Unveiling the Importance of SIC in NOMA Systems—Part 1: State of the Art and Recent Findings

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(Invited Paper)

***Abstract*— The key idea of non-orthogonal multiple access (NOMA) is to serve multiple users simultaneously at the same time and frequency, which can result in excessive multiple-access interference. As a crucial component of NOMA systems, successive interference cancelation (SIC) is key to combating this multiple-access interference, and is the focus of this letter, where an overview of SIC decoding order selection schemes is provided. In particular, selecting the SIC decoding order based on the users' channel state information (CSI) and the users' quality of service (QoS), respectively, is discussed. The limitations of these two approaches are illustrated, and then a recently proposed scheme, termed hybrid SIC, which dynamically adapts the SIC decoding order is presented and shown to achieve a surprising performance improvement that cannot be realized by the conventional SIC decoding order selection schemes individually.**

***Index Terms*— Non-orthogonal multiple access (NOMA), hybrid successive interference cancellation (SIC), outage probability error floors.**

I. Introduction

As a paradigm shift for the design of multiple access techniques, non-orthogonal multiple access (NOMA) encourages spectrum sharing among multiple users, instead of forcing them to individually occupy orthogonal resource blocks as in conventional orthogonal multiple access (OMA) [1]. As a result, NOMA can significantly improve spectral efficiency, reduce access delay, and support massive connectivity. As one of the most promising multiple access techniques, NOMA has been extensively studied under the 3rd Generation Partnership Project (3GPP) framework, from Release 14 in 2015 to Release 16 in 2019, where NOMA was formally adopted for downlink transmission in Release 15, also termed Evolved Universal Terrestrial Radio Access (E-UTRA) [2]–[4]. With the current rollout of the fifth-generation (5G) wireless systems, significant efforts are being made towards the full inclusion of NOMA in beyond 5G systems [5].

A unique feature of NOMA systems is the existence of excessive multiple-access interference, which is caused by the spectrum sharing among the users. Successive interference cancelation (SIC) has been shown to be an effective method to combat this interference [6], [7]. Due to the sequential nature of SIC, the SIC decoding order is a key issue in the implementation of SIC, and will be focused on in this two-part invited paper. The first part of the paper aims to provide an overview for how the SIC decoding order has been determined in NOMA, and to illustrate its impact on the performance of NOMA. In particular, selecting the SIC decoding order based on the users' channel state information (CSI) is considered first, since this is a straightforward choice and has been used since the invention of NOMA [6], [8]. Then, selecting the SIC decoding order based on the users' quality of service (QoS) requirements is considered, the rationale behind this approach is explained, and ideal application scenarios for it are illustrated [9], [10]. We note that in most existing NOMA works, the SIC decoding order is prefixed and based on either of the two aforementioned criteria, which may suggest that swapping the SIC decoding order is trivial and does not yield a significant performance gain. However, a recent work [11] has shown the opposite to be true. In fact, dynamically switching the SIC decoding order can achieve a surprising performance improvement that cannot be realized by the two conventional schemes. This improvement is illustrated in this paper, and the underlying reasons are explained in detail.

II. NOMA Using CSI-Based SIC Decoding Order

For the purpose of illustration, this letter considers an uplink communication scenario with $(M+1)$ users, denoted by U_m, $0 \leq m \leq M$, where U_m's channel gain is denoted by h_m. Using the users' channel conditions to select the SIC decoding order is a straightforward choice and has been adopted in many forms of NOMA [6], [8]. Take two-user power-domain NOMA as an example, which can serve two users with different channel conditions simultaneously. Without loss of generality, assume that U_n, $1 \leq n \leq M$, is scheduled and paired with U_0 for NOMA transmission, under the condition that $|h_n|^2 \geq |h_0|^2$.

Conventional OMA serves the two users in different resource blocks, and the users' data rates are $R_i^O = \frac{1}{2}\log\left(1+P^O|h_i|^2\right)$, $i \in \{0, n\}$, respectively, where the users' transmit powers are assumed to be identical and denoted by P^O.[1] The shortcomings of OMA can be illustrated by considering the extreme case $h_0 \rightarrow 0$, i.e., U_0 experiences

[1]The assumption of identical transmit powers can be justified by the fact that for many important applications of NOMA, such as the Internet of Things (IoT) and machine-type communications, power control might not be possible due to the limited capabilities of IoT sensors and devices. We note that the issue of transmit power control will be considered in the second part of this invited paper.

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deep fading. In this case, the resource block allocated to U_0 is wasted due to the user's poor channel conditions.

Power-domain NOMA serves the two users simultaneously, and applies SIC at the base station for signal separation. A natural SIC strategy is to first decode the signal from the strong user, U_n, and then decode U_0's signal if U_n's signal can be decoded and removed successfully, which yields the following achievable data rates:

$$R_n^N = \log\left(1 + \frac{P|h_n|^2}{1+P|h_0|^2}\right), \quad (1)$$

and

$$R_0^N = \log\left(1 + P|h_0|^2\right), \quad (2)$$

respectively, where the users' transmit powers are also assumed to be identical and equal to P. The benefits of NOMA can be clearly demonstrated by again considering the extreme case $h_0 \to 0$. Assume $P = \frac{1}{2}P^O$ for a fair comparison between OMA and NOMA. The sum rate of NOMA can be approximated as follows:

$$R_{sum}^N = R_0^N + R_n^N \underset{h_0 \to 0}{\longrightarrow} \log\left(1+P|h_n|^2\right) \underset{P\to\infty}{\longrightarrow} \log P, \quad (3)$$

which is almost two times the sum rate of OMA, $R_{sum}^O \triangleq R_0^O + R_n^O \to \frac{1}{2}\log P$, where we assume that $P|h_0|^2 \to 0$.

Remark 1: In the above example, U_n may suffer from severe interference because its signal is decoded in the presence of U_m's signal. Therefore, U_n's QoS experience deteriorates and there is little incentive for U_n to participate in NOMA. This QoS issue becomes more severe in the general case with more than two users, which is a disadvantage of power-domain NOMA compared to other forms of NOMA.

Remark 2: Another disadvantage of power-domain NOMA is that the users' channel conditions need to be sufficiently different in order to yield a reasonable performance gain over OMA, which can be illustrated by considering the special case $h_0 = h_n$ and $P = \frac{1}{2}P^O$. It is straightforward to show that, in this case, $R_{sum}^N = R_{sum}^O = \log\left(1 + 2P|h_0|^2\right)$. In other words, if the users' channel qualities are identical, the performance of NOMA is the same as that of OMA, but the system complexity of NOMA is higher than that of OMA. These disadvantages can be avoided by using QoS-based SIC.

III. NOMA Using QoS-Based SIC Decoding Order

Cognitive-radio inspired NOMA (CR-NOMA) is a well-known example for using the users' QoS requirements to select the SIC decoding order [9], [10]. Unlike power-domain NOMA, in CR-NOMA, U_0 is assumed to be a delay-sensitive user with a low target data rate, denoted by R_0, e.g., U_0 may be a voice-call user or an IoT healthcare device which needs to send urgent health status changes. On the other hand, it is assumed that U_n, $1 \leq n \leq M$, can be served in a delay tolerant manner, e.g., U_n may be a peer-to-peer file sharing user or an IoT device sending personal health records. In OMA, because of its delay-sensitivity, U_0 is allowed to occupy a dedicated resource block, such as a time slot, which results in low spectral efficiency since U_0 has only a small amount of data to be delivered to the base station.

The key idea of CR-NOMA is to treat NOMA as a special case of a CR system, where U_0 is viewed as the primary user and the U_n, $1 \leq n \leq M$, are viewed as secondary users. CR-NOMA ensures that the secondary users are admitted to the channel, which in OMA would be solely occupied by U_0, while guaranteeing U_0's QoS requirements. In CR-NOMA, the primary user's signal is decoded first. For illustration purposes, we assume that a single secondary user, U_n, $1 \leq n \leq M$, is scheduled based on the following metric:

$$\log\left(1 + \frac{P|h_0|^2}{1+P|h_n|^2}\right) \geq R_0, \quad (4)$$

in order to guarantee U_0's QoS requirements. If the constraint in (4) is feasible, the first stage of SIC is guaranteed to be successful, and U_n's achievable data rate is given by

$$R_n^{CR} = \log\left(1 + P|h_n|^2\right). \quad (5)$$

If none of the secondary users can satisfy the constraint in (4), OMA is used to avoid any performance degradation for U_0. In other words, the use of CR-NOMA is transparent to U_0.

1) Rationale Behind the Used SIC Decoding Order: CR-NOMA decodes first the signals from U_0, the user with the low data rate requirement. The rationale behind this SIC decoding order is two-fold. Firstly, the user whose signals are decoded in the first stage of SIC suffers strong interference, as can be observed from (4), which means that the user's achievable data rate will be small. However, this is not an issue, since U_0's target data rate is assumed to be not demanding. Secondly, since U_n's signals are decoded in the last stage of SIC, they do not suffer from any interference, as can be observed from (5). Recall that U_n's data rate constitutes the performance gain of CR-NOMA over OMA. Therefore, the fact that there is no interference in (5) promises a significant performance gain of NOMA over OMA, as discussed in the following subsection.

2) The Benefits of QoS-Based SIC: We use two examples to illustrate the benefits of using QoS-based SIC. The first example is to show that QoS-based SIC can be easily extended to a general case with more than two users, while guaranteeing the users' QoS requirements. In particular, we assume that there are M delay-sensitive users to be served at low data rates, and one delay-tolarent user. In OMA, $(M+1)$ time slots are needed to serve these users. By using NOMA with QoS-based SIC, it is possible to serve all users in a single time slot, which means that the spectral efficiency can be improved $(M+1)$ times compared to OMA. This benefit is particularly important for the application of NOMA in the context of massive multiple access, where massive connectivity has to be provided to reduce the access delay in IoT networks [12].

For the second example, we consider the special case, where U_0's channel gain is the same as U_n's, i.e., $h_0 = h_n = h$. As discussed in Remark 2, the use of NOMA with CSI-based SIC does not offer any performance gain over OMA if $h_0 = h_n$. With QoS-based SIC, the sum rate gain of NOMA over OMA is simply U_n's data rate, if U_n can be admitted, i.e., $\log\left(1 + \frac{P|h|^2}{1+P|h|^2}\right) \geq R_0$, otherwise the performance gain is zero. Therefore, the sum rate gain of NOMA over OMA is given by

$$\Delta_{sum} = \mathbf{1}_0 \log\left(1 + P|h|^2\right), \quad (6)$$

where $\mathbf{1}_0$ is an indicator function, i.e., $\mathbf{1}_0 = 1$ if $\log\left(1 + \frac{P|h|^2}{1+P|h|^2}\right) \geq R_0$, otherwise $\mathbf{1}_0 = 0$. Assume that h is a Rayleigh fading channel gain, i.e., h is complex Gaussian distributed with zero mean and unit variance. Then, it is straightforward to show that

$$\mathrm{P}(\mathbf{1}_0 = 1) = e^{-\frac{2^{R_0}-1}{P\left(2-2^{R_0}\right)}} \to 1, \tag{7}$$

for $P \to \infty$, where we assume that $R_0 < 1$ bit/s/Hz. Therefore, $\Delta_{sum} \to \infty$, for $P \to \infty$, which means that NOMA with QoS-based SIC can offer a significant performance gain over OMA, even if all users have the same channel condition. In contrast, the performance gain of NOMA with CSI-based SIC diminishes in this case. This property is particularly important for the application of NOMA in indoor communication environments, where the users' channel conditions are expected to be similar.

3) The Implications of the Channel Conditions: Because the SIC decoding order of CR-NOMA is not decided by the users' channel conditions, it may happen that U_0's channel conditions are weaker than U_n's, i.e., $|h_0|^2 < |h_n|^2$. In other words, during the first step of SIC, the signal strength might be weaker than the interference strength, which leads to the common question whether this situation results in a decoding failure. We note that whether a signal can be decoded correctly depends on whether the data rate supported by the channel is larger than the target data rate, i.e., $\log\left(1+\frac{P|h|^2}{1+P|h|^2}\right) \geq R_0$. As long as this condition holds, the use of error correction coding can ensure that the signal is correctly decoded, even if the signal strength is weaker than the interference strength. Error correction coding injects redundant information, which reduces the information data rate. But if U_0's target data rate is small, a significant amount of redundant information can be added. For example, with $R_0 = 0.1$ bits/s/Hz, a repetition code with a code rate of $\frac{1}{10}$ is affordable, where one bit is repeated 10 times. With so much redundant information added, signals can be successfully decoded, even in the presence of strong interference, at the expense of an increased system complexity introduced by the error correction decoding scheme.

IV. NOMA Using Hybrid SIC With Adaptive Decoding Order

Hybrid SIC was originally proposed for NOMA assisted semi-grant-free (SGF) transmission in [11]. In this section, the motivation for using hybrid SIC with adaptive decoding order is provided first, the key idea behind hybrid SIC is then illustrated for a general NOMA uplink scenario, and finally its performance is demonstrated by using the CSI and QoS based SIC decoding orders as benchmarks.

A. Limitations of CSI/QoS-Based SIC

Without loss of generality, we focus on the same uplink scenario as in Section III, i.e., one of the M secondary users is admitted to the channel which would be solely occupied by U_0 in OMA [13]. In addition, we assume that the secondary users' channel gains are ordered as $|h_1|^2 \leq \cdots \leq |h_M|^2$.

NOMA with CSI-based SIC decodes the strong user's signal first. One possible scheme, termed SGF Scheme I in [13], is to schedule the user with the strongest channel gain among the M secondary users, i.e., U_M, and require the base station to decode U_M's signal in the first stage of SIC. In order to guarantee that U_0 experiences the same QoS as in OMA, U_M needs to use the following data rate for its transmission

$$R_M^{CSI} = \log\left(1+\frac{P|h_M|^2}{1+P|h_0|^2}\right), \tag{8}$$

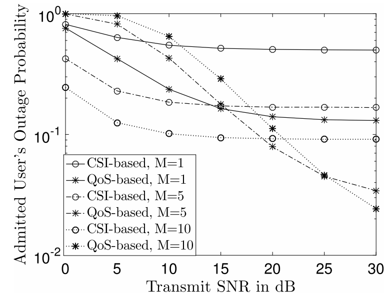


Fig. 1. Outage performance achieved by NOMA transmission with the two types of SIC. Independent and identically distributed (i.i.d.) Rayleigh fading, $R_0 = 0.2$ bits/s/Hz, and $R_s = 1$ bits/s/Hz.

which guarantees that the first stage of SIC can be carried out successfully. Therefore, in the second stage of SIC, U_0's signal can be decoded without suffering any interference. In other words, an additional user, U_M, is admitted to the channel, while U_0 transmits as if it solely occupied the channel, which is an advantage of this scheme. In addition, this scheme can efficiently exploit multi-user diversity, i.e., increasing M can reduce the admitted user's outage probability, defined by $\mathrm{P}^{CSI} \triangleq \mathrm{P}\left(R_M^{CSI} < R_s\right)$, as shown in Fig. 1.

A disadvantage of this scheme is that there is an error floor for U_M's outage probability. In particular, P^{CSI} can be approximated as follows:

$$\begin{aligned}\mathrm{P}^{CSI} &= \mathrm{P}\left(\log\left(1+\frac{P|h_M|^2}{1+P|h_0|^2}\right) < R_s\right)\\ &\underset{P\to\infty}{\to} \mathrm{P}\left(\log\left(1+\frac{|h_M|^2}{|h_0|^2}\right) < R_s\right),\end{aligned} \tag{9}$$

which is a constant and not a function of the transmit signal-to-noise ratio (SNR), where the approximation is obtained for $P \to \infty$ and we assume that all secondary users have the same target data rate, denoted by R_s. This error floor can potentially lead to a degradation of transmission robustness. In addition, the approximation in (9) indicates that U_M's data rate is capped at high SNR. Therefore, the performance gain of NOMA over OMA is also capped since this gain is related to the admitted user's data rate as shown in (6).

NOMA with QoS-based SIC first decodes the signal from primary user, U_0, by treating the admitted secondary user's signal as noise. In order to minimize the performance degradation of U_0, one possible scheme, termed SGF Scheme II in [13], is to schedule the secondary user with the weakest channel gain, i.e., U_1, which yields the following data rate:

$$R_1^{QoS} = \log(1+|h_1|^2 P), \tag{10}$$

if $\log\left(1+\frac{P|h_0|^2}{1+P|h_1|^2}\right) > R_0$, otherwise $R_1^{QoS} = 0$. Therefore, U_1's outage probability is given by

$$\begin{aligned}\mathrm{P}^{QoS} = &\,\mathrm{P}\left(\log\left(1+\frac{P|h_0|^2}{1+P|h_1|^2}\right) < R_0\right)\\ &+\mathrm{P}\left(\log\left(1+\frac{P|h_0|^2}{1+P|h_1|^2}\right) > R_0,\right.\\ &\left.\log\left(1+P|h_1|^2 < R_s\right)\right).\end{aligned} \tag{11}$$

An advantage of this scheme is that the admitted user's signal is interference free, as is evident from (10), which means that the performance gain of NOMA over OMA is not capped, unlike in CSI-based SIC. This is also the reason why

QoS-based SIC outperforms CSI-based SIC at high SNR in Fig. 1. A disadvantage of QoS-based SIC is that it cannot efficiently use multi-user diversity. For example, Fig. 1 shows that increasing M deteriorates its outage probability, since the channel gain $|h_1|^2$ becomes weaker as M increases. Another disadvantage of QoS-based SIC is that an outage probability error floor still exists, as shown in Fig. 1.

B. NOMA With Hybrid SIC

The discussions in the previous subsection suggest that realizing NOMA transmission without outage probability error floors is a mission impossible. However, the surprising findings recently reported in [11] show that error floors can be indeed avoided by using hybrid SIC, where the SIC decoding order is opportunistically chosen, as explained in the following.

Prior to user scheduling, define a threshold for evaluating the secondary users' channel conditions as follows:

$$\tau = \max\left\{0, \frac{|h_0|^2}{2^{R_0}-1} - \frac{1}{P}\right\}. \tag{12}$$

By using τ, the secondary users are divided into two groups:

- Group 1, denoted by $\mathcal{S}_1$, contains the users with strong channel conditions, i.e., $|h_n|^2 > \tau$. If a user in $\mathcal{S}_1$ is scheduled, U_0's signal cannot be decoded in the first stage of SIC, because $|h_n|^2 > \tau$ leads to $\log\left(1+\frac{P|h_0|^2}{1+P|h_n|^2}\right) < R_0$, i.e., the first stage of SIC would fail. Therefore, a user in $\mathcal{S}_1$ can support one SIC decoding order only, i.e., decoding U_n's signal first and then decoding U_0's signal, which yields the following achievable data rate:

$$R_n^1 = \log\left(1+\frac{P|h_n|^2}{1+P|h_0|^2}\right), \quad \text{for } n \in \mathcal{S}_1. \tag{13}$$

- Group 2, denoted by $\mathcal{S}_2$, contains the users which have relatively weak channel conditions, i.e., $|h_n|^2 < \tau$. If a user from $\mathcal{S}_2$ is scheduled, its signal can be decoded in either of the two SIC stages. If its signal is decoded in the first stage of SIC, its data rate is $\log\left(1+\frac{P|h_n|^2}{1+P|h_0|^2}\right)$, otherwise, its data rate is $\log(1+|h_n|^2P)$. Therefore, the achievable data rate for a user in $\mathcal{S}_2$ is given by

$$R_n^2 = \max\left\{\log\left(1+\frac{P|h_n|^2}{1+P|h_0|^2}\right), \log(1+P|h_n|^2)\right\} = \log(1+P|h_n|^2), \quad \text{for } n \in \mathcal{S}_2, \tag{14}$$

where $\max\{a,b\}$ denotes the maximum of a and b.

With global CSI at the base station, the user with the maximum achievable data rate is admitted into the channel, which yields the following achievable data rate:

$$R^* = \max\left\{\max\left\{R_n^1, \forall n \in \mathcal{S}_1\right\}, \max\left\{R_n^2, \forall n \in \mathcal{S}_2\right\}\right\}. \tag{15}$$

Remark 3: The considered SIC scheme can be viewed as a hybrid version of CSI- and QoS-based SIC, since both decoding orders can be used. Intuitively, one would expect that this straightforward combination cannot avoid an outage probability error floor, since both SIC decoding orders suffer individually from this drawback. However, contrary to intuition, this simple hybrid scheme can indeed eliminate those error floors, as explained in the following subsection. We note that NOMA with hybrid SIC can be implemented without global CSI at the base station by applying distributed contention control as shown in [11].

C. The Performance of Hybrid SIC

The the admitted user's outage probability is given by

$$\begin{aligned}\mathrm{P}^o &= \mathrm{P}\left(R^* < R_s\right)\\ &= \mathrm{P}\left(R_n^1 < R_s, \forall n \in \mathcal{S}_1, R_m^2 < R_s, \forall m \in \mathcal{S}_2\right).\end{aligned} \tag{16}$$

By using the assumption that the users's channels are ordered as $|h_1|^2 \leq \cdots \leq |h_M|^2$, the outage probability can be upper bounded as follows:

$$\begin{aligned}\mathrm{P}^o &= \mathrm{P}\left(R_n^1 < R_s, \forall n \in \mathcal{S}_1, R_m^2 < R_s, \forall m \in \mathcal{S}_2, |\mathcal{S}_2| > 0\right)\\ &\quad + \mathrm{P}\left(R_n^1 < R_s, \forall n \in \mathcal{S}_1, |\mathcal{S}_2| = 0\right)\\ &\leq \mathrm{P}\left(\log(1+|h_m|^2P) < R_s, \forall m \in \mathcal{S}_2, |\mathcal{S}_2| > 0\right) \quad (17)\\ &\quad + \underbrace{\mathrm{P}\left(R_M^1 < R_s, |h_1|^2 > \tau\right)}_{Q_0}, \quad (18)\end{aligned}$$

where $|\mathcal{S}|$ denotes the size of set $\mathcal{S}$. It is straightforward to show that the probability in (17) goes to zero when $P \to \infty$, but the probability in (18), denoted by Q_0, is less straightforward to analyze.

Since $R_M^{CSI} = R_M^1$, the outage probability for CSI-based SIC can be rewritten as $\mathrm{P}^{CSI} = \mathrm{P}\left(R_M^1 < R_s\right)$, which is quite similar to Q_0 in (18), where the only difference is that there is an extra term $|h_1|^2 > \tau$ in Q_0. At first glance, the event $|h_1|^2 > \tau$ is trivial, and an error floor should still exist for Q_0, similar to that for P^{CSI}. However, the additional term $|h_1|^2 > \tau$ introduces a hidden constraint which effectively eliminates any error floors, as explained in the following. Q_0 can be first rewritten as follows:

$$Q_0 = \mathrm{P}\left(|h_M|^2 < \frac{(1+P|h_0|^2)(2^{R_s}-1)}{P}, |h_1|^2 > \tau\right).$$

The fact that the upper bound on $|h_M|^2$ needs to be larger than the lower bound on $|h_1|^2$ results in the following constraint:

$$\frac{(1+P|h_0|^2)(2^{R_s}-1)}{P} > \tau. \tag{19}$$

This hidden constraint can be rephrased as follows:

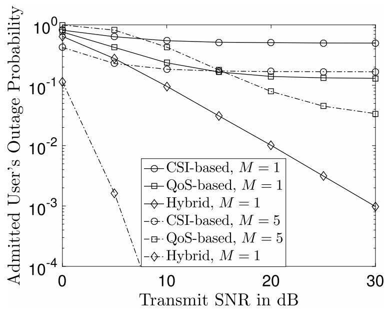
$$|h_0|^2 < \frac{2^{R_s}}{P\left(\frac{1}{2^{R_0}-1} - (2^{R_s}-1)\right)}, \tag{20}$$

where we assume that $\tau > 0$ and $\left(2^{R_s}-1\right)\left(2^{R_0}-1\right) < 1$. Therefore, Q_0 can be upper bounded as follows:

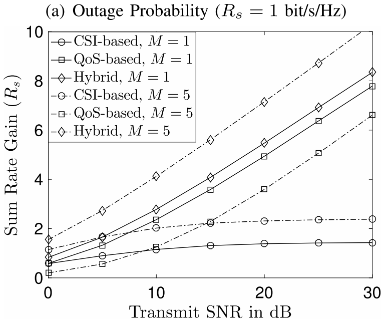
$$Q_0 \leq \mathrm{P}\left(|h_0|^2 < \frac{2^{R_s}}{P\left(\frac{1}{2^{R_0}-1} - (2^{R_s}-1)\right)}\right), \tag{21}$$

which goes to zero when $P \to \infty$. Combining (17), (18), and (21), it is straightforward to show that an error floor for P^o does not exist. We note that hybrid SIC can also realize a multi-user diversity gain of M, as shown in detail in [11].

Numerical Studies: In Fig. 2, the performance of NOMA with hybrid SIC is demonstrated by using computer simulations, where QoS- and CSI-based SIC are used as benchmark schemes. In Fig. 2(a), the outage performance achieved by the three NOMA schemes is shown. The figure demonstrates that hybrid SIC always outperforms CSI- and QoS- based SIC. More importantly, hybrid SIC can avoid outage probability error floors, as shown in Fig. 2(a). Furthermore, the fact that



(a) Outage Probability ($R_s = 1$ bit/s/Hz)



(b) Sum Rate Gain (R_s)

Fig. 2. The performance achieved by NOMA transmission using the three types of SIC. I.i.d. Rayleigh fading, and $R_0 = 0.2$ bits/s/Hz.

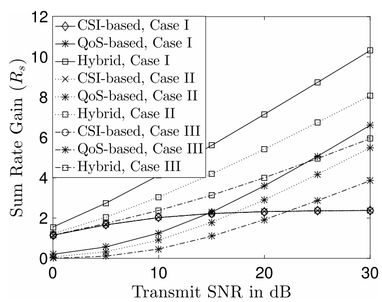


Fig. 3. Impact of R_0 on NOMA transmission using the three types of SIC. I.i.d. Rayleigh fading, $M = 5$. Case I: $R_0 = 0.2$ bits/s/Hz. Case II: $R_0 = 1$ bit/s/Hz. Case III: $R_0 = 2$ bits/s/Hz.

the slope of the curve for NOMA with hybrid SIC is increased by increasing M indicates that hybrid SIC can effectively exploit multi-user diversity.

All three NOMA schemes can ensure that a secondary user is admitted while guaranteeing that the primary user achieves the same performance as in OMA. Therefore, the difference between the sum rates achieved by OMA and NOMA is simply the admitted secondary user's data rate R_s. Fig. 2(b) illustrates the sum rate gains offered by the three NOMA schemes. In particular, the figure demonstrates that hybrid SIC always achieves the largest performance gain among the three schemes. In addition, increasing M improves the performance gain offered by hybrid SIC. An interesting observation in Fig. 2(b) is that the performance of NOMA with QoS-based SIC is degraded by increasing M, since R_1^{QoS} shown in (10) is a function of $|h_1|^2$ and the value of $|h_1|^2$ decreases as M grows.

The impact of R_0 on NOMA performance is studied in Fig. 3, which shows that reducing R_0 can significantly improve the performance of QoS-based SIC, since U_0's signal is decoded in the first stage of SIC and reducing R_0 improves the probability of successful decoding in this stage. For a similar reason, R_0 has an important impact on the performance of hybrid SIC. On the other hand, CSI-based SIC schedules the strongest user and decodes its signal directly, which means that U_0's target data rate has no impact on its performance.

V. Conclusion

In this first part of this two-part invited letter, we have reviewed the state of the art and recent progress regarding the selection of the SIC decoding order for NOMA systems. In particular, the limitations of CSI- and QoS-based SIC were illustrated first, and used as the motivation for the recently proposed hybrid SIC scheme with adaptive decoding order. A comparison of these SIC schemes was provided, and the reasons behind their performance differences were also explained in detail.

The recent findings in [11] are particularly exciting. Using the simple trick of switching between the possible SIC decoding orders, hybrid SIC yields a significant performance gain, i.e., removing the outage probability error floors, which cannot be achieved by CSI- and QoS-based SIC. These findings are particularly valuable given the fact that most existing works on NOMA adopt a prefixed SIC decoding order. Therefore, a natural question is whether these recent findings can be extended to other types of NOMA communication scenarios, which will be discussed in the second part of this invited paper.

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