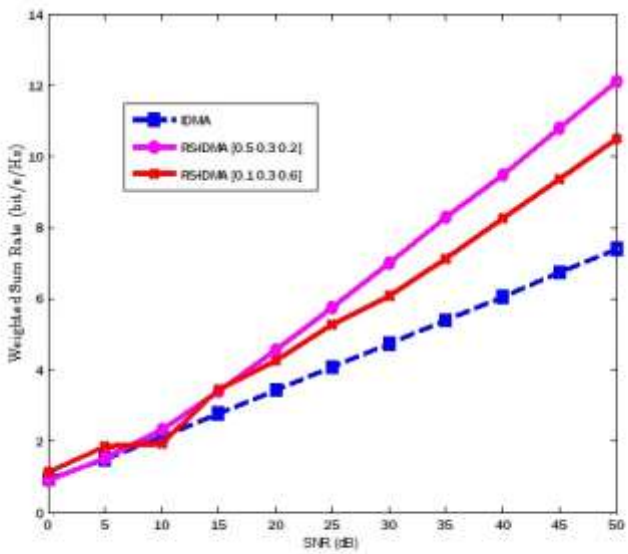

Fig. 4. Weighted Sum Rate Vs SNR comparison of IDMA and RS-IDMA ($N_{t=4}$, $w=[0.1\ 0.3\ 0.6]$ $w'=[0.5\ 0.3\ 0.2]$).

Apart from WSR vs SNR analysis, the energy cost analysis is also required in 5G and 6G communication. So, Energy efficiency (EE) maximization has also been considered to validate the proposed system performance. The EE maximization for RSMA can be considered as

$$EE_k = \frac{C_k + R_k(\mathrm{P})}{\frac{1}{\eta} tr(\mathrm{PP^H}) + \mathrm{P_{cir}}}, \forall k \in \{1, 2\} \quad (10)$$

On the other hand, Energy Efficiency of RS-IDMA can be written as

$$EE_{j,k} = \frac{C_{j,k} + R_{j,k}(\mathrm{P})}{\frac{1}{\eta} tr(\mathrm{PP}^{\mathrm{H}}) + \mathrm{P}_{\mathrm{cir}}}, \forall k \in \{1,2\} \quad (11)$$

The SINR of decoding the common stream s_c for RS-IDMA Where j denotes the unique interleaver at users-k can also be calculated with the equation (11). As per equation no (10) and (11) it can be concluded that proposed joint system has approximately same EE, as interleaving process just scramble the position of bits and have no significant impact on EE maximization [14]. Further, the proposed RS-IDMA scheme can efficiently handle the channel ambiguities due the concept of rate splitting, which is well illustrated in [10].

Further, the proposed scheme performs better in terms of complexity too, the encoding complexity of RSMA is higher than RS-IDMA due to the encoding of the common streams on top of the private streams. The computational complexity of proposed scheme is almost same as RSMA However, RS-IDMA requires multiple layers of SIC, which lead to error propagation in RS-IDMA. The computational complexity of proposed scheme is almost same as RSMA.

V. Concluding Remarks

IDMA has already been considered as code domain NOMA system for future communication networks. However, in multiuser scenario the rate of IDMA system saturates with imperfect CSIT. Rate splitting approach can tackle the degradation of performance of system due to multiple access interference (MAI). Hence, in this paper the joint rate splitting approach based IDMA (RS-IDMA) system has been proposed. Remarkably, RS improved the proposed system performance. Moreover, the simulation results which are based on weighted sum rate (WSR) approach, validated the proposed system performance. Moreover, the use of different interleavers in IDMA can be used as future work for further improvement of the proposed system. The sensitivity analysis can also be done as a future work plan, to ensure the effect of channel and other parameter ambiguities.

Appendix-I

Power allocated to each message is given by $\mathrm{P_c = P(1\text{-}t)}$ and $\mathrm{P_m = Pt/m}$ where $t \in (0,1]$. To enhance the sum rate performance, power splitting ratio t is optimized. The basic idea is to allocate a fraction of t of the total power to transmit the private message of RS and achieve approximately same rate as the NoRS scheme with full power. The sum rate gain of RS over NoRS can be quantified as [xx]

$$\Delta \mathrm{R}^{\mathrm{RS}} = \mathrm{R_c} + \sum_{k=1}^{m} \mathrm{R_k} \text{-} \mathrm{R_k}^{\mathrm{NoRS}} \quad (10)$$

In the equation (10) equality holds for the power splitting ratio $t = \min\left\{\frac{m}{P\tau}, 1\right\}$. Due to the reduction in the power to private message, first the upper bound of rate loss is calculated. So the equation (10) can be elaborated as

$$\begin{aligned} &= \sum_{k=1}^{m} (\log_2(1+\frac{\mathrm{S}}{\mathrm{P}\tau_k + 1}) \text{-} \log_2(1+\frac{\mathrm{S}}{\mathrm{P}\tau_k + 1/t})) \\ &= \sum_{k=1}^{m} \{\log_2(S + P\tau_k + 1) - \log_2(S + P\tau_k + 1/t) \\ &\quad + \log_2(P\tau_k + 1/t) - \log_2(P\tau_k + 1)\} \end{aligned} \quad (11)$$

where $S = P/m$, since $1/t \geq 1$ as $t \in (0,1]$, with this assumption, equation (11) can be reiterated as

$$\leq \sum_{k=1}^{m} (\log_2(P\tau_k + 1/t) - \log_2(P\tau_k + 1))$$

$$\begin{aligned} &\leq \sum_{k=1}^{m} (\log_2(1 + 1/k) - \log_2(1 + 1/P\tau_k)) \\ &\leq m \log_2(1 + 1/m) \\ &\leq \log_2(e) \end{aligned} \quad (12)$$

Hence, the upper bound of the rate loss between the private messages of the NoRS and RS can be expressed as

$$\sum_{k=1}^{m} \mathrm{R_k} \text{-} \mathrm{R_k}^{\mathrm{NoRS}} \leq \log_2(e)$$

By plugging the result of equation (12) in to (10), the sum rate can be easily visualized.

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