Rate-Splitting Multiple Access for Short-Packet Uplink Communications: A Finite Blocklength Error Probability Analysis

Jiawei Xu, Onur Dizdar, Member, IEEE, and Bruno Clerckx, Fellow, IEEE

Abstract—In this letter, we investigate Rate-Splitting Multiple Access (RSMA) for an uplink communication system with finite blocklength. Considering a two-user Single-Input Single-Output (SISO) Multiple Access Channel (MAC), we study the impact of Signal-to-Noise Ratio (SNR), blocklength, power allocation and target rate on the error probability performance of RSMA where one user message is split. We demonstrate that RSMA can improve the error probability performance significantly compared to Non-Orthogonal Multiple Access (NOMA) and RSMA can have a larger rate region than NOMA.

I. INTRODUCTION

Rate-Splitting Multiple Access (RSMA) has been proven to be a strong multi-user transmission scheme and reliable interference management strategy for multi-antenna wireless networks [1]–[3], and has the potential to tackle numerous challenges of modern communication systems [4]. RSMA relies on Rate-Splitting (RS) at the transmitters and Successive Interference Cancellation (SIC) at the receivers. It has been shown to bridge and outperform existing multiple access schemes, such as Space-Division Multiple Access (SDMA), Non-Orthogonal Multiple Access (NOMA), Orthogonal Multiple Access (OMA) and multicasting under perfect and imperfect Channel State Information at the Transmitter (CSIT).

In the downlink, the benefit of RSMA lies in its flexibility to partially decode the multi-user interference and partially treat it as noise; in contrast with SDMA, which fully treats the interference as noise, and NOMA, which fully decodes the interference [1]–[3], [5], [6].

A majority of recent studies on RSMA consider downlink multi-antenna multiple-access scenarios. However, it has been demonstrated that uplink RSMA can achieve the optimal rate region of an $M$-user Gaussian Multiple Access Channel (MAC) using up to $2M-1$ virtual point-to-point Gaussian channels created by message splitting [7]. In [8]–[11], uplink RSMA was shown to lead to better outage probability, sum-throughput, sum-rate performance, high minimum date rate and lower latency compared to NOMA and OMA.

A major application area for uplink multiple-access schemes is Ultra-Reliable Low-Latency Communications (URLLC). The low-latency requirements in URLLC force systems to operate with short blocklength, bringing out the necessity to analyze the system performance with Finite Blocklength (FBL) codes. In the pioneering work [12], the authors have laid the fundamental limits for the achievable rate with FBL codes for given blocklength and error probability, leading the path for theoretical performance analysis with FBL codes. Motivated by the trade-off between achievable rate and error probability, the error probabilities have been derived for NOMA in Additive White Gaussian Noise (AWGN) channel and Rayleigh fading channel with FBL in [13]–[16], and NOMA was shown to achieve higher effective throughput and reduced latency compared to OMA. The authors in [17] have shown RSMA can outperform OMA and NOMA in a network slicing scenario.

In this letter, we investigate for the first time the performance of uplink RSMA with FBL in a two-user system. We study the sum-throughput and rate region maximization problems. We derive the analytical expressions of the error probability and come up with Successive Convex Approximations-based (SCA) algorithms to solve those problems. Our numerical results demonstrate that uplink RSMA achieves more reliable communication with FBL codes compared to uplink NOMA.

II. SYSTEM MODEL

A. RSMA for Uplink Communications

In this section, we consider a two-user uplink scenario with perfect CSIT and Channel State Information at Receiver (CSIR), where two single-antenna users indexed by $K = \{1, 2\}$ communicate with a single antenna Base Station (BS). Following uplink RSMA principle in [7], the message of one user is split, resulting in a total of three streams transmitted to the BS. Fig. 1 illustrates the two-user uplink RSMA example for the SISO MAC. User-1 splits its message $W_1$ into two parts, $W_{1,1}$, $W_{1,2}$, and $W_2$ denote the message of user-2. The messages $W_{1,1}$, $W_{1,2}$, and $W_2$ are encoded into streams $s_{1,1}$, $s_{1,2}$ and $s_2$, respectively. Use $P_k$ to denote the transmit power of user-$k$, $k \in \{1, 2\}$, so the received signal is expressed as

$$y = h_1 \sqrt{P_{1,1}} s_{1,1} + h_1 \sqrt{P_{1,2}} s_{1,2} + h_2 \sqrt{P_2} s_2 + n,$$

where $P_{1,1}$ and $P_{1,2}$ are the transmit power of $s_{1,1}$ and $s_{1,2}$, respectively and $P_{1,1} + P_{1,2} \leq P_1$. $n \sim CN(0, \sigma^2_n)$ is the AWGN at the BS. All possible decoding orders at the BS can be classified into three cases, i.e., (i) $s_{1,1} \rightarrow s_2 \rightarrow s_{1,2}$ (i.e. the BS decodes $s_{1,1}$ first, followed by $s_2$, and finally $s_{1,2}$), (ii) $s_1,1 \rightarrow s_{1,2} \rightarrow s_2$ and (iii) $s_2 \rightarrow s_{1,1} \rightarrow s_{1,2}$. 1

1By exchanging the orders of $s_{1,1}$ and $s_{1,2}$, there are three other decoding orders which are ignored in this letter without loss of generality.
the decoding order (i) to write the Signal-to-Interference-plus-Noise (SINR) sequentially. Accordingly, $s_{1,1}$ is decoded first at the BS by treating other signals as noise. The SINR $\gamma_{1,1}$ of the first decoded stream $s_{1,1}$ is

$$\gamma_{1,1}^1 = \frac{P_{1,1}|h_1|^2}{P_{1,2}|h_1|^2 + P_2|h_2|^2 + \sigma_n^2},$$

where superscript $1$ represents the index of the user with split message. Assuming that $s_{1,1}$ is successfully decoded, it is reconstructed into $\hat{W}_{1,1}$ and subtracted from the original received signal $y$ to obtain $y'$. The SINR of the second decoded stream $s_2$ is

$$\gamma_{1,2}^1 = \frac{P_2|h_2|^2}{P_{1,2}|h_1|^2 + \sigma_n^2}.$$  

Assuming that $s_2$ is successfully decoded to obtain $\hat{W}_2$, it is reconstructed and subtracted from the received signal $y'$. Assuming $s_{1,1}$ and $s_2$ are correctly decoded, the SINR of the last decoded stream $s_{1,2}$ is

$$\gamma_{1,2}^1 = \frac{P_{1,2}|h_1|^2}{\sigma_n^2}.$$  

Finally, if $s_{1,2}$ is successfully decoded, the estimated message $\hat{W}_1$ for user-1 is obtained by combining $\hat{W}_{1,1}$ and $\hat{W}_{1,2}$.

B. NOMA for Uplink Communications

NOMA is a particular instance of the system model of Section II-A, since $0 \leq P_{1,1} \leq P_1$, we can regard NOMA as a subset of RSMA. The messages $W_1$ and $W_2$ from user-1 and user-2 are encoded into $s_{1,1}$ and $s_2$, respectively. The received signal at the BS is expressed as $y = h_1\sqrt{P_1}s_1 + h_2\sqrt{P_2}s_2 + n$. We assume the decoding order as $s_1 \rightarrow s_2$ to demonstrate the SINR sequently and we denote this order as ‘NOMA-1’. Accordingly, the SINR expressions of the streams under the assumption of successful decoding are written as $\gamma_{1,1}^{NOMA-1} = \frac{P_{1,1}|h_1|^2}{P_{1,2}|h_1|^2 + \sigma_n^2}$ and $\gamma_{2,1}^{NOMA-1} = \frac{P_2|h_2|^2}{\sigma_n^2}$, where the superscript ‘NOMA-1’ stands for ‘NOMA-1’.

III. ERROR PROBABILITY ANALYSIS

The finite blocklength achievable rate expression is given by [12]

$$r \approx 0.5 \log_2(1 + \gamma) - \sqrt{\frac{V}{N}} Q^{-1}(\epsilon)$$

where $V = \log^2_2(1 - (1 + \gamma)^{-2})$ is the channel dispersion, $\epsilon$ is the error probability, $\gamma$ is the SINR of the stream, $N$ is the blocklength, and $Q$ is the Q-function. Based on (5), we can write the error probability for a given transmission rate as

$$\epsilon = Q\left(\frac{0.5 \log_2(1 + \gamma) - r}{\sqrt{V/\gamma}/N}\right) = Q(\gamma, r).$$

A. RSMA

Let us denote the target rates of user-1 and user-2 as $r_1$ and $r_2$, respectively. Given that user-1’s message is split, the target rates of two split streams are given by $r_{1,1} = \beta r_1$ and $r_{1,2} = (1 - \beta)r_1$, where $0 \leq \beta \leq 1$ is the rate allocation factor.

We can write the error probability for each event listed above as $Q(\gamma^{NOMA-1}_{1,1}, r_1)$, $Q(\gamma^{NOMA-1}_{1,2}, r_2)$ and $Q(\gamma^{NOMA-1}_{1,2}, r_{1,2})$, respectively. For decoding order (i), the decoding error occurs due to three events listed as $^1$: a) $s_{1,1}$ is incorrectly decoded; b) $s_{1,1}$ is correctly decoded but $s_2$ is incorrectly decoded; c) $s_{1,1}$ and $s_2$ are both correctly decoded but $s_{1,2}$ is incorrectly decoded. Thus, the overall error probabilities for the message of user-1 and user-2 can be calculated as

$$\epsilon_{a}^1 = \epsilon_a^1 + (1 - \epsilon_a^1)\epsilon_b^1 + (1 - \epsilon_a^1)(1 - \epsilon_b^1)\epsilon_c^1$$

$$\epsilon_{b}^2 = \epsilon_a^1 + (1 - \epsilon_a^1)\epsilon_b^1.$$  

B. NOMA

There are two events for incorrect decoding of $s_2$ : a) $s_1$ is incorrectly decoded; b) $s_1$ is correctly decoded but $s_2$ is incorrectly decoded. The probabilities of the specified events are calculated by $\epsilon_a^{NOMA-1} = Q(\gamma^{NOMA-1}_{1,1}, r_1)$ and $\epsilon_b^{NOMA-1} = Q(\gamma^{NOMA-1}_{1,2}, r_2)$, respectively. Accordingly, the overall error probabilities for the message of user-1 and user-2 are given by $\epsilon_{a}^{NOMA-1} = \epsilon_a^{NOMA-1} + (1 - \epsilon_a^{NOMA-1})\epsilon_b^{NOMA-1}$.

IV. PROBLEM FORMULATION AND ALGORITHM

According to Shannon capacity definition, any rate inside the capacity region can be achieved with arbitrarily small error probability under the assumption of infinite blocklength (FBL). However, chances are that the rate inside the capacity region cannot be achieved with an arbitrarily small error probability in FBL regime. Therefore we investigate the sum-throughput achieved by RSMA and NOMA to examine whether RSMA can achieve a lower error probability than NOMA. We define the throughput of each user as $T_k = r_k(1 - \epsilon_k)$ where $\epsilon_k$ is the overall error probability of user-$k$. For a given target rate pair $(r_1, r_2)$, we formulate an optimization problem to maximize the sum-throughput as

$$\max_{P, \beta} T_{tot} = T_1 + T_2$$

s.t. $P_{1,1} + P_{1,2} \leq P_1$ 

$P_2 \leq P_t$, 

$0 \leq \beta \leq 1$, 

where $P = [P_{k,1}, P_{k,2}, P_t]$ represents the transmit power of each stream.

$^2$Q-function is the tail distribution function of the standard normal distribution. Normally, Q-function is defined as: $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{t^2}{2}} dt$.

$^3$Recall that for $\hat{W}_1$ to be equal to the original message $W_1$, both $s_{1,1}$ and $s_{1,2}$ have to be correctly decoded.
We propose a SCA-based algorithm to optimize the transmit power. [18] has introduced a SCA-based algorithm for downlink RSMA where cooperative user relaying is enabled in the system with IFBL. The SCA approach discussed in this section differs from [18] because it takes FBL into consideration and it is for uplink RSMA.

We consider the scenario where the message of user-k is split. \( P_{k,1} \) and \( P_{k,2} \) represent the transmit power of \( s_{k,1} \) and \( s_{k,2} \), respectively and \( P_j \) represents the transmit power of user-j \((j \neq k)\), which does not perform message splitting. We demonstrate the proposed algorithm over decoding order (i), written as \( s_{k,1} \rightarrow s_j \rightarrow s_{k,2} \). The sum-throughput is defined as \( T_{tot} = T_k + T_j = r_k + r_j = TP \). According to the error probability expressions, we can rewrite TP as

\[
TP = (r_k + r_j)(\epsilon^k_a + \epsilon^k_b - \epsilon^k_c + \epsilon^k_d + \epsilon^k_e + \epsilon^k_f).
\]

Since \( r_k + r_j \) is a constant, we can ignore it in the following analysis and minimize the value of TP. Thus, Problem (8) translates into

\[
\begin{align*}
\min_{\mathbf{P},\beta} & \quad TP \\
\text{s.t.} & \quad P_{k,1} + P_{k,2} \leq P_t, k \in \mathcal{K} \\
& \quad P_j \leq P_t, j \neq k \in \mathcal{K} \\
& \quad 0 \leq \beta \leq 1.
\end{align*}
\]

(10a) (10b) (10c) (10d)

Problem (10) is not convex due to the non-convex terms, \( \epsilon^k_a \) and \( \epsilon^k_j \) in (9). We introduce slack variables \( t, \theta = [\theta_a, \theta_b, \theta_c] \) and \( \rho = [\rho_{k,1}, \rho_{j}, \rho_{k,2}] \). With the aid of new variables, Problem (10) is transformed into Problem (11).

\[
\begin{align*}
\min_{\mathbf{P},\theta,\rho,\beta} & \quad t \\
\text{s.t.} & \quad (r_k + r_j)(\theta^a_a + \theta^a_b - \theta^a_c \theta^b_a) + r_k(\theta^a_c - \theta^b_c \theta^c_a) \\
& \quad - r_k(\theta^a_b \theta^b_a - \theta^b_c \theta^c_a) \leq t, k \in \mathcal{K}, j \neq k \in \mathcal{K} \\
& \quad \epsilon^k_i \geq \epsilon^k_i, i \in \{a, b, c\}, k \in \mathcal{K} \\
& \quad \frac{P_{k,1}|h_k|^2}{P_{k,2}|h_k|^2 + P_{j}|h_j|^2 + \sigma^2_n} \geq \rho_{k,1}, k \in \mathcal{K}, j \neq k \in \mathcal{K} \\
& \quad \frac{P_{k,2}|h_k|^2}{P_{k,2}|h_k|^2 + \sigma^2_n} \geq \rho_j, k \in \mathcal{K}, j \neq k \in \mathcal{K} \\
& \quad \frac{P_{k,1}^2|h_k|^2 + \sigma^2_n}{P_{k,2}^2|h_k|^2 + \sigma^2_n} \geq \rho_{k,2}, k \in \mathcal{K} \\
& \quad P_{k,1} + P_{k,2} \leq P_t, k \in \mathcal{K} \\
& \quad P_j \leq P_t, j \neq k \in \mathcal{K} \\
& \quad 0 \leq \beta \leq 1.
\end{align*}
\]

(11a) (11b) (11c) (11d) (11e) (11f) (11g) (11h) (11i)

Problem (11) is still not convex because \( \theta_a \theta_b, \theta_a \theta_c, \theta_b \theta_c \) and \( \theta_a \theta_b \theta_c \) in (11b) are not convex. Therefore, they are approximated at the point \( (\theta^{n}) \) at iteration \( n \) by the first-order Taylor approximation, which can be written as

\[
\begin{align*}
\theta_a \theta_b & \geq \theta_a \theta_b + (\theta_a - \theta^b_a) \theta^b_a \\
\theta_a \theta_c & \geq \Psi^n(\theta_a, \theta_c) \\
\theta_b \theta_c & \geq \Psi^n(\theta_b, \theta_c) \\
\theta_a \theta_b \theta_c & \geq \Phi^n(\theta_a, \theta_b, \theta_c) \\
\theta_a \theta_c + \Psi^n(\theta_a, \theta_c) & \geq \Theta^n(\theta_a, \theta_c) \\
\theta_b \theta_c + \Psi^n(\theta_b, \theta_c) & \geq \Theta^n(\theta_b, \theta_c) \\
\theta_a \theta_b \theta_c + \Phi^n(\theta_a, \theta_b, \theta_c) & \geq \Theta^n(\theta_a, \theta_b, \theta_c).
\end{align*}
\]

(12a) (12b) (12c) (12d)

For constraint (11c), recall from (6) that \( \epsilon^k_i \) is not convex. Thus, we also approximate it around the point \( (\rho^{n}) \) by the first-order Taylor approximation which is given by

\[
\epsilon^k_i \geq Q(s(\rho^{n}_{k,1})) + (\rho_{k,1} - \rho^{n}_{k,1}) \frac{dQ(s(\rho^{n}_{k,1}))}{d\rho^{n}_{k,1}}
\]

(13)

If the argument of Q-function is larger than 0, Q-function is convex, otherwise it is concave. To keep \( \epsilon^k_i \geq \Phi^n(\rho_{k,1}) \), we define an additional constraint given as

\[
s(\rho_{k,1}) \geq 0 \leftrightarrow 0.5 \log_2(1 + \rho_{k,1}) - \beta r_k \geq 0, k \in \mathcal{K}.
\]

(14)

Therefore, constraint (11c) is approximated around the point \( (\rho^{n}) \) at iteration \( n \) as

\[
\Phi^n(\rho_{k,1}) \geq \theta_a, k \in \mathcal{K} \\
\Phi^n(\rho_{j}) \geq \rho_{b}, j \neq k \in \mathcal{K} \\
\Phi^n(\rho_{k,2}) \geq \rho_{c}, k \in \mathcal{K}
\]

(15)

Constraints (11d) and (11e) are respectively approximated around the point \( (\rho^{n}, \rho^{n}) \) at iteration \( n \) by

\[
\begin{align*}
P_{k,1}|h_k|^2 + P_{j}|h_j|^2 + \sigma^2_n & \leq 0, k \in \mathcal{K} \\
P_{k,2}|h_k|^2 + \sigma^2_n & \leq 0, j \neq k \in \mathcal{K}
\end{align*}
\]

(16)

Based on the above approximation methods, the original non-convex problem is transformed into a convex one and can be solved using the SCA method. SCA solves the problem by approximating a sequence of convex sub-problems. At iteration \( n \), based on the optimal solution \( (P^{n}, \theta^{n}, \rho^{n}) \) obtained from the previous iteration \( n - 1 \), we solve the following problem:

\[
\begin{align*}
\min_{\mathbf{P},\theta,\rho,\beta} & \quad t \\
\text{s.t.} & \quad (r_k + r_j)(\theta_a + \theta_b - \Psi^n(\theta_a, \theta_b)) \\
& \quad + r_k(\theta_c - \Psi^n(\theta_b, \theta_c) - \Psi^n(\theta_a, \theta_c) \\
& \quad + \Omega^n(\theta_a, \theta_b, \theta_c)) \leq t, k \in \mathcal{K}, j \neq k \in \mathcal{K} \\
& \quad (11f), (11g), (11h), (11i), (14), (15), (16).
\end{align*}
\]
The SCA-based power allocation algorithm is outlined in Algorithm 1 and the value of $\beta$ is optimized by exhaustive search. $\tau$ is the tolerance of convergence. Since the solution of Problem (17) at iteration $n-1$ is a feasible point of Problem (17) at iteration $n$ and the transmit power constraints (11g) and (11h), the objective function $t$ is monotonically increasing which implies that the convergence of this proposed SCA-based algorithm is guaranteed.

Algorithm 1: Proposed SCA-based algorithm

$\textbf{Initialize:}$ $n \leftarrow 0$, $t^{[n]} \leftarrow 0$, $P^{[n]}, \theta^{[n]}, \rho^{[n]}$;

1 repeat
2 $n \leftarrow n + 1$;
3 Solve problem (17) using $P^{[n-1]}, \rho^{[n-1]}$ and denote the optimal objective as $t^*$ and the optimal variables as $P^*, \theta^*, \rho^*$;
4 Update $t^{[n]} \leftarrow t^*, P^{[n]} \leftarrow P^*, \theta^{[n]} \leftarrow \theta^*, \rho^{[n]} \leftarrow \rho^*$;
5 until $|t^{[n]} - t^{[n-1]}| \leq \tau$;

V. Numerical Results

In this section, we perform our simulations for AWGN channel. Without loss of generality, we assume that the noise variance is equal to 1 and $P_t = 10$ dB. Results of four blocklength which are $N = 500, 1500, 2500$ and 5000 are compared. To evaluate the sum-throughput achieved by RSMA and NOMA according to different target rate pairs, we choose three kinds of symmetric target rate pairs which are noted as low, middle and high inside the capacity region with IFBL, respectively. To make target rate pairs symmetric, we choose these three kinds of target rate pairs to be on three circles with different radius. Thus, the selected target rate pairs are on the circles with radius of 0.8, 1.2 and 1.4 corresponding to low, middle and high, respectively. Then, we compare the rate region of NOMA and RSMA with different blocklengths. We use 'NOMA-1' and 'NOMA-2' to refer to the NOMA schemes with the decoding orders $s_1 \rightarrow s_2$ and $s_2 \rightarrow s_1$, respectively. 'RSMA-1' and 'RSMA-2' refer to the case where the message of user-1 and user-2 is split, respectively.

A. Error Probability

1) Without Time-Sharing: Fig.2 shows the results of NOMA and RSMA. In Fig.2(a), 'NOMA-1' and 'NOMA-2' can achieve the low and middle target rate pairs. However, the performance of NOMA deteriorates rapidly when $r_1$ is larger than 0.5 or $r_2$ is larger than 0.5 and even with large blocklength NOMA still cannot achieve every high target rate pairs. In Fig.2(b), we note that 'RSMA-1' and 'RSMA-2' have the same performance and RSMA can achieve the high target rate with very low error probabilities even with short blocklength.

2) With Time-Sharing: The result with time-sharing is shown in Fig.3. Compared to the result of no-time-sharing in Fig.2(a), the performance of NOMA becomes better. It can achieve the same throughput as RSMA by transmitting at two target rate pairs with time-sharing. When blocklength is equal to 5000, NOMA can achieve all the target rate pairs with small error probability.

B. Rate Region

We know that both 'NOMA-1' and 'NOMA-2' cannot achieve all the high target rate pairs in Sec.V-A, thus we investigate the max target rate pairs that can be achieved by 'NOMA-1' and RSMA. In the simulation, we set the error probability of each user is no larger than $10^{-3}$ and we plot the rate region can be achieved by RSMA and 'NOMA-1' with this error probability constraint.

In Fig.4, one can observe that as the blocklength increases, the rate region of RSMA becomes closer to the capacity region while the rate region of 'NOMA-1' is always smaller than RSMA. It can be concluded that RSMA with decoding order of $s_{1,1} \rightarrow s_2 \rightarrow s_{1,2}$ can achieve a larger rate region while NOMA can only achieve it by cooperating with time-sharing. The reason is that if we allocate all the transmit power to
RSMA performs like ‘NOMA-1’ and if we allocate all the transmit power to $s_{1,2}$, RSMA performs like ‘NOMA-2’. By changing the allocation of the transmit power between two split streams, RSMA bridges ‘NOMA-1’ and ‘NOMA-2’ without time-sharing.

![Fig. 3. Throughput of user-1 and user-2 with N=500](image1)

$s_{1,1}$, RSMA performs like ‘NOMA-1’ and if we allocate all the transmit power to $s_{1,2}$, RSMA performs like ‘NOMA-2’. By changing the allocation of the transmit power between two split streams, RSMA bridges ‘NOMA-1’ and ‘NOMA-2’ without time-sharing.

![Fig. 4. Rate region of user-1 and user-2](image2)

**VI. CONCLUSION**

This letter studies whether RSMA can improve the error probability performance, sum-throughput and the rate region with FBL in SISO MAC. The numerical results show that RSMA can achieve significantly higher results than NOMA without time-sharing. When time-sharing is included, NOMA can achieve the same sum-throughput as RSMA by transmitting at two different target rate pairs while RSMA can directly achieve it by transmitting at one target rate pair. When users transmit at the same target rate pair with RSMA and NOMA respectively, RSMA outperforms NOMA. Secondly, the max transmit target rate with constrained error probabilities is studied. The result shows that the rate region of RSMA is always larger than NOMA without time-sharing. In summary, when the target rates are fixed, RSMA provides lower error probabilities than NOMA and when the error probabilities are fixed, RSMA achieves a larger rate region than NOMA.

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