Data-Oriented Downlink RSMA Systems

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***Abstract*— Rate-splitting multiple access (RSMA) provides a flexible and promising non-orthogonal multiple access paradigm which relies on splitting user messages into common and private parts and utilizing successive interference cancellation at the receivers. By doing so, the achievable degrees of freedom can be increased so that different frameworks are available, ranging from the infinite blocklength regime to the finite blocklength regime. The latter one attracted considerable attention over the fifth generation (5G) and beyond 5G networks in the context of short packet transmission. In this respect, data-oriented approach introduces a transient performance metric for small data transmissions where the amount of data and available bandwidth play an essential role in the performance evaluation. Motivated by this fact, this letter represents the first framework where a data-oriented approach is applied to downlink RSMA systems under finite blocklength regime. Particularly, the optimization of the RSMA downlink system in the context of the data-oriented approach is proposed and the numerical results show that data-oriented RSMA systems introduce an efficient design for multi-user short-packet transmissions.**

***Index Terms*— Data-oriented approach, downlink RSMA, short-packet transmission.**

I. INTRODUCTION

THE 6G applications introduce massive access constraints over different applications and robust interference management mechanisms become more important than ever [1]. This trend can be observed in ongoing 5G standardization efforts where non-orthogonal multiple access (NOMA) was introduced. By doing so, a dedicated frequency channel is shared with multiple users simultaneously to provide capacity enhancement, and it was shown that the NOMA systems outperform the existing orthogonal multiple access (OMA) systems in terms of the capacity over infinite and finite blocklength regimes [2]. However, it appeared that using successive interference cancellation (SIC) receivers end up with an inefficient multiplexing gain in multi-antenna NOMA systems [3]. Then, the need for a new strategy to address the massive accessibility requirements along with the need for better interference management inherited from the early development of the 6G standardization.

Within this direction, non-orthogonal unicast and multicast (NOUM) transmission attracts growing interest in the development of the 6G. Particularly, it enables unicast and multicast messages to be transmitted using the same time-frequency resource blocks [4]. For instance, the transmitting message consists of two separate streams in the case of multi-user linear precoding (MU-LP); the multicast stream is intended for all users, and the independent unicast streams are linearly precoded and superimposed before the transmission. In this case, single-layer SIC is applied in the decoding process at each user once the multicast stream is decoded. Then, the single-layer SIC has been extended to a multi-layer SIC-based version along with a new principle that implies partially decoding the interference and partially treating it as noise [4]. Then, the RSMA has emerged as a powerful non-orthogonal transmission framework and a robust interference management strategy for wireless networks [5]. The RSMA is based on splitting the message into certain common and private parts in each user, and while the common parts are jointly encoded into a common stream, different encoders can be used for the private parts and these can be superimposed on the common stream. At the receiver side, the SIC is applied at each user to enable decoding of the common stream and the intended private stream, respectively.

After latency requirements that appeared in 5G and 6G created a rejuvenated interest in short blocklength transmissions, performance analysis based on finite blocklength becomes popular. When the finite block length is considered, the information-theoretic limits on the achievable rate and Block Error Rate (BLER) diverge from those along with the infinite blocklength capacity formulation [6]. Most existing RSMA design frameworks are initially based on Shannon capacity, so they simply ignored finite blocklength regimes and latency constraints. Then, [7] has introduced the performance of the RSMA for the uplink communication system with finite blocklength, and the similar analysis for downlink systems has been presented along with the precoder design in [8].

Apart from finite blocklength consideration, data-oriented transmission also brought a new transmission perspective [9] that focuses on individual data-transmission sessions rather than considering performance evaluation based on long-term average channel statistics, the so-called channel-oriented approach. In the channel-oriented approach, a very large number of coherence time intervals are assumed during data transmission, so ergodic capacity analysis is utilized to evaluate the performance for a given wireless communication system. In the data-oriented approach, the amount of data

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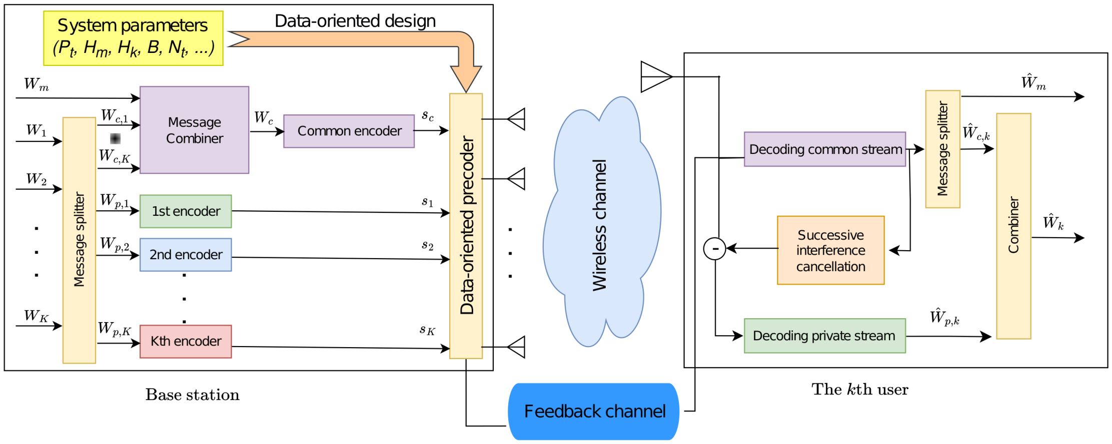


Fig. 1. The downlink RSMA system model where the details of the BS and the decoding procedure of the kth user are illustrated.

and available bandwidth start to play an essential role in the performance evaluation since data transmission sessions are completed within one channel coherence time over short packet transmission sessions [10]. For instance, consider a case where a packet of 1 Kbit is required to be transmitted over a wireless channel where 1 Mbit/s data rate is achieved along with an average bit error rate of 10^{-4}. Under these conditions, taking into account of fluctuations in fading effects, there is no guarantee of successful transmission with 99.999999% certainty based on the given average channel performance within 1 ms [9]. In the data-oriented approach, a new metric, called delay outage ratio (DOR) [9], was introduced where the impact of latency on various network configurations becomes the focus of the performance evaluation.

The DOR metric for the short packet transmission over fading channels was presented in [10] and inspired by it, [11] represented how the DOR expression can be utilized for searching optimum constellation point over a coded scenario in [11]. The DOR metric has been recently utilized in the coverage analysis of reflective intelligent surfaces (RIS)-aided communication systems [12] and over visible light communication scenarios [13].

This letter is the first study to adopt the data-oriented approach in downlink RSMA systems. For this purpose, the DOR expression of a downlink RSMA system has been initially defined. Once DOR analysis is presented, two different precoder designs are investigated based on this new metric and the successive convex approximation (SCA) is utilized over the optimization formulations. In the first design, the objective is to minimize the duration for packet delivery time, while in the second design, the focus is on minimizing the transmitted power under a given threshold for each user. The simulation results illustrate that applying the data-oriented approach to the downlink RSMA systems achieves better performance in terms of packet delivery time and transmitted power for individual transmissions compared to the existing MU-LP and NOMA downlink systems and the simulation results illustrate the effectiveness of the data-oriented approach in providing better insight into the delay transmission of individual data transmission periods compared to average performance results.

Notation- The superscripts $(\cdot)^T$ and $()^H$ denote transpose and conjugate-transpose (Hermitian) operators, respectively. Also $\mathrm{tr}(\cdot)$ represents trace, $\mathbb{E}[\cdot]$ is the expectation operator, and $\mathbf{I}$ refers the identity matrix. $\Re\{\cdot\}$ is the real part and $Q^{-1}(\cdot)$ corresponds to the inverse of the Gaussian Q function.

II. Downlink RSMA System

Fig. 1 illustrates a downlink RSMA system model where a Base Station (BS) and the kth user are presented. Particularly, the BS is equipped with N_t transmit antennas and it serves K single-antenna users indexed by $k \in \{1, \dots, K\}$. It is also assumed that the BS intends to transmit a multicast message, W_m, and K unicast messages, W_k, to K users. The W_k is split into two parts: the common part, $W_{c,k}$, and the private part, $W_{p,k}$. Then W_m and each $W_{c,k}$ are combined into a common message denoted as W_c and it is encoded into a common stream s_c, while the private parts of the unicast messages are separately encoded into the private stream s_k. Then, the transmitted stream vector can be expressed as $\mathbf{s} = [s_c, s_1, \dots, s_K]^T$. After superposing the precoded common and private streams, the transmitted signal vector at the BS can be expressed as

$$\mathbf{x} = \mathbf{P}\mathbf{s} = \mathbf{p}_c s_c + \sum_{k=1}^{K} \mathbf{p}_k s_k, \tag{1}$$

where $\mathbf{P}$ is the precoding matrix, $\mathbf{P} = [\mathbf{p}_c, \mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_K]$, and $\mathbf{p}_c$, $\mathbf{p}_k \in \mathbb{C}^{N_t \times 1}$ are precoding vectors of the common and the private streams, respectively. It is assumed that unit symbol energy such that $\mathbb{E}\left[\mathbf{s}\mathbf{s}^H\right] = \mathbf{I}$ and the transmit signal power is limited by $\mathbb{E}\left[\mathbf{x}\mathbf{x}^H\right] \leq P_t$ where P_t is the maximum transmit power at the BS. At the kth user, the received signal is expressed as $y_k = \mathbf{h}_k^H \mathbf{x} + n_k$, where n_k is the additive white Gaussian noise sample with zero-mean and unit noise variance, and $\mathbf{h}_k$ is the channel vector between the BS and the kth user.

As illustrated in Fig. 1, the data-oriented precoder design, which will be described in the next section, starts with feeding a set of system parameters, such as the bandwidth, the lengths of the private and common messages, and N_t, to the design algorithms. Once the optimal data-oriented precoder is obtained, these values are assumed to be shared with each user via a feedback channel.

Note that the channel state information (CSI) at the kth user is assumed to be perfectly known, while the imperfect

CSI at the transmitter (CSIT) is considered. More specifically, $\mathbf{h}_k$ can be expressed as $\mathbf{h}_k = \sqrt{1-\delta}\hat{\mathbf{h}}_k + \sqrt{\delta}\tilde{\mathbf{h}}_k$ as in [14], where δ is the corresponding average CSIT error power. $\hat{\mathbf{h}}_k$ and $\tilde{\mathbf{h}}_k$ are the erroneous CSIT and the channel estimation error terms, respectively. In this letter, they are assumed to be independent and identically distributed complex Gaussian entries with $\mathcal{CN}(0,1)$.

At the receiver side, each user initially decodes the common message, $\hat{W}_c$, while treating the private streams as noise during this process. After assuming the unit average symbol energy, the corresponding signal to interference and noise ratio (SINR) of the kth user for the common stream is expressed as

$$\Gamma_{c,k} = \frac{|\mathbf{h}_k^H \mathbf{p}_c|^2}{\sum_{j=1}^{K} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}. \tag{2}$$

Once the decoding of the common message is completed, the decoded multicast message, $\hat{W}_m$, and the decoded common part of the kth user, $\hat{W}_{c,k}$, can be obtained from $\hat{W}_c$. Then, a SIC mechanism is implemented where the common stream is first reconstructed and then subtracted from the received signal, y_k. After that, the remaining signal is used to decode the private stream into $\hat{W}_{p,k}$, while treating the other users' private streams as noise. Then, the corresponding SINR of the kth user for the private stream is expressed as

$$\Gamma_{p,k} = \frac{|\mathbf{h}_k^H \mathbf{p}_k|^2}{\sum_{j=1, j\neq k}^{K} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}. \tag{3}$$

Finally, the common and private parts intended for the kth user, $\hat{W}_k$, can be reconstructed after combining $\hat{W}_{c,k}$ and $\hat{W}_{p,k}$.

III. Data-Oriented Downlink RSMA

For any wireless communication scenario, when the finite blocklength regime is considered, Shannon capacity is no longer achievable and becomes inefficient for characterizing the reliability and latency of a given system [6]. In this aspect, achievable rates of the common and private streams, $R_{c,k}$ and $R_{p,k}$, at the kth user for the downlink RSMA system under finite blocklength regime are given by [6]

$$R_{i,k} \approx \log_2(1+\Gamma_{i,k}) - \log_2(e)\sqrt{\frac{V(\Gamma_{i,k})}{l_{i,k}}}Q^{-1}(\epsilon) \tag{4}$$

in the unit of bits per second per Hz, where ϵ represents the block error rate (BLER), $V(\Gamma_{i,k})$ is the backoff from channel capacity [6], and $l_{i,k}$ denotes the length of the kth user's common and private streams such that $i \in \{c,p\}$, respectively. Specifically, $V_{i,k}$ can be expressed as $V(\Gamma_{i,k}) = 1 - (1+\Gamma_{i,k})^{-2}$, and the Gaussian codebooks are considered similar to [8]. It is also assumed that the achievable rate for the common stream is limited by the achievable rate of the user with the worst channel quality as $R_c = \min\{R_{c,1}, R_{c,2}, \ldots, R_{c,K}\}$ to ensure that the common stream is decoded by all users [8].

As proposed in [9], the data-oriented approach focuses on individual transmission sessions rather than considering long-term channel statistics. For this purpose, the delay outage ratio (DOR) is defined as the probability that the required information delivery time for a specific transmission exceeds the predefined threshold, T_{th} [9]. Then, the DOR expression for K-user downlink system can be defined by

$$\mathrm{DOR} = \Pr\left[\mathrm{T_{th}} < \max\left\{\mathrm{DT_m}, \mathrm{DT_1}, \mathrm{DT_2}\cdots, \mathrm{DT_K}\right\}\right] \tag{5}$$

where $\mathrm{DT_m}$ and $\mathrm{DT_k}$ are the information delivery times for the multicast message and the unicast messages, respectively. Particularly, the information delivery times of multicast and unicast messages consisting of H_m and H_k bits can be expressed as $\mathrm{DT}_m = H_m/BC_m$ and $\mathrm{DT}_k = H_k/BR_k$, where R_k corresponds to the rate of the unicast message of the kth user such that $R_k = C_k + R_{p,k}$ and B is the channel bandwidth. Here, C_m and C_k are the portions of R_c for transmitting W_m and $W_{p,k}$, respectively. In finite blocklength regime, the rate for common and private parts can be calculated from (4).

The data-oriented approach is introduced to a downlink RSMA system via two different data-oriented precoder designs. Note that since the BS has imperfect CSIT, in the precoder designs the achievable rate expressions are calculated using $\hat{\mathbf{h}}_k$ instead of $\mathbf{h}_k$ in the SINR expressions in (2) and (3). To begin with, the first one aims to minimize the maximum information delivery time under the transmit power constraint, P_t, for given B, H_m, and H_k, which is given by

$$\min_{\mathbf{P},\mathbf{c}} \max\left\{\frac{H_m}{BC_m}, \frac{H_1}{BR_1}, \frac{H_2}{BR_2}, \ldots, \frac{H_K}{BR_K}\right\} \tag{6a}$$

$$\text{s.t.} \quad \mathrm{tr}\left(\mathbf{P}\mathbf{P}^{\mathrm{H}}\right) \le \mathrm{P_t} \tag{6b}$$

$$C_m + \sum_{k=1}^{K} C_k \le R_{c,k}, \quad \forall k \tag{6c}$$

$$\mathbf{c} \ge 0 \tag{6d}$$

where $\mathbf{c} = [C_m, C_1, C_2, \ldots C_K]$.

The non-convex min-max problem given in (6) can be initially converted into max-min problem with respect to $\mathbf{P}, \mathbf{c}$ using successive convex approximation (SCA) as in [8]. In this way, a new set of variables, $\boldsymbol{\beta}_p = [\beta_{p,1}, \beta_{p,2}, \cdots, \beta_{p,K}]$, $\boldsymbol{\rho}_i = [\rho_{i,1}, \rho_{i,2}\cdots, \rho_{i,K}]$ and $\boldsymbol{\sigma}_i = [\sigma_{i,1}, \sigma_{i,2}\cdots, \sigma_{i,K}]$, is introduced, where $\beta_{p,k}$ is the lower bound on the private rate $R_{p,k}$, $\rho_{i,k}$ is the lower bound on the SINR, and $\sigma_{i,k}$ is the upper bound on the interference plus noise term. Then, considering these new variables and utilizing the first-order Taylor series as in [8], a new precoder design problem originally given in (6) can be rewritten as

$$\max_{\mathbf{P},\mathbf{c},\boldsymbol{\beta}_p,\boldsymbol{\rho}_r,\boldsymbol{\rho}_p,\boldsymbol{\sigma}_c,\boldsymbol{\sigma}_p} \xi \tag{7a}$$

$$\text{s.t.} \quad \log_2(1+\rho_{\mathrm{c,k}}) - \nu_{\mathrm{c,k}}^{(\mathrm{n})} \ge \mathrm{C_m} + \sum_{\mathrm{k=1}}^{\mathrm{K}} \mathrm{C_k}, \ \forall \mathrm{k} \tag{7b}$$

$$\log_2(1+\rho_{p,k}) - \nu_{p,k}^{(n)} \ge \beta_{p,k}, \qquad \forall k \tag{7c}$$

$$\frac{2\Re\{(\mathbf{p}_u^{(n)})^H \hat{\mathbf{h}}_k \hat{\mathbf{h}}_k^H \mathbf{p}_\mathbf{u}\}}{\sigma_{i,k}^{(n)}} - \frac{|\hat{\mathbf{h}}_k^H \mathbf{p}_u^{(n)}|^2 \sigma_{i,k}}{(\sigma_{i,k}^{(n)})^2} \ge \rho_{i,k},$$

$$\{i,u\} \to \{\{c,c\},\{p,k\}\}, \quad \forall k \tag{7d}$$

$$\sigma_{i,k} \ge \sum_{j=1}^{K} |\hat{\mathbf{h}}_k^H \mathbf{p}_j|^2 + 1, \quad i \in \{c,p\}, \quad \forall k \tag{7e}$$

$$\xi \le \frac{B(C_k + \beta_{p,k})}{H_k}, \quad \forall k \tag{7f}$$

$$\xi \leq \frac{BC_m}{H_m}, \tag{7g}$$

$$\mathrm{tr}\left(\mathbf{P}\mathbf{P}^H\right) \leq P_t, \quad C_m, C_k, \beta_{p,k} \geq 0. \tag{7h}$$

Herein, ξ is the lower bound for all BR_q/H_q, $q \in \{m, 1, \cdots, K\}$, $\nu_{i,k}^{(n)} \triangleq D_{i,k}\Big\{[V(\rho_{i,k}^{(n)})]^{\frac{1}{2}} + (\rho_{i,k} - \rho_{i,k}^{(n)})(1+\rho_{i,k}^{(n)})^{-3}[V(\rho_{i,k}^{(n)})]^{-\frac{1}{2}}\Big\}$, and $D_{i,k} = Q^{-1}(\epsilon)\log_2(e)/\sqrt{l_{i,k}}$. Also, $x^{(n)}$ corresponds to the value of x after the n-th iteration. The solution of (7) can be found by implementing the SCA-based algorithm as used in [8].

In the second data-oriented design, the objective is to minimize the transmitted power at the BS by considering the information delivery time under a given threshold such that

$$\min_{\mathbf{P},\mathbf{c}} P_t \tag{8a}$$

$$\text{s.t.} \quad \mathrm{tr}\left(\mathbf{P}\mathbf{P}^{\mathrm{H}}\right) \leq \mathrm{P_t} \tag{8b}$$

$$\mathrm{DT_m} \leq \mathrm{T_{th}}, \quad \mathrm{DT_k} \leq \mathrm{T_{th}}, \forall \mathrm{k} \tag{8c}$$

$$C_m + \sum\nolimits_{k=1}^{K} C_k \leq R_{c,k}, \quad \forall k \tag{8d}$$

$$\mathbf{c} \geq 0 \tag{8e}$$

Since (8) is non-convex due to non-convex constraints, similar to the first precoder design, it can be relaxed into a convex problem given by

$$\min_{\mathbf{P},\mathbf{c}} P_t \tag{9a}$$

$$\text{s.t.} \quad \frac{\mathrm{H_m}}{\mathrm{T_{th}}} \leq \mathrm{BC_m} \tag{9b}$$

$$\frac{H_k}{\mathrm{T_{th}}} \leq B(C_k + \beta_{p,k}), \quad \forall k \tag{9c}$$

$$(7b) - (7e), (7h). \tag{9d}$$

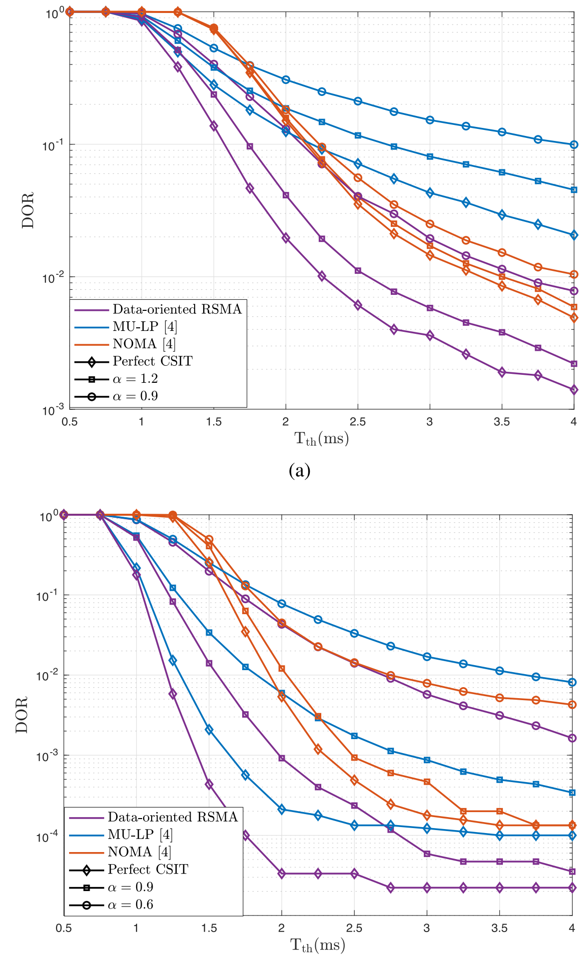
Then, the convex form, (9), can be solved using the SCA-based algorithm given in [8].

IV. Simulation Results

In this section, the benefits of the data-oriented approach over the two-user downlink RSMA system ($K = 2$) are investigated, and the performance of the proposed data-oriented RSMA system is compared with the downlink MU-LP and NOMA systems. For consistency, only the multicast message is encoded in s_c, and the unicast message W_k is encoded without having distinct private and common parts in the MU-LP system. In the NOMA system, the multicast message and the unicast message of the first user are encoded together, and the other unicast messages are encoded separately.

In the simulations, each user's channel is assumed to be independent and identically distributed complex Gaussian entries with $\mathcal{CN}(0,1)$. Also, the lengths of the common and private streams are set to $l_{c,k} = l_{p,k} = 500$ bits and BLER of the finite blocklength channel is chosen as $\epsilon = 10^{-4}$ along with $B = 2$ MHz. The CVX toolbox [15] was applied to two precoder designs where approximated convex problems given in (7) and (9) are solved after applying the SCA algorithm to the original ones.

In the first design, formulated in (6), the performance of the data-oriented precoder is compared with NOMA and MU-LP systems for $N_t = 2$ and $N_t = 4$ cases with $P_t = 20$ dB, $H_m = 2.5$ kbits, $H_1 = H_2 = 10$ kbits. The CSIT error power is given as $\delta = P_t^{-\alpha}$, and perfect CSIT is achieved



(a)

(b)

Fig. 2. The DOR comparison of the data-oriented RSMA, MU-LP, and NOMA with $P_t = 20$ dB, $H_m = 2.5$ kbits, $H_1 = H_2 = 10$ kbits. (a) $N_t = 2$. (b) $N_t = 4$.

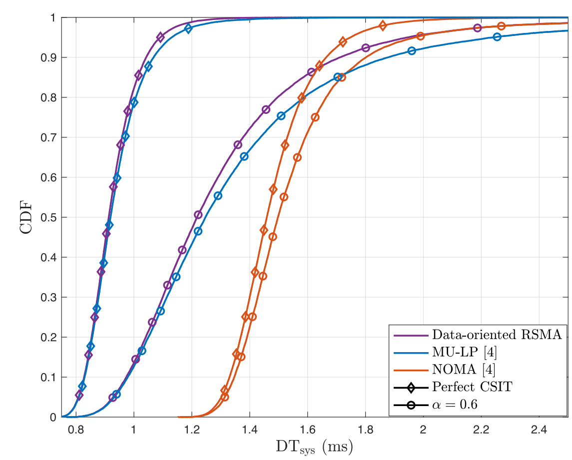


Fig. 3. The CDFs of the information delivery times of the data-oriented RSMA, MU-LP, and NOMA systems for $N_t = 4$ with $H_m = 2.5$ kbits, $H_1 = H_2 = 10$ kbits.

when $\alpha \rightarrow \infty$. As can be seen from Fig. 2, for perfect CSIT, the MU-LP is much better than the NOMA system for the underloaded case (when $N_t > K$), and the data-oriented RSMA outperforms both MU-LP and NOMA in terms of DOR, achieving the lowest information delivery time. The DOR performance of all systems decreases with increasing

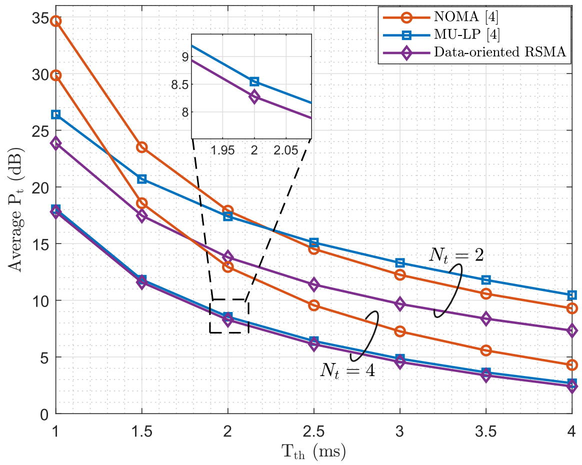


Fig. 4. The average P_t comparison of the data-oriented RSMA, MU-LP, and NOMA for $N_t = 2, 4$ with $H_m = 2.5$ kbits, $H_1 = H_2 = 10$ kbits.

CSIT error power, and the DOR performance increases with higher number of N_t, as expected. For the imperfect CSIT scenarios, the data-oriented RSMA provides significantly better DOR performance than those of the MU-LP and NOMA systems for both $N_t = 2$ and $N_t = 4$. For example, when $N_t = 4$ and $\alpha = 0.9$, a DOR of 10^{-3} can be achieved at $T_{\text{th}} = 2$, 2.5, and 2.9 ms for the data-oriented RSMA, MU-LP, and NOMA, respectively. Moreover, the NOMA system outperforms the MU-LP system especially at moderate and higher T_{th} values, except for $N_t = 4$ under perfect CSIT. This behavior can be explained by using Fig. 3 where it shows the CDFs of the information delivery times of the systems, $\text{DT}_{\text{sys}} = \max\{\text{DT}_{\text{m}}, \text{DT}_1, \text{DT}_2 \cdots, \text{DT}_{\text{K}}\}$ for all considered systems when $N_t = 4$. From this figure, the RSMA and MU-LP systems provide lower DT_{sys} than the NOMA system under perfect CSIT. For the imperfect CSIT scenario, e.g., for $\alpha = 0.6$, the MU-LP system provides better performance than the NOMA system when $\text{DT}_{\text{sys}} < 1.7$ ms, while the performance of the NOMA system is better than that of the MU-LP system when $\text{DT}_{\text{sys}} > 1.7$. In addition, the RSMA, MU-LP, and NOMA systems achieve average delivery times of 1.31, 1.47, and 1.60 ms, respectively, under imperfect CSIT. However, the corresponding delivery times are achieved at dramatically lower DOR values of 4×10^{-1}, 3×10^{-1}, and 3×10^{-1} for the RSMA, MU-LP, and NOMA systems, respectively, as shown in Fig. 2(b). This result illustrates the effectiveness of the data-oriented approach in providing a better insight into the delay performance of individual data transmission periods compared to average results.

For the second data-oriented precoder design which is given in (8), the average P_t out of each individual transmission is plotted in Fig. 4. It can be observed that the data-oriented design, which focuses on minimizing the transmitted power, enables a more energy-efficient precoder for the considered downlink system. Fig. 4 shows that the data-oriented RSMA system performs slightly better than the MU-LP system for the underloaded case and requires 5 dB less average transmit power compared to the NOMA system for $T_{\text{th}} = 2$ ms. For $N_t = 2$ and $T_{\text{th}} = 2$ ms, the data-oriented RSMA system outperforms both the MU-LP and NOMA systems, requiring approximately 4 dB less average transmit power.

V. Conclusion

In this letter, the performance of small data transmissions over downlink RSMA is presented after following a recently proposed data-oriented approach. In particular, instead of utilizing long-term channel statistics, the individual short packet data transmissions are considered, where the available bandwidth and the length of the data become design parameters along with the instantaneous channel conditions. In this aspect, two different precoder design formulations are proposed to minimize the information delivery time and transmit power in the presence of channel state information errors at the base station. The simulation results show that the proposed precoder design resulting from the data-oriented approach provides an enhanced transmission strategy with respect to finite block length and delay constraints, and an opportunity to improve system performance for individual short data transmission periods.

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