Network Slicing for eMBB and mMTC with Finite Blocklength Codes

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***Abstract*—Network slicing appears as a key enabler for next-generation wireless networks and together with multiple access schemes can meet the quality of service (QoS) requirements of various users and services. Thus, in this work, a heterogeneous uplink network is investigated, where enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC) users coexist and share the same resources. The problem of maximizing the sum-rate of eMBB users utilizing the rate-splitting multiple access (RSMA) protocol is formulated and optimally solved, whereas the optimal decoding order and power splitting factor are investigated. In addition, short packet communications are taken into account for the mMTC users and their optimal transmission power is derived in closed form. Simulation results verify the enhancement that the RSMA scheme provide compared to the NOMA counterpart.**

***Index Terms*—eMBB, mMTC, short packet communications, uplink RSMA**

I. Introduction

The emergence of sixth-generation (6G) wireless networks marks a significant advancement beyond fifth-generation (5G) networks, with a focus on enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC) [1]. Specifically, eMBB targets exceptionally high data rates, improved connectivity, and user mobility, with high reliability, while mMTC addresses the needs of a growing array of sporadically active Internet of Things (IoT) devices that transmit small data payloads, tackling cost and power consumption challenges. Due to their sporadic and relatively low-rate transmission of short packets, finite blocklength (FBL) codes are commonly utilized [2]. Finally, URLLC focuses on the rapid and reliable transmission of small data packets.

In this direction, the adoption of Open Radio Access Network (O-RAN) stands out as a pivotal architectural approach to optimize and tailor the network architecture to these diverse requirements. To accommodate customized and on-demand network services, the concept of network slicing has been introduced, which facilitates the simultaneous operation of diverse use cases with different requirements on the same RAN infrastructure [3]. To effectively coordinate and distribute resources among various users and services, multiple access appears as a critical facilitator. Non-orthogonal protocols have been suggested as supplementary to orthogonal ones, providing enhanced connectivity. Rate-splitting multiple access (RSMA) stands out as a promising technique, capable of managing heterogeneity in wireless networks and achieving the entire capacity region effectively [4], [5].

A heterogeneous uplink network, featuring eMBB and multiple mMTC or URLLC users, was investigated in [6]–[8] and the potential improvement of the RSMA protocol over the orthogonal (OMA) and non-orthogonal multiple access (NOMA) counterparts was observed. Furthermore, the performance under short packet communications has been examined in [9]–[12]. An energy-efficient resource allocation strategy for cellular-based mMTC users with short packets in an uplink network with the coexistence of cellular users was performed in [9]. In [10], secure transmission in an FBL regime for IoT applications was investigated, with the NOMA protocol outperforming the OMA counterpart in both uplink and downlink scenarios. Moreover, the performance of two-user uplink RSMA with FBL codes for throughput maximization was examined in [11] and a successive convex approximation algorithm was used to handle non-convexity. In [12], the optimal resource allocation for URLLC users was investigated and an approximation for their achievable rate in short blocklength regime was taken into account. Therefore, although the use of RSMA for heterogeneous network slicing [6], [7] and short packets in a network with diverse users [9] were studied, the use of RSMA for heterogeneous network slicing with an FBL regime has yet to be investigated.

To this end, we investigate the RSMA protocol for a heterogeneous uplink network consisting of two eMBB and multiple mMTC users, where FBL codes are utilized for the mMTC. Our primary interest is to maximize the sum-rate of the eMBB users under given quality of service (QoS) requirements of all users. An approximation is employed in the rate expression of mMTC users and a closed-form expression of their optimal transmission power is derived. For the RSMA scheme of eMBB users, the optimal decoding order and power splitting factor are investigated. Simulation results show that the eMBB users achieve better performance utilizing the RSMA scheme compared to NOMA.

II. System Model

We assume a heterogeneous uplink system consisting of two eMBB, M mMTC devices, and a base station (BS). Both eMBB and mMTC users are assigned to a single frequency channel with bandwidth B. Rayleigh fading is assumed, thus the channel coefficients of eMBB user i and mMTC user m are given by $h_{\mathrm{B}_i} \sim \mathcal{CN}(0,1)$ and $h_{\mathrm{M}_m} \sim \mathcal{CN}(0,1)$, and the channel gains, denoted as $|h_{\mathrm{B}_i}|^2$ and $|h_{\mathrm{M}_m}|^2$, follow exponential distribution. We denote the path loss as $l_n = l_0\, d_n{}^{-\kappa}$, where d_n is the distance between a user n and the BS, κ is the path loss exponent and l_0 is the path loss at reference distance d_0. The transmit power of eMBB and mMTC users' messages is denoted as p_i, $i \in \{1,2\}$, and q_m, $m \in \{1,\ldots,M\}$, respectively. We also assume that the eMBB users are decoded first, so they have interference from the mMTC users, while the mMTC users do not interfere with the eMBB users. Perfect channel state information is available for users of both services.

The eMBB users communicate with the BS utilizing the RSMA protocol, whereas the mMTC use the NOMA counterpart. For the eMBB devices, they are sorted by their channel gains in descending manner, i.e., $|h_{\mathrm{B}_1}|^2 \geq |h_{\mathrm{B}_2}|^2$, and the first user splits its message into two sub-messages, $s_{\mathrm{B}_{1,1}}, s_{\mathrm{B}_{1,2}}$. We denote the power splitting factor of $s_{\mathrm{B}_{1,1}}$ as $\beta \in [0,1]$. The received signal at the BS is given by

$$\begin{aligned} y = &\sqrt{\beta\, p_1\, l_1}\, h_{\mathrm{B}_1} s_{\mathrm{B}_{1,1}} + \sqrt{(1-\beta)\, p_1\, l_1}\, h_{\mathrm{B}_1} s_{\mathrm{B}_{1,2}} \\ &+ \sqrt{p_2\, l_2}\, h_{\mathrm{B}_2} s_{\mathrm{B}_2} + \sum_{m=1}^{M} \sqrt{q_m\, l_m}\, h_{\mathrm{M}_m} s_{\mathrm{M}_m} + n, \end{aligned} \tag{1}$$

where n is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

Assuming that $s_{\mathrm{B}_{1,1}}$ is decoded prior to $s_{\mathrm{B}_{1,2}}$, the possible decoding orders of the eMBB users' message are

$$\begin{gathered} \mathrm{r}_1\!: s_{\mathrm{B}_{1,1}} \to s_{\mathrm{B}_2} \to s_{\mathrm{B}_{1,2}}, \quad \mathrm{r}_2\!: s_{\mathrm{B}_{1,1}} \to s_{\mathrm{B}_{1,2}} \to s_{\mathrm{B}_2}, \\ \mathrm{r}_3\!: s_{\mathrm{B}_2} \to s_{\mathrm{B}_{1,1}} \to s_{\mathrm{B}_{1,2}}. \end{gathered} \tag{2}$$

The SINR expressions of all eMBB users' streams are derived according to the first decoding order and can be written as

$$\gamma_{\mathrm{B}_{1,1}} = \frac{\beta\, p_1\, l_1\, |h_{\mathrm{B}_1}|^2}{(1-\beta)\, p_1\, l_1\, |h_{\mathrm{B}_1}|^2 + p_2\, l_2\, |h_{\mathrm{B}_2}|^2 + I_{\mathrm{m}} + B\,\sigma^2} \tag{3a}$$

$$\gamma_{\mathrm{B}_2} = \frac{p_2\, l_2\, |h_{\mathrm{B}_2}|^2}{(1-\beta)\, p_1\, l_1\, |h_{\mathrm{B}_1}|^2 + I_{\mathrm{m}} + B\,\sigma^2} \tag{3b}$$

$$\gamma_{\mathrm{B}_{1,2}} = \frac{(1-\beta)\, p_1\, l_1\, |h_{\mathrm{B}_1}|^2}{I_{\mathrm{m}} + B\,\sigma^2}\ , \tag{3c}$$

where $I_{\mathrm{m}} = \sum_{m=1}^{M} q_m l_m\, |h_{\mathrm{M}_m}|^2$ is the interference from the mMTC users. These expressions can be adapted to any decoding order. The corresponding data rates are given by

$$R_{\mathrm{B}_n} = B\, \log_2(1+\gamma_{\mathrm{B}_n}) \ \text{(bps)}, \ \ n \in \{1{,}1\,,\ 2\,,\ 1{,}2\}. \tag{4}$$

The data rate of the eMBB user 1 is also split into two subrates, i.e., $R_{\mathrm{B}_1} = R_{\mathrm{B}_{1,1}} + R_{\mathrm{B}_{1,2}}$.

The eMBB users' data rate is equal to the Shannon capacity with infinite blocklength assumption. However, as for the mMTC users, they utilize FBL codes to achieve low transmission latency. These users are sorted in descending order by their channel gains, i.e., $|h_{\mathrm{M}_1}|^2 \geq |h_{\mathrm{M}_2}|^2 \geq \ldots \geq |h_{\mathrm{M}_M}|^2$, and their messages s_{M_m} are decoding by this order. The SINR and the corresponding rate of a mMTC user m can be written, respectively, as

$$\gamma_{\mathrm{M}_m} = \frac{q_m\, l_m\, |h_{\mathrm{M}_m}|^2}{\sum_{k=m+1}^{M} q_k\, l_k\, |h_{\mathrm{M}_k}|^2 + B\,\sigma^2}, \tag{5}$$

$$R_{\mathrm{M}_m} = B \left(\log_2(1+\gamma_{\mathrm{M}_m}) - \log_2(e) \sqrt{\frac{V(\gamma_{\mathrm{M}_m})}{L}}\, Q^{-1}(\epsilon_{\mathrm{M}}) \right), \tag{6}$$

where $V(\gamma) = 1 - (1+\gamma)^{-2}$ is the channel dispersion parameter and is a function of SINR, L is the blocklength, $Q(\cdot)^{-1}$ is the inverse of the Gaussian Q-function, with $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$, and ϵ_{M} is the error probability.

III. Sum Rate Maximization for eMBB Users

The objective of this section is to maximize the sum rate of the eMBB users' messages under given quality of service (QoS) requirements, i.e., rate threshold requirements, for all eMBB and mMTC users. In addition, since users of both services are power-limited, transmission power constraints are taken into account and a resource allocation is performed. The optimization problem is then formulated as

$$\begin{aligned} \max_{\mathbf{p},\mathbf{q},\beta} \quad & \sum_{i=1}^{2} R_{\mathrm{B}_i} \\ \textbf{s.t.} \quad & C_1 : \ R_{\mathrm{B}_i} \geq R_{\mathrm{B}}^{\mathrm{th}}, \qquad\qquad i \in \{1,2\} \\ & C_2 : \ R_{\mathrm{M}_m} \geq R_{\mathrm{M}}^{\mathrm{th}}, \quad m \in \{1,\ldots,\mathcal{M}\} \\ & C_3 : \ p_i \leq p_{\max}, \qquad\qquad i \in \{1,2\} \\ & C_4 : \ q_m \leq q_{\max}, \qquad m \in \{1,\ldots,\mathcal{M}\} \\ & C_5 : \ \beta \in [0,\,1]\ . \end{aligned} \tag{7}$$

To maximize the transmission rate of the eMBB users implies a maximization in their SINR, hence a minimization in their interference. This can be achieved, if the mMTC users transmit in their minimum rate, i.e., $R_{\mathrm{M}_m} = R_{\mathrm{M}}^{th}$, $\forall m \in \{1,\ldots,M\}$. Therefore, from the equality in constraint C_2 it can be noted that a closed-form expression for the transmission power of mMTC users' messages can be derived. However, the expression for V in (6), which contains the power variables, poses a challenge. To overcome this issue, we assume $V \approx 1$, to make the rate expression more accessible for algebraic manipulation. The approximation is accurate for high SINR values, i.e., $\gamma_{\mathrm{M}_m} \gg 1$. Furthermore, when transmission rate is concerned, the performance gap between the real value of V and the approximation is negligible [13]. At this point, we set

$$D = \log_2(e) \sqrt{\frac{V(\gamma_{\mathrm{M}_m})}{L}}\, Q^{-1}(\epsilon_{\mathrm{M}}) \approx \frac{\log_2(e)\; Q^{-1}(\epsilon_{\mathrm{M}})}{\sqrt{L}}\ , \tag{8}$$

and (6) is rewritten as

$$R_{\mathrm{M}_m} = B\left(\log_2(1+\gamma_{\mathrm{M}_m}) - D\right). \quad (9)$$

Furthermore, we also set $g_{\mathrm{B}_i} = l_i\,|h_{\mathrm{B}_i}|^2$, $i \in \{1,2\}$, and $g_{\mathrm{M}_m} = l_m\,|h_{\mathrm{M}_m}|^2$, $m \in \{1,\ldots,M\}$. The optimal transmission power of a mMTC user m is given by

$$q_m^* = \min\left\{\frac{B\sigma^2}{g_{\mathrm{M}_m}}\left(2^{\frac{R_{\mathrm{M}}^{th}}{B}+D}-1\right)2^{(M-m)\left(\frac{R_{\mathrm{M}}^{th}}{B}+D\right)},\ q_{\max}\right\}, \quad (10)$$

where $\min\{\cdot\}$ is used to denote that q_m^* satisfies constraint C_4. The optimization variables are p_i, $i \in \{1,2\}$, and β and the optimization problem can be written as

$$\begin{aligned} \max_{\mathbf{p},\beta} \quad & \sum_{i=1}^{2} R_{\mathrm{B}_i} \\ \textbf{s.t.} \quad & C_1:\ R_{\mathrm{B}_i} \geq R_{\mathrm{B}}^{\mathrm{th}}, \quad i \in \{1,2\} \\ & C_2:\ p_i \leq p_{\max}, \quad i \in \{1,2\} \\ & C_3:\ \beta \in [0,\,1]\,. \end{aligned} \quad (11)$$

It is observed that problem (11) is non-convex, due to the objective function and constraint C_1. The main reason for that is the term of interference in the denominator, which includes the power variable, and the existence of products of the power and splitting power variables in the SINR expressions in the transmission rate. To this end, we introduce the variables

$$\tau_1 = R_{\mathrm{B}_{1,1}}^{min}, \quad \tau_2 = R_2^{min} \quad \text{and} \quad \tau_3 = R_{1,2}^{min}, \quad (12)$$

that denote the minimum rate of each eMBB user's stream. Hence, $R_1^{min} = R_{1,1}^{min} + R_{1,2}^{min} = \tau_1 + \tau_3$ and $R_2^{min} = \tau_2$. We also set $\beta = \beta_1$ and $1-\beta = \beta_2$. The optimization problem can now be written as

$$\begin{aligned} \max_{\mathbf{p},\beta_1,\beta_2,\tau} \quad & \sum_{k=1}^{3} \tau_k \\ \textbf{s.t.} \quad & C_1:\ R_{\mathrm{B}_{1,1}} \geq \tau_1, \quad R_{\mathrm{B}_2} \geq \tau_2, \quad R_{\mathrm{B}_{1,2}} \geq \tau_3 \\ & C_2:\ \tau_1 + \tau_3 \geq R_{\mathrm{B}}^{\mathrm{th}}, \quad \tau_2 \geq R_{\mathrm{B}}^{\mathrm{th}} \\ & C_3:\ p_i \leq p_{\max}, \quad i \in \{1,2\} \\ & C_4:\ \beta_1 + \beta_2 = 1\,. \end{aligned} \quad (13)$$

It is noted that problem (13) is still non-convex, due to constraint C_1. To tackle this issue and avoid having products of the optimization variables in the final expressions, we introduce the following transformations:

$$p_i = \exp(\tilde{p}_i), \quad \beta_i = \exp(\tilde{\beta}_i), \quad \forall\, i \in \{1,2\}. \quad (14)$$

After some algebraic manipulations, C_1 can be written in convex form. Hence, the non-linear optimization problem can be formulated as

$$\begin{aligned} \max_{\tilde{\mathbf{p}},\tilde{\beta}_1,\tilde{\beta}_2,\tau} \quad & \sum_{k=1}^{3} \tau_k \\ \textbf{s.t.} \quad & C_{1a}:\ -\tilde{\beta}_1 - \tilde{p}_1 - \log(g_{\mathrm{B}_1}) + \log\left(2^{\frac{\tau_1}{B}} - 1\right) \\ & \quad + \log\left(e^{\tilde{\beta}_2+\tilde{p}_1} g_{\mathrm{B}_1} + e^{\tilde{p}_2} g_{\mathrm{B}_2} + \sum_{k=1}^{M} q_k^*\, g_{\mathrm{M}_k} + B\sigma^2\right) \leq 0 \\ & C_{1b}:\ -\tilde{p}_2 - \log(g_{\mathrm{B}_2}) + \log\left(2^{\frac{\tau_2}{B}} - 1\right) \\ & \quad + \log\left(e^{\tilde{\beta}_2+\tilde{p}_1} g_{\mathrm{B}_1} + \sum_{k=1}^{M} q_k^*\, g_{\mathrm{M}_k} + B\sigma^2\right) \leq 0 \\ & C_{1c}:\ -\tilde{\beta}_2 - \tilde{p}_1 - \log(g_{\mathrm{B}_1}) + \log\left(2^{\frac{\tau_3}{B}} - 1\right) \\ & \quad + \log\left(\sum_{k=1}^{M} q_k^*\, g_{\mathrm{M}_k} + B\sigma^2\right) \leq 0 \\ & C_2:\ -\tau_1 - \tau_3 + R_{\mathrm{B}}^{\mathrm{th}} \leq 0, \quad -\tau_2 + R_{\mathrm{B}}^{\mathrm{th}} \leq 0 \\ & C_3:\ e^{\tilde{p}_i} - p_{max} \leq 0, \quad \forall\, i \in \{1,2\} \\ & C_4:\ e^{\tilde{\beta}_1} + e^{\tilde{\beta}_2} - 1 = 0, \end{aligned} \quad (15)$$

where log denotes the natural logarithm. Apart from the convex constraint C_1, the objective function and the inequality constraints C_2 and C_3 are also convex as linear and exponential functions, while the equality constraint C_4 is convex as sum of exponential terms. Therefore, the optimization problem (15) is convex. The optimal solution can be obtained by any mathematical tool for solving non-linear and constrained optimization problems, e.g., an interior-point method algorithm.

IV. Numerical Results and Discussion

In this section, Monte Carlo simulation results are presented for a network consisting of two eMBB and five, $M = 5$, mMTC users. The performance of the RSMA protocol is evaluated and compared with NOMA, while the optimal decoding order in the RSMA scheme is also investigated. The parameters used for the simulations and their values, if not otherwise stated, are given in Table I.

TABLE I: Simulation parameters.

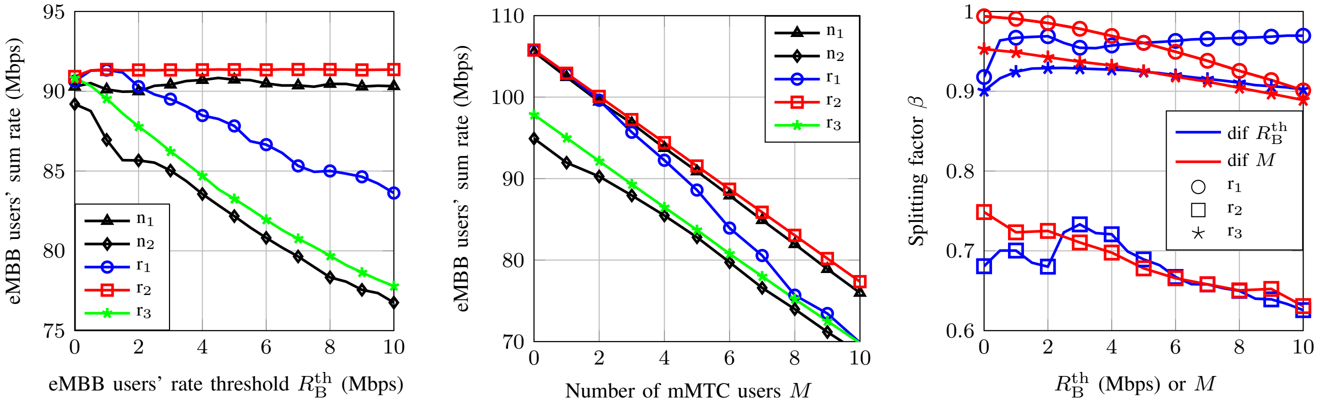
Parameter	Value	Parameter	Value
$p_{\max}$	1 mW	$q_{\max}$	0.5 mW
$R_{\mathrm{B}}^{\mathrm{th}}$	5 Mbps	$R_{\mathrm{M}}^{\mathrm{th}}$	1 Mbps
B	10 MHz	σ^2	4×10^{-15} mW/Hz
L	100	ϵ_M	10^{-1}
l_0	44 dB	κ	2.2

Setting $\beta = 0$ or $\beta = 1$, the RSMA scheme degenerates to NOMA. The possible decoding orders of the messages of eMBB users utilizing the NOMA protocol are

$$\mathrm{n}_1\!: s_{\mathrm{B}_1} \rightarrow s_{\mathrm{B}_2}, \quad \mathrm{n}_2\!: s_{\mathrm{B}_2} \rightarrow s_{\mathrm{B}_1}. \quad (16)$$

In the following figures, 'r_k' and 'n_k' refer to the access protocols that utilize the eMBB users, i.e. the RSMA and the NOMA protocols, with the decoding order k, as introduced in (2) and (16), respectively.

Fig. 1a illustrates the sum-rate of eMBB users versus different values of their rate threshold. It is noted that the optimal decoding order of the RSMA scheme in this heterogeneous network is r_2, different from r_1, which is presented in literature as optimal. Utilizing the RSMA protocol with decoding order r_2 the eMBB users achieve a better sum-rate compared to



(a) Sum-rate vs rate threshold of eMBB users.

(b) Sum-rate of eMBB users vs number of mMTC users.

(c) Power splitting factor vs eMBB users' rate threshold and number of mMTC users.

Fig. 1: Sum-rate maximization and power splitting factor allocation for eMBB users.

NOMA, while the other two decoding orders outperform both NOMA schemes for low values of rate threshold. Moreover, an increase in R_B^{th} does not affect r_2 and n_1 so much, while leads to a decrease in sum-rate in the other cases.

In Fig. 1b, the relationship between the sum-rate of eMBB users and the number of active mMTC users is examined. The eMBB users can utilize the RSMA or the NOMA protocol. Taking into account that eMBB users' messages are decoded first, they all receive the same amount of interference from the mMTC users. As the number of mMTC users increases, the interference they create to the eMBB users increases as well, resulting in a lower transmission rate. It is observed that the RSMA scheme with decoding order r_2 outperforms the NOMA counterpart, while the performance of the other two decoding orders lies between both decoding orders of NOMA.

To achieve the sum-rates of Fig. 1a, 1b utilizing the RSMA protocol, the power splitting factor of each sub-message needs to be adjusted. Hence, the optimal splitting factor β of the first eMBB user's message is plotted for different values of R_B^{th} and M in Fig. 1c. It is observed that for r_1, $s_{B_{1,1}}$ is transmitted with $\beta \geq 0.9$ of total power. This enables the decoding of s_{B_2}, since the interference of $s_{B_{1,2}}$ is reduced. For RSMA with r_2, it is noted that $0.62 < \beta < 0.75$, which favors $s_{B_{1,2}}$ to achieve a satisfactory rate, and combined with $s_{B_{1,1}}$ to satisfy its QoS requirement. Moreover, for r_3, $s_{B_{1,1}}$ has to be transmitted with a high fraction of total power in order to achieve maximum rate. It should also be noted that this form of the curves is responsible for the declining trend of the sum-rate, especially in Fig. 1a.

V. Conclusion

In this work, the co-existence of two eMBB and multiple mMTC users is investigated. The eMBB users utilize the RSMA protocol, whereas the mMTC use the NOMA counterpart in the FBL regime. A closed-form expression of the transmission power of mMTC users is derived. By adjusting the splitting factor and selecting the optimal decoding order, eMBB users can achieve a higher sum-rate, taking into account different QoS requirements of all users.

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