Multi-Symbol Rate NOMA for Improving Connectivity in 6G Communications Networks

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The authors consider a generalized scenario in which the user-paring process may include users with different symbol rates.

Abstract

In non-orthogonal multiple access (NOMA), user pairing, power allocation, and performance evaluation are typically performed assuming all users have equal symbol rates. However, such an assumption can significantly limit the design flexibility of NOMA and devalue its potential. Therefore, this article considers a generalized scenario in which the user-paring process may include users with different symbol rates. Hence, the proposed configuration is denoted multi-symbol rate NOMA (MR-NOMA). In MR-NOMA, the relationship between symbol rate and energy is exploited to add a new degree of freedom when assigning power to paired users. That is, the fact that the symbol energy is proportional to the symbol duration extends the range of power values that can be allocated to high symbol rate users while satisfying the quality-of-service requirements for all users. Consequently, the number of users served can be increased, or such a feature can be used to increase the link throughput. The results obtained for the two-user scenario show that with optimal power selection, users of high and low symbol rates can achieve lower bit error rates (BERs), which in turn increases system throughput as a result of improved transmission reliability.

Introduction

According to the Ericsson mobility report [1], the mobile network data traffic grew by 44% between 2020 and 2021, reaching 72 Exabyte per month generated by about 8 billion subscribers. Internet of Things (IoT) is another major source of data traffic and demand for wireless connectivity. According to the Cisco report [2], 50% of all IoT devices in 2023 will be connected to cellular networks. Therefore, fifth generation (5G) networks are expected to extend connectivity to 10-100 more devices compared to fourth generation (4G), while sixth generation (6G) is ultimately projected to increase connectivity by ten times compared to 5G. Therefore, the wireless network is expected to support about 15 billion IoT devices in addition to 8 billion mobile users.

Generally, efficient spectrum-sharing techniques can be vital to increase spectrum occupancy for bursty traffic. For example:

- Cognitive radio allows unlicensed users to opportunistically access the spectrum of licensed users in the uplink.
- Grantfree transmission is reemerging as an efficient approach to maximize spectrum utilization by allowing users to access the spectrum without scheduling.
- Non-orthogonal multiple access (NOMA) is another promising spectrum-sharing technology that has attracted much attention in the last few years [3–7]. NOMA, which is the focus of this article, allows users to share the same transmission resources. NOMA has been proposed for a wide range of applications, such as 4G and 5G wireless networks [4], massive machine type communication (mMTC) [8], IoT [9], visible light communications (VLC) [10], and many others [11].

It is worth noting that NOMA should not be considered as an alternative for certain technologies such as massive multiple-input multiple-output (MIMO) (mMIMO), which is expected to play an important role in 6G. Instead, NOMA can be integrated with mMIMO to aggregate the spectral efficiency gain offered by each technology where certain users can be jointly multiplexed using NOMA and space division multiple access (SDMA) using mMIMO. Moreover, indoor, outdoor, and mobile small cells are expected to be deployed at a large scale 6G. In small cells, the base station (BS) has a small size and cannot support a large number of antennas. Consequently, the role of NOMA becomes even more prominent in such scenarios.

The main principle of NOMA is to allow multiple users to use the same transmission resources simultaneously while using successive interference cancellation (SIC) or other detection schemes to separate the signals at the receiver [12]. However, SIC has generally lower complexity than other detectors because it applies the single user maximum likelihood detector (MLD) successively to detect the symbols of all users [12]. In power domain (PD) NOMA, which is considered in this work, each user is assigned a specific power value to allow the SIC detector to operate efficiently. NOMA can be applied in the downlink and uplink, however, the operational requirements and performance for each transmission are different. PDNOMA has recently been included in ATSC 3.0, a forthcoming digital TV standard. Moreover, it has been included by the 3rd generation partnership project (3GPP) long-term evolution (LTE) enhancements under the name multi-user superposition transmission. Although NOMA has been extensively considered in the literature [3, 5–7], there is a key configuration that has

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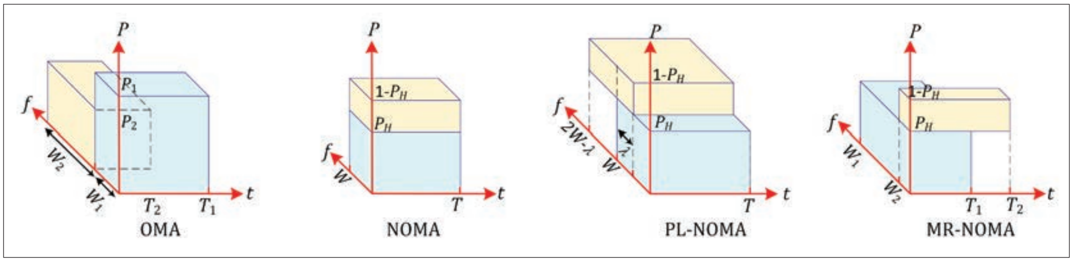

FIGURE 1. A simple diagram for a two-user orthogonal multiple access (OMA), NOMA, PL-NOMA, and MR-NOMA.

In most of the reported literature [3, 5–7], some of the fundamental features of NOMA are still preserved. In particular, the spectrum or time overlap among all users is equal. In such scenarios, all users occupy exactly the same spectrum.

not yet been fully explored. Therefore, this article aims to present a key form of NOMA that can provide unique features over conventional NOMA.

Related Work

Although the basic NOMA design may offer reasonable performance for various applications, modifying the basic NOMA structure can provide several additional features, particularly in terms of interference cancellation. A comprehensive review of NOMA design variants has been reported by Budhiraja *et al*. [3]. Some of the modifications proposed to NOMA focus on signal design. In such techniques, the users' data symbols are modified before superposition to enhance the interference cancellation process, for example, coordinate interleaving, phase rotation, asynchronous superposition, and waveform-domain NOMA. Several other modifications have generally focused on the operational aspects of NOMA. For example, dynamic NOMA is proposed in [9] where the power is varied according to the transmitted data. Other modifications included improving the user pairing process, opportunistic, and cognitive NOMA [3].

In most of the reported literature [3, 5–7], some of the fundamental features of NOMA are still preserved. In particular, the spectrum or time overlap among all users is equal. In such scenarios, all users occupy exactly the same spectrum. Therefore, Beomju *et al*. [13] proposed a new NOMA configuration, referred to as partial NOMA (PL-NOMA) where the spectrum overlap can be less than the entire spectrum. The results presented in [13] show that PL-NOMA can provide a sum-rate improvement over the full overlap case. In addition to the full spectrum overlap, it is typically assumed that all NOMA paired users have equal signal bandwidth [3, 5–7]. Such an assumption also implies that the symbol rates for all paired users are the same. The users might have different bit rates by using different modulation orders or code rates. However, in 5G networks, users might be assigned different numerologies based on their quality-of-service (QoS) requirements. Consequently, NOMA users pairing with multi-numerologies is considered in [14, 15], which analyzed the interference and spectral efficiency of the multi-numerologies scenario. However, both works consider SIC with perfect interference cancellation. Furthermore, using SIC in such systems may cause significant performance degradation compared to the optimum detector, and therefore the benefits of multisymbol rate NOMA (MR-NOMA) are underestimated. The justification for this phenomenon is provided at the end of Sec. Several other critical issues have not been considered, such as power-energy degree of freedom, error rate performance, optimum power allocation, and optimum receiver design.

Motivation and Contribution

Unlike previous wireless standards, 5G networks can support different symbol rates for different users [14]. The same argument also applies to 6G, particularly for IoT applications. Such flexibility will significantly increase network connectivity because it will be able to serve users with different data rate requirements more efficiently. Although NOMA can play a major role in future wireless networks, the vast majority of work in the open literature considers pairing users with the same bandwidth, that is, equal symbol rate. However, such consideration may limit the potential of NOMA due to constraints on power assignment. Therefore, the main motivation of this article is to develop efficient solutions to relax the power assignment process by considering pairing users with different bandwidths, allowing trade-off of power and energy for certain users. More specifically, the main contributions of this article are:

- Propose pairing users with different symbol rates to enable flexible power allocation, the proposed scheme is referred to MR-NOMA.
- Derive the optimal detector and compare it to the low complexity SIC detector.
- Evaluate the error rate performance of MR-NOMA and compare it with the equal rate NOMA.
- Demonstrate that MR-NOMA can offer higher throughput than the equal rate NOMA for several cases of interest.
- Propose open research problems that can be addressed using MR-NOMA.

Multi-Rate NOMA

Multiple access schemes can generally be classified as OMA or NOMA. As depicted in Fig. 1, each OMA user has its own bandwidth, power, bit rate, and symbol rate. Without loss of generality, this work considers frequency division multiple access (FDMA)-OMA and power-domain NOMA. In contrast, NOMA assigns users common transmission resources that are equally shared by all users. The bandwidths and symbol rates for all users are typically equal, while different bit rates can be achieved by assigning each user a different modulation order. Demultiplexing and multi-user interference (MUI) can be controlled via the power allocated to each user. To provide further control of MUI in NOMA, PL-NOMA was introduced where users can only share part of the transmission spectrum. As shown in Fig. 1, the spectral overlap between the two users is denoted as . Similar to NOMA, the symbol rates and bandwidths for all users are typically considered equal. It is also worth noting that all NOMA users are assumed to be synchronous, that is, the

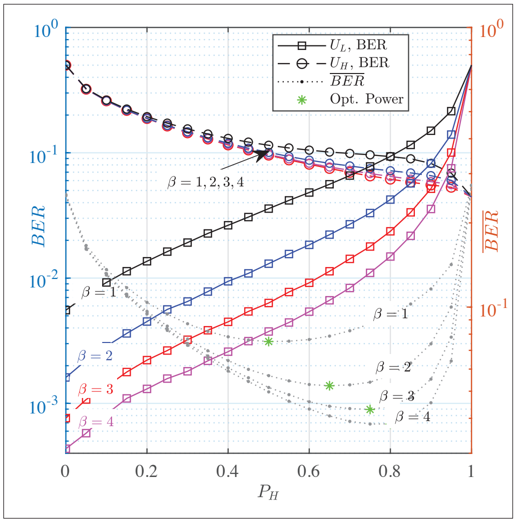

FIGURE 2. BER and average BER ($\overline{BER}$) versus P_H for $\beta = 1, 2, 3, 4$, $m = 2$, SNR = 10 dB, and $d_H = 2d_L$.

transmission of all users is performed based on a common clock. The power for each NOMA user is assigned such that the QoS for each user is satisfied, and the data symbols for all users can be reliably detected. Different users can be provided different data rates by changing the modulation order for each user while keeping the symbol rate equal for all users. Therefore, the symbols' periods for all users should be identical.

During the NOMA system setup, the BS pairs particular users based on the channel strength and QoS requirements of each user. A user with a low channel gain, denoted as the weak user, is typically assigned more power than a user with a high channel gain, denoted as the strong user. In downlink NOMA, the power control is simpler than in uplink because the power control is performed locally at the BS. For the uplink, power control is more challenging because BS should know the available power and channel gain of each remote user.

In this work, we consider the uplink MR-NOMA scenario where users are transmitting data with nonidentical symbol durations. The symbols' periods are assumed to be different where the period for any user is an integer multiple of other users with shorter periods. This requirement is needed to unify the sampling rate of the receiver side, that is, the BS. The BS assigns to each user a certain power value based on a given criterion. Similar to conventional uplink NOMA, all users transmit their symbols synchronously. The transmitted symbols of all users propagate through independent and identically distributed wireless channels with certain fading characteristics and arrive as a superposed signal at the BS front-end. To simplify the system presentation, all channels are assumed to be slowly changing over time so that the longest symbol period is less than the coherence time of the channels. Moreover, the maximum bandwidth, which is proportional to the bandwidth of the signal with the shortest symbol period, is assumed to be less than the coherence bandwidth of the channel. Therefore, the channel is flat in time and frequency. The distances of the high- and low-rate users from the BS can be varied. Therefore, the high-rate user can be either a strong or a weak user.

At the BS, after radio frequency (RF) downconversion and matched filtering, the received signal is sampled at a rate that is equal to the maximum symbol rate, which is the sampling rate for the high-rate symbols. Therefore, the receiver will have two samples for each low-rate symbol, which is different from transmit diversity. The receiver can be configured to use joint multiuser MLD (JMuMLD) or the lower complexity SIC detector. Unlike downlink NOMA, the JMuMLD offers lower bit error rate (BER) performance compared to SIC. Therefore, the JMuMLD is adopted because the BS usually have substantial computational power. The detection process generally requires knowledge of the power allocated to each user and the channel gain. Due to the difference in the symbols' periods, the detection process has to be performed over a period of time that equals the lowest symbol period. Therefore, the detection process should consider that there may be high-rate symbols within a single period of the low-rate symbol. The number of symbols for other users will be between the two aforementioned limits. Consequently, detectors should take this unique structure into account. For example, the two-user JMuMLD where the low-rate user symbol period is twice that of the high-rate user can be written as

$$\hat{\mathbf{S}} \arg\min_{\mathbf{s}} \left[\left|r_1 - h_L\sqrt{P_L}S_1^L - h_H\sqrt{P_H}S_1^H\right|^2 + \left|r_2 - h_L\sqrt{P_L}S_1^L - h_H\sqrt{P_H}S_1^H\right|^2\right]^2 \quad (1)$$

where r_1 and r_2 are the received samples in the first and second time slots, the superscripts L and H refer to the low and high-rate users, the power is denoted as P where the total transmit power is normalized to unity, and h is the channel gain. During the period of one low-rate symbol, the low-rate user will transmit one symbol S_1^L while the high-rate user will transmit two symbols S_1^H and S_2^H. As can be noted, it is straightforward to generalize the detector in Eq. 1 for a larger number of users. Moreover, the detector is a joint sequence NOMA detector where the low-rate data symbol exists in both parts of the objective function.

From the objective function, it can be observed that when zero power is allocated to the low-rate user, the first and second parts of the detector become independent, and thus the high-rate user can perform symbol-by-symbol detection to extract its data symbols. On the other hand, if zero power is allocated to the high-rate user, the detector becomes a maximum ratio combiner. However, because the channel gain is common for both parts, we only obtain the processing gain. For other power values, the performance will depend on the channel strength of the users and signal-to-noise ratio (SNR). However, it should be noted that there is an optimum power value that can minimize the average BER of both users for a given channel strength and β. Therefore, increasing the power for one of the users does not necessarily decrease its BER.

SIC detection can also be considered for MR-NOMA. Assuming that all user equipment (UE) have an equal sampling rate that is equal to symbol rate of the highest rate user, then the highest rate user signal will be sampled, after matched filtering, at a rate of one sample per symbol, while for the low-rate user, it will be β samples per symbol. If the low-rate symbol is detected first, then

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the β samples are added and applied to a single-user MLD. The remaining processing is similar to NOMA. If the high-rate symbols are detected first, then each of the β samples is initially applied to a singleuser MLD, and then they are used to cancel the interference caused by the high-rate symbols from the β samples. Then, the β samples are added and applied to a single-user MLD to produce the low-rate symbol. Consequently, the high-rate receiver will not utilize the fact that the interference in all β symbols is the same, which may affect its performance.

Unlike downlink NOMA, SIC detectors may severely deteriorate the performance of uplink users [12]. Although the SIC detectors are less complex than JMuMLD, which can be critical for the UE, it is not the case for the uplink because BSs have substantial computational power. Moreover, the receiver might have to switch the order of detection based on the signals' strengths, which can be a burden in time-varying channels. It is worth noting that the complexity of NOMA and MR-NOMA receivers is generally equivalent when SIC is used. For JMuMLD, MR-NOMA requires slightly more operations because the search space for MR-NOMA should consider three symbols, while in NOMA it should consider only two symbols. Similar to NOMA, the SIC and JMuMLD design for MR-NOMA might have to be modified when channel coding is used. For example, when channel coding is used with SIC, the near-user should decode and then encode the far-user bits before the interference cancellation step. For JMuMLD, the design also depends on the decoding process. With hard-decision decoding, the detector design remains as described in Eq. 1, which is considered in this work. With soft-decision decoding, log-likelihood information must be calculated for each individual bit before it is fed to the decoder.

To summarize, MR-NOMA is a generalized version of conventional NOMA where each user may have different symbol rate. The detection of MR-NOMA can be performed using the SIC and JMuMLD, but with some modifications. MR-NOMA may offer several advantages over conventional NOMA with a single symbol rate.

Numerical Results

The performance of the proposed MR-NOMA is evaluated over a Nakagami-*m* fading channel. SNR is defined as $1/\sigma^2$ where σ^2 is the additive white Gaussian noise (AWGN) variance. Each point in the results is obtained using 2×10^7 Monte Carlo simulation run. The results are obtained for a two-user MR-NOMA where the low-rate symbol period is equal to 1, 2, 3, 4 times the high-rate symbol period. The case of equal symbol periods, β = 1, corresponds to the conventional NOMA, which is used for benchmarking purposes. In the results, the high-rate and low-rate users are referred to as U_H and U_L, respectively. The distances between each user and the BS are denoted as d_H and d_L for high-rate and low-rate users, respectively. All results are obtained for binary phase shift keying (BPSK) modulation.

Figure 2 shows the BER for the two users where the highrate user is the weak user. The relative distance between the two users is 2, which corresponds to an additional 6 dB path loss for the weak user. The value of m = 2 and SNR = 10 dB. Therefore, the channel is generally poor for both users, particularly for the high-rate user due to the additional path loss attenuation. As can be noted from the figure, the high-rate user does not achieve a significant BER improvement by boosting its power. Such results are obtained because at such channel conditions, the sensitivity of the BER to the power variation is small. For the low-rate user, the scenario is different where its BER changes significantly versus its power. The figure also illustrates the impact of β where increasing β shows significant improvement for the low-rate user while the high-rate user obtains marginal improvement. The improvement for the low-rate user is due to the combining gain while the improvement for the high-rate is due to the fact that the MUI can be canceled successfully more frequently for higher values of β. Moreover, the relative signal-to-interference ratio (SIR) of the high-rate user improves by increasing β when the interference cancellation fails because the MUI decreases when increasing . Figure 2 also shows the average BER $\overline{BER}$ of the two users. As can be seen from the figure, increasing β decreases $\overline{BER}$ because the BER of both users generally improves by increasing β. Moreover, it can be observed that the optimal power that minimizes $\overline{BER}$ increases with increasing β, which is due to the fact that the low-rate user can allocate part of its power to the high-rate user. For equal-rate NOMA, it can be seen that the case of equal power is the optimum.

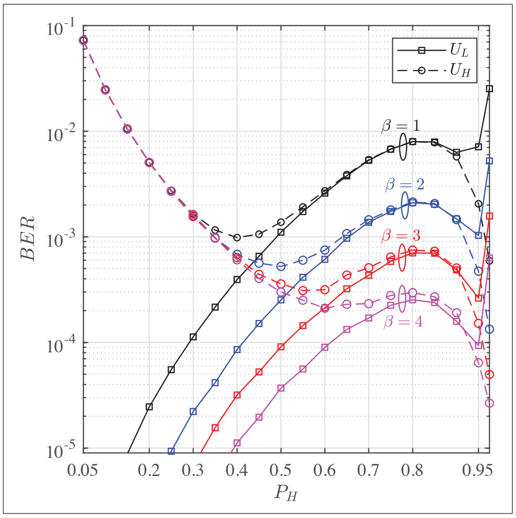

FIGURE 3. BER versus P_H for β = 1, 2, 3, 4, m = 5, SNR = 20 dB, and $d_H = 2d_L$.

Figure 3 shows the BER versus the high-rate user transmit power for m = 5 and SNR = 20 dB. The high-rate user is the weak user. Therefore, the channel for this case is generally good for both users. In this figure, the impact of the power variation becomes more apparent as compared to the poor channel scenario. As the figure shows, the BER of both users improves by increasing β, however, the amount of improvement depends on SNR. For example, at low P_H, only the low-rate user BER improves while the high-rate user BER remains roughly unchanged. At P_H = 0.85, both users generally achieve the same BER improvement. At high P_H values, both can still get roughly the same improvement, except that the BER curves change direction where the highrate outperforms the low-rate user at such high P_H values.

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Similar to NOMA, MR-NOMA can be detected using the SIC detector. When SIC is used, the effectiveness of the SIC processes depends on the reliability of the weak user symbol detection process because it is first detected and then used for the SIC process. Therefore, if the detection of the weak user symbols frequently fails, interference cancellation will have limited benefit due to error propagation. Consequently, the use of error correction coding for the weak user can be beneficial for both users.

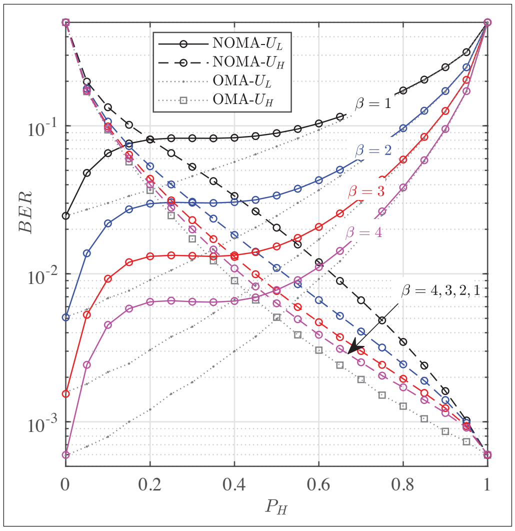

FIGURE 4. NOMA-OMA BER versus P_H for $\beta = 1, 2, 3, 4$, $m = 5$, SNR = 10 dB, and $d_L = 2d_H$.

The figure also shows that there are multiple minimum points while the global minimum is at $P_H \approx 0.95$ for all values of β. Furthermore, the interaction between BER and the power of both users shows that increasing P_H or P_L does not necessarily improve the BER of both users, which is due to the MUI, which can be successfully eliminated more frequently for particular power values.

Figure 4 shows BER versus P_H where $m = 5$ and SNR = 10 dB, Unlike the other figures, the low rate user, in this case, is considered to be the weak user. Generally speaking, increasing β managed to significantly reduce BER of both users. Moreover, it can be seen that the low rate user BER exhibits a plateau for a wide range of P_H values. This behavior is interesting because the low-rate user may allow allocating more power to the high-rate user without noticeable BER degradation. Moreover, it can be observed that the additional path loss attenuation was compensated for by the gain obtained by increasing the ratio between the symbols' rates, which enabled both users to perform very well for several values of of the high-rate user transmit power. However, such performance cannot be obtained using NOMA where the weak user suffers poor BER performance. The figure also shows the BER for OMA. As can be seen from the figure, OMA BER is a lower bound for all NOMA scenarios, and both NOMA and OMA converge for the edge powers, that is, $P_H \in \{0, 1\}$. Moreover, it can be observed that the BER for NOMA/OMA U_L converge for $P_H \gtrsim 0.7$.

Figure 5 shows the total throughput versus SNR where the low-rate user is the weak one, $m = 2$, and both users are using equal power values. The results of Fig. 5a are obtained when the (127, 113, 5) Bose-Chaudhuri-Hocquenghem (BCH) code is used. This code has a code rate $R = 0.89$ and can correct up to two errors with hard-decision decoding. The throughput is defined as the total number of bits received correctly during one signaling period. The packet length for all scenarios is 127 bits and the packets with one or more uncorrected errors are dropped. As can be seen in the figure, the throughput at low SNRs is proportional to β due to the fact that higher values of β can significantly reduce BER and consequently reduce the packet error rate (PER) and packet drop rate. At high SNRs, the reliability of all schemes improves, which implies that the equal-rate NOMA will outperform all other cases where the throughput approaches $2R$. This performance is obtained because, at high SNRs, the number of packets dropped becomes very small for all values of β, reducing the impact of varying β. Consequently, pairing two high-rate users becomes feasible and provides maximum throughput. For SNR > 20 dB, the throughput can be calculated as $(1 + 1/\beta)R$. Figure 5b is similar to Fig. 5a except that the turbo product code (TPC) $(32, 21, 6)^2$ is used. Generally, the two figures demonstrate the same trends, however, the TPC provides a better gain at low SNRs due to the error correction capability of the TPC. The results in the figure emphasize the advantage of MR-NOMA where throughput can be effectively increased under severe channel conditions.

Similar to NOMA, MR-NOMA can be detected using the SIC detector. When SIC is used, the effectiveness of the SIC processes depends on the reliability of the weak user symbol detection process because it is first detected and then used for the SIC process. Therefore, if the detection of the weak user symbols frequently fails, interference cancellation will have limited benefit due to error propagation. Consequently, the use of error correction coding for the weak user can be beneficial for both users. Due to lack of space, only selected cases of the uncoded BER results using SIC are presented. The results are obtained for an ordered Nakagami-m channel where $m = 1$, $P_H = P_L = 0.5$, and $\beta = 2$. The low-rate user is considered as the strong user, and thus is detected first. The BER is evaluated for SNR = 20 dB, and the results are as follows:

- SIC: $BER_L = 1.91 \times 10^{-3}$, $BER_H = 5.51 \times 10^{-2}$.
- JMuMLD: $BER_L = 6.68 \times 10^{-4}$, BERH = 1.02×10^{-2}.

System Challenges and Future Directions

The open research problems for MR-NOMA are listed below, and can be considered for both uplink and downlink.

Performance Analysis: Evaluate the performance analytically in terms of BER, outage probability (OP), and capacity for various channel models and a number of users. The analysis can be extended to scenarios where different users may employ various modulation orders and symbol rates using JMuMLD and SIC detectors.

Power and Energy Optimization: Should be performed to improve various performance metrics while considering the limited energy sources at the users' devices, the interference that might affect other users in other cells, and the users' QoS requirements.

User Pairing: Derive optimum pairing in large networks where users have a wide range of symbol rates. Various objective functions can be considered, such as maximizing the network sum-rate, maximizing the network connectivity with QoS constraints, and so on.

Grant-Free MR-NOMA: Apply MR-NOMA in the context of grant-free transmission with various levels of coordination and synchronization, in particular, asynchronous transmission for grant-free applications.

Practical System Limitations: Evaluate the performance with imperfect knowledge of channel state information. In addition, accurate control and knowledge of the uplink transmission power are necessary for the detection process.

Interference Cancellation: Because part of the spectrum will be utilized only by the high-rate user, a low-rate user may use short-sequence spreading, source coding, or channel coding to enhance interference cancellation by the high-rate user. The total bandwidth after spreading or coding should not exceed the high-rate user bandwidth. However, such a process should be performed considering the receiver efficiency.

Time-Selective Channels: Evaluate the impact of the channel time variation. Such a consideration is critical because the channel for a low-rate user may become time-selective while it is time-flat for a high-rate user. Similarly, the high-rate user signal may experience frequency selectivity, while the low-rate user may experience frequency-flat fading. In such scenarios, the low-rate users may achieve a diversity gain by combining the multiple parts of the over-sampled low-rate signal.

Detector Design: Derive an efficient detector for a large number of users and various values of . In such cases, a hybrid JMuMLD-SIC can be used to provide design flexibility and allow trading the performance versus complexity.

Advanced Applications: Design and evaluate the performance of cooperative, cognitive, and coded MR-NOMA with various diversity schemes.

Hardware Implementation: Evaluate the performance of MR-NOMA in real-world scenarios using a testbed and measurements campaign.

Conclusion

The article presented a new class of NOMA, where different users may have different bit and symbol rates. The new NOMA configuration introduced a new degree of freedom that can be used to provide more design flexibility compared to conventional NOMA. In particular, it is shown in this work that varying the symbol energy, in addition to the symbol power, can improve the error rate and throughput of all users for a wide range of operating conditions. Users with relaxed data rate requirements can allocate most of their power to high-rate users without compromising their QoS requirements. Such features can be attractive for IoT applications where the nodes have heterogeneous data rates and QoS requirements. The article also discussed several open research problems that need to be addressed to explore the full potential of MRNOMA.

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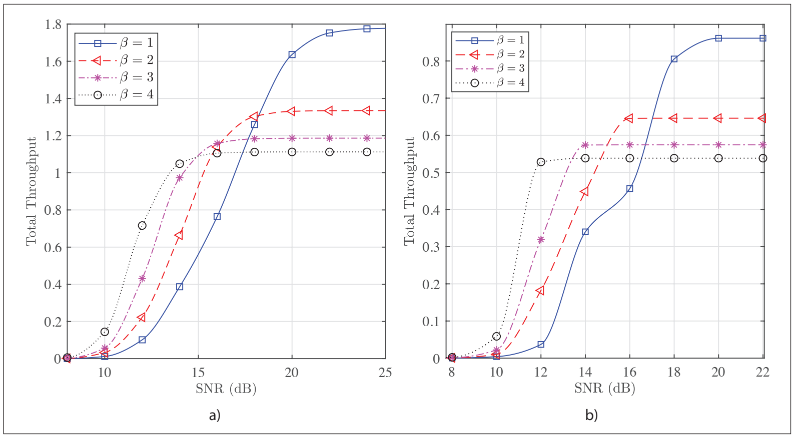

FIGURE 5. Total throughput versus SNR of a coded MR-NOMA for $\beta = 1, 2, 3, 4$, $d_L = 2d_H$, $P_H = P_L = 0.5$, $m = 2$: a) BCH(127, 113, 5); b) TPC(32, 21, 6)^2.

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