Modelling and Compensation of SIC Imperfection in IRS-NOMA based 5G-System

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Received: May 29, 2023; Accepted: August 05, 2023; Published: August 30, 2023

Abstract

This article considers the impairments in the application of successive interference cancellation (SIC) at the detection phase of non-orthogonal multiple access (NOMA) users. A practical approach is proposed to model the SIC impairment which takes into account the number of multiplexed users in NOMA's power domain, in addition to the overall number of shared radio resources. In such case the imperfection of the SIC varies in accordance with the number of users. This strategy is closer to the situation in practice than the case where the SIC is modeled with fixed error factor as in the previous research articles that already considered the matter. A channel estimation approach is also proposed, which depends on the user's channel gain variations to predict the change in its peers' channel so as to compensate for the error resulting from SIC imperfection. The outcome of the proposed compensation strategy is promising as the simulation results reflect significant improvement in the achievable rate and energy efficiency.

Keywords: SIC Imperfection, IRS-NOMA, 5G-System.

1 Introduction

It is expected that in the beyond the 5th generation, and 6th generation of wireless communication systems there would be a huge demand of high spectral resource, i.e., wide bandwidth (Abbasi et al., 2021a; Dampahalage et al., 2020; Salman et al., 2023). This is due to the variety of the services to be provided in addition to the expected very high demand. In recent years, Non-Orthogonal multiple access (NOMA) has been proposed as multiple access technique to replace the currently adopted orthogonal techniques. NOMA offers the advantage of effective bandwidth usage by multiplexing all the communicating users in the power domain so that they instantaneously share the available bandwidth resource (Al-Abbasi et al., 2021a). The power domain multiplexing of the user is maintained by applying the super-position multiplexing at the transmitter, which in turn requires performing successive interference cancellation (SIC) at the receiver end (Al-Abbasi et al., 2021b; Pan et al., 2021). By doing

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Journal of Internet Services and Information Security (JISIS), volume: 13, number: 3 (August), pp. 31-40.
DOI: *10.58346/JISIS.2023.I3.003*

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so, NOMA has revolutionized the idea of efficient air interface for the next generations of communication systems (Ilyas et al., 2021). However, separating the super-imposed users at the receiver side offers several challenges to apply SIC, on these challenges is the SIC imperfection (Mahady et al., 2021; Mouni et al., 2021).

At the receiver side, SIC plays a key role in enabling the application of NOMA because it performs the separation of the multiple users' signals. SIC follows a uniform ordering process when it applies signal separation. Usually, the users are ordered in such a way that the decoding is applied firstly to the users that have strong channel conditions. After that their signals are being subtracted away from the overall received signal. This is necessary to reduce the interference and improve the decoding performance for other weaker users that have bad channel conditions. SIC has proved its ability to significantly boost the overall spectral efficiency and system capacity of NOMA (Ilyas et al., 2021; Mouni et al., 2021). In practice, however, there are several SIC impairments act as challenges that poses in practical wireless communication scenarios. Those impairments could be hardware-related, non-linear behavior of the operation amplifiers, and errors in channel estimation, etc. hence, it is important to understand the impact that these impairments have upon SIC so as to achieve successful NOMA application.

Various technologies have been addressed to enhance the sum rate, spectral and energy efficiencies, connectivity, capacity, and other criteria of NOMA systems (Al-Abbasi & Khamis, 2021; Dani et al., 2017). For instance, the authors of (Dani et al., 2017) proposed applying layered coding to boost the sum rate of NOMA systems and (Al-Abbasi & Khamis, 2021) considered iterative power allocation approach to improve the spectral efficiency. The imperfection of the SIC in NOMA systems have drawn a notable interest in recent works as a benchmark to realize near to practice scenarios in works that consider NOMA. For example, the authors in (Arzykulov et al., 2021; de Sena et al., 2020) promoted the application of different 5G technologies, such as MIMO, cognitive radio (CR), and space time block coding (STBC) that based on NOMA to provide massive connectivity (Nowaczewski, S., 2020). The authors took into account the imperfection at the SIC to avoid the fact that considering a perfect SIC scenario is far from practical. One of the motivations behind investigating the impairments is to provide better understanding of the communication scenario limitations in practice so as to implement NOMA with SIC in real-time wireless networks. This in turn would lead to achieve an effective design of the solutions, algorithms, and techniques to those impairments. The consideration of SIC design is vital due to its role in achieving the goal of NOMA by optimizing the spectral efficiency. In addition, it allows vendors and researchers to devise new methodologies that could maintain a compromise between high performance trends and low or acceptable complexity while, at the same time, maximizing the overall spectral efficiency. It is worth mentioning that identifying the SIC impairments could play a pivot role in setting the standards and shaping the direction of the future generations of wireless technology and multiple access techniques.

The Proposed IRS-NOMA Combination

It has become paramount for next generations of wireless communication technology to increase the achievable data rates, enhance the user experience, and improve the maintained spectral efficiency to meet the increasing demands of the evolving landscape. One of the recently proposed approaches to meet such goals is to combine NOMA with IRS so that the potential of both technologies is exploited to its full. Engineers and researchers proposed IRS-NOMA because of, firstly, NOMA's promising properties in exploiting the frequency domain as it permits multiple users to communicate simultaneously over the same radio frequency bandwidth. Secondly, adopting IRS with NOMA means a better control of the communication environment that IRS offers as well as maintain a high level of QoS and accurate estimation of the communication channel, this is because the fact that each user will receive more one signal, a direct transmission from the BS and a reflected version from the IRS surface.

Intelligent reflective surface (IRS) is introduced into consideration to be combined with 5G and 6G systems to enhance the energy and spectral efficiencies as well as battling against the rough communications environment for controlling the communication channel fluctuations (Dampahalage et al., 2020). IRS represents a plane-surface contains a large matrix of reflective, small, and intelligent elements with their size being equal to or less than the reflected signal's wavelength (Abbasi et al., 2021a; Dampahalage et al., 2020).

The IRS-NOMA combination has come into lights not long ago. As NOMA establishes high spectral efficiency by fully exploiting the radio bandwidth among the multiplexed users, IRS boost the received signal power and maintains high signal to noise ratio (SNR). It is important to mention that IRS boosts NOMA received signal without the need for extra transmission power, IRs could also assist the cell-center and the cell-edge users in NOMA based system to equally maintain QoS requirements as IRS deployment allows more cell-edge users to be served. A considerable number of previous literature works have already highlighted the pros of adopting IRS to underlie other techniques. For instance, the authors in (Abbasi et al., 2021b) considered boosting the performance of massive-MIMO networks by adding IRS within the coverage area. The authors concluded that IRS assisted to improve the received signal strength by all users and also enhanced the cell-edge users' experience. In addition, IRS was considered in (Dampahalage et al., 2020) to underly vehicular communication network that applies millimeter-wave (mmWaveIRS) in the uplink. The authors of (de Sena et al., 2020)mentioned the challenges encountered in channel estimation which motivates the work in here to adopt NOMA as underlying technology because NOMA applies SIC at the receiver which help alleviate the need for channel estimation. In (Zhao et al., 2021), the authors conducted a survey about IRS assisted massive MIMO systems. The authors stated that including IRS creates more intelligent communication environment which significantly boost the overall system energy and spectral efficiencies. They also highlighted that IRS is predicted to be a better contender to massive MIMO as the former provides a linear relationship between the transmission power and the achieved capacity as compared to the later, which in turn provides this relationship in a logarithmic form.

In IRS-assisted communication set up, each user will receive a direct signal component from the source and another reflected signal component reflected from the IRS surface. These signal copies will suffer several fluctuations, especially the IRS-reflected copy, that makes it highly unlikely to perfectly cancel/recover using SIC. Hence, it is vital to address the imperfections in SIC as well as a compensation strategy to tackle this problem.

2 Contribution

In the convenient NOMA systems, SIC is the decoding technique that is used at the receiver side to separate the multiple overlapping signals that belongs to different users and are multiplexed over the same time-frequency resource. Basically, the principles of SIC is to firstly decode the strongest signal and then remove its effect from the overall received signal. After that, this procedure is repeated by decoding the next strongest signal from the remaining signals, and this procedure is repeated and so on. There are several factors that affect the effectiveness of application of SIC; namely, the power imbalance among the multiplexed users, the wireless channel conditions, the level of the received signal-to-noise ratio (SNR), and the decoding of the signals. These factors could result in imperfections at the SIC application process at the receiver end. In practice, these imperfections are often modeled as a random variable in due to several reasons such as trade-off in the system design and time-frequency users' multiplexing, users' fairness, complexity and overhead, propagation environment fluctuations and variability of performance of the overall system. Hence, the contribution offered by this paper could be summarized, but not limited to, the following items:

The Proposed Fixed-Weight Modelled SIC Impairments

The first considered case is where the imperfection of the SIC is modelled as a fixed weight that is detrimentally affecting the detection process. However, having fixed weight is not practically accurate since the SIC detection process is affected by several factors such as the users' channel power and the number of users multiplexed together in the power domain. In particular, the users' channel power is largely affected by a combination of factors that reflect the effects of large-scale fading and small-scale fading, for instance, the distance between the users and the base station, the distance between the user and the IRS surface, the shadowing effects that arise from the obstacles within the coverage area, the movement of the user, etc. All those factors and other elements could affect the SIC process as it affects the order of users in applying the SIC at the receiver end.

The Proposed Random-Weight Modelled SIC Impairments

Random SIC-imperfection weight is proposed in this paper to be used as a benchmark to model the SIC imperfection. Where this weight takes into consideration the overall number of active users who are involved in the SIC process, in addition to the overall number of the shared radio subcarriers. Including the number of users and the subcarriers in the SIC-imperfection process is necessary for practical accuracy. This is to guarantee that the imperfections of the SIC varies in accordance with the number of users. This strategy is closer to the situation in practice than the case where the SIC is modeled with fixed error factor as it accounts for the factors that play a vital role in SIC application fluency.

The Proposed Channel Prediction and SIC Compensation

To compensate for the imperfections of the SIC. A user channel prediction mechanism is proposed where each user tend to predict the fluctuations in its peers' channels through evaluating the variations in its own chaFnnel state. This prediction is necessary to assist NOMA users to cancel the effect of the weaker users' channel and/or consider the stronger user-channels as noise while applying SIC detection. The principle behind the proposed prediction process is that each user records the change in its channel power from moment to moment and record the changes in a prediction weight ε. Accordingly, each user applies the recorded variations along with the imperfect-SIC so as to reduce the detrimental effect of the imperfection as well as for the best possible SIC recovery process. This is practically possible to be applied as each user would already and definitely read its channel variations. This assumption, although might not be perfectly accurate, is possible to implement in practice.

3 System Model and Simulation Set-Up

The simulated scenario considers N users equipped with single antennas being served by L base stations each equipped with a single antenna as can be seen in Figure 1 below. In addition, a reflecting surface with K reflecting elements is considered in the coverage area to boost the communication process. Both the base stations and the users are assumed to be distributed within a circular geographic area of radius r. The wireless channel is modeled following the 3GPP-LTE standards where the path-loss is modeled as $-22.8-26.1*log_{10}(fc)-36.7*log_{10}(x)$, where fc stands for the carrier frequency and x refers to the distance between the user and the base station. Consider $h_{m,n}^{r-b}$ as the complex channel between the reflecting surface and the serving base station. Moreover, let $h_{m,n}^{r-n}$ be the channel between the user and the reflecting surface. Furthermore, consider $h_{m,n}^{b-n}$ as the channel that links the base station directly to the user. It must be noted that the reflecting elements have the possibility to cause phase shift to the incident signals on the reflecting surface. The phase of these signals could shift to S different discrete levels. Where in this article, S is considered to have values in the range from 0 to 2π. Hence, each reflecting element has a set of phase shifts that is denoted by:

$$\zeta = \{0, \Delta\emptyset, 2\Delta\emptyset, 3\Delta\emptyset, \dots\dots, (S-2)\Delta\emptyset, (S-1)\Delta\emptyset\} \qquad (1)$$

$$\Delta\emptyset = \frac{2\pi}{S} \qquad (2)$$

Consider the k-th reflecting element has a phase shift as $\emptyset_k \in \zeta$. Then let's denote the reflecting matrix of the IRS surface to be:

$$\Theta = diag\left(\begin{bmatrix} \exp^{(j\emptyset_1)} \ , \exp^{(j\emptyset_2)} \ , \exp^{(j\emptyset_3)} \ , \dots\dots\dots\dots\dots \\ \dots\dots\dots.\exp^{(j\emptyset_{K-1})} \ , \exp^{(j\emptyset_K)} \end{bmatrix}^T\right). \quad (3)$$

The received signal at the user end is given as:

$$y = \left(h_{m,n}^{b-n} + \left(h_{m,n}^{r-b}\right)^H \Theta h_{m,n}^{r-n}\right) x + n \qquad (4)$$

where x refers to the signal transmitted by the base station and n stands for the additive white Gaussian noise (AWGN).

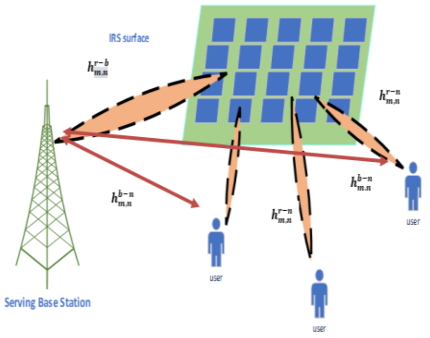

Figure 1: The System Model Setup with IRS Assisted Transmission

As a system performance criterion, the energy efficiency (EE) is applied to assess the behavior of the proposed techniques. It is important to mention that it is given by:

$$EE = \frac{\varphi_{m,n}}{P^t + P^c} \qquad (5)$$

where $\varphi_{m,n}$ denotes the rate achieved by the n-th user who is being served by the m-th base station, and it is given as:

$$\varphi_{m,n} = Blog_2\left(1 + \gamma_{m,n}\right) \qquad (6)$$

with B refers to the radio bandwidth and the SINR of each user is given as:

$$\gamma_{m,n} = \frac{P^{m,n}|\beta^{m,n}|^2}{N_0 + \varepsilon P^{m,n}|\beta^{m,n}|^2} \qquad (7)$$

note that $P^{m,n}$ models the power assigned to the n-th user at the m-th BS and $|\beta^{m,n}|^2 = \left|h_{m,n}^{b-n} + h_{m,n}^{r-b}\,\Theta h_{m,n}^{r-n}\right|^2$ denotes the magnitude of its channel power. Moreover, N_0 refers to the noise power spectral density. The term ε represent the imperfection SIC factor which takes a fraction of values that ranges between 0 and 1, where 0 denotes the case of perfect SIC performance where the user with strong channel conditions will be able to completely cancel the effect of the weaker users. While the case where $\varepsilon = 1$ states that SIC is imperfectly performs and each user would suffer a rate degradation. The inclusion of these parameters into the denominator of the expression in (7) is necessary in order to incorporate the SIC impairment models into the applied SIC algorithm, a modification to the existing SIC equations are applied in this paper to account for the effects of impairments which is introduced as new parameters that represent the factors that are related to the SIC-impairment. Another performance criterion is adopted in this article is the spectral efficiency (SE), which is determined by dividing the achievable sum rate over the total system bandwidth:

$$SE = \frac{\varphi_{m,n}}{B} \qquad (8)$$

4 Simulation Results and Discussion

MATLAB software was depended on to simulate the system model based of the parameters listed in Table I. A Monte-Carlo based simulation results were obtained for four different IRS-NOMA cases and a fifth case were SISO-NOMA is adopted without the existence of the IRS. The latter case is included to examine the impact that IRS has on NOMA based systems. On the other hand, each case of IRS-NOMA system emulates different SIC imperfection condition in order to obtain a close-to-practice outcomes.

For the purpose of recognition and to make the paper easy to read; each case was assigned a special color and curve style. For instance, the solid, Black line is used to represent the imperfect SIC-NOMA case with the imperfection weight being modeled as a fixed value. This case is not considered practically accurate as in reality the channel fluctuations might cause the imperfection weight to fluctuate as well. The Green, solid line is used to model the imperfection error weight as a random value that takes into consideration the number of users to be cancelled while applying SIC. This case might be considered as more practical due to its close-to reality determination. The compensation of both of the aforementioned cases was modeled by Magenta- and Red- dotted lines, respectively. Finally, the SISO-NOMA case where no IRS is applied is modeled with Cayan dashed line. Figure 2 shows the performance of the considered techniques in terms of the sum rate as a function of different transmission powers. In general, the achieved sum rate increases in proportion to the transmission power, and this is because increasing the transmission power level improves the signal to noise ratio, which in turn improves the achievable throughput and rate. In particular, it is obvious that the cases where NOMA is assisted with IRS plane offers better sum rate than the SISO NOMA case where IRS does not exist. This is clear evidence that IRS has significantly improved the communication environment and provided better user experience.

Table 1: Lists the Simulation Parameters that were Adopted to Obtain the Performance Results. Those Parameters are Chosen in Accordance with 3GPP-LTE Standards

Element	Value
System bandwidth	20 MHz
Carrier frequency	5GHz
Number of reflecting elements in the IRS	20, 100
Number of users	20
Number of serving base stations	5
Distance between the BS and IRS	80m
Minimum distance from IRS to each user	10m
Total transmission power	20 dBm
Noise figure (F)	8dB
No	-174+F

Figure 3 below shows the relationship between the energy efficiency and the spectral efficiency of the considered approaches at different transmission power values. This relation is important to consider as it reflects the trade-off in the system behavior and how efficiently each scheme will exploit the extra power resource for overall system benefit. To summarize, figure 3 shows that the privilege among the schemes is in the same order as in figure 2, this is another supporting evidence of the proposed techniques to have the upper hand in the presented comparison.

Regarding the simulated NOMA-IRS cases in figures 2 and 3, the imperfect SIC cases which were compensated for (i.e., magenta and red curves) offers better behavior than the case with no compensation which is convenient. However, it is worth noting that using a variant compensation weight has a better outcome which reflects better adaptations to SIC imperfections.

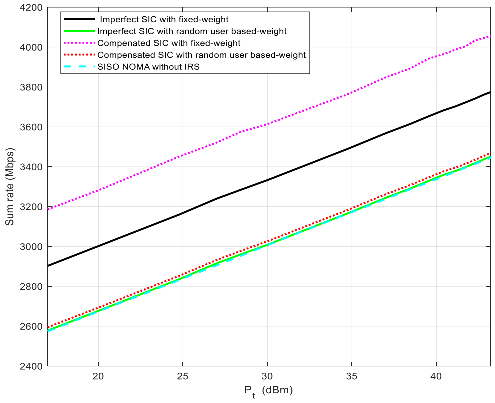

Figure 2: Sum-rate Performance Accounted at Different Transmission Power Levels with K=20 for Various Transmission Power Levels

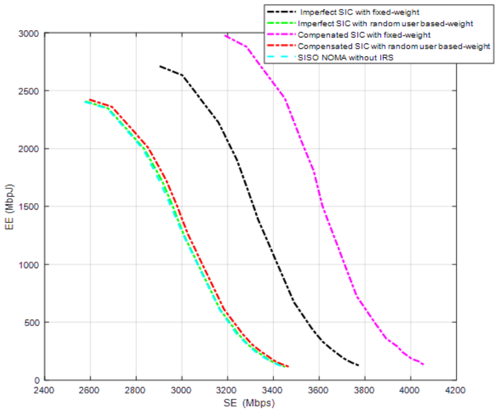

Figure 3: Energy Efficiency Performance Accounted Against Different Spectral Efficiency Levels with K=20 for Various Transmission Power Levels

To analyze the effect of the number of reflecting elements upon the compared schemes, figure 4 and figure 5 illustrate the achieved sum rate at different transmission power levels but, unlike in the previous figures case, here we have K=100. The trends of the results curves are similar to that in figure 2, however, the achievable sum rate is higher which means that increasing the number of reflecting elements K enhances the received signal powers and improves the communication environment especially with respect to the users with bad channel conditions.

Figure 5 shows the energy efficiency trade off against the achievable spectral efficiency with K=100. This figure also shows that the tradeoff is better for the system that consider the existence of IRS plane as compared to the SISO NOMA case. In the light of SIC compensation, the privilege order of the compared scheme still the same as in the previous figures. This proves the robustness of the proposed approaches under different simulation parameters and scenarios.

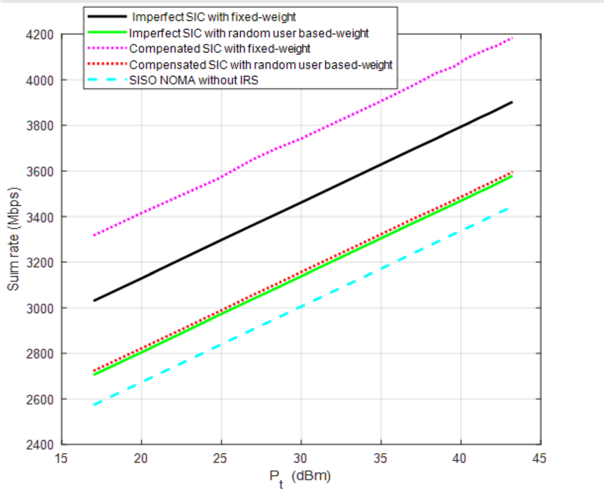

Figure 4: Energy Efficiency Performance Accounted Against Different Spectral Efficiency Levels with K=100 for Various Transmission Power Levels

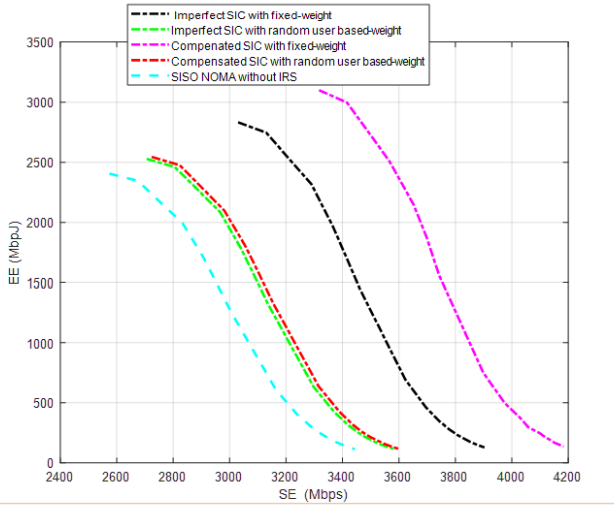

Figure 5: Energy Efficiency Performance Accounted Against Different Spectral Efficiency Levels with K=100 for Various Transmission Power Levels

5 Conclusion and Future Suggestion

This paper considers SIC modeling and compensation in the downlink of NOMA based systems. In addition, the effect of adopting IRS to assist NOMA systems is also examined and the performance of both cases, with and without SIC was examined. The simulation results reflected that, in general, all the considered cases where IRS assisted NOMA offered a great improvement as compared to the case where NOMA worked without IRS assistance, in terms of the achievable sum rate and the energy efficiency.

The paper also examined other aspects of NOMA-SIC application and in particular, the paper investigated the imperfection behavior of the SIC at the receiver end. Studying the impairments of SIC in NOMA and NOMA assisted systems is of great importance in practical wireless communication systems to exploit the full potential of NOMA in optimizing the spectral efficiency and also for meeting the huge growth of user's requirements in the near future. For accuracy, the imperfection at the SIC was modeled with a weight that takes fixed and variant values. Where with fixed weight values the imperfection kept a constant level of faulty performance regardless of the channel variations and not taking into account the number of users multiplexed in the power domain. On the other hand, the other imperfection representation included modelling the imperfection weight as a changing variable that follows the changes in the channel conditions and the number of users. It could be concluded that the later case is more practical and accurate than the former case. For future research work, it is recommended to study the case of movable IRS where their position is changed to optimize the overall system performance. Keeping in mind the practical conditions that constraint the mobility of the IRSs within the coverage area.

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