



On the performance of SIC-free spatial modulation aided uplink NOMA under imperfect CSI

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Abstract

In this paper, a spatial modulation aided uplink non-orthogonal multiple access (SM-NOMA) without successive interference cancellation (SIC) is proposed. The SIC-free SM-NOMA system is investigated under both perfect and imperfect channel state information (CSI). Moreover, on the receiver side, both SIC-based and SIC-free detection techniques are used to analyze the bit error rate (BER) performance of SM-NOMA. Finally, the performance of SIC-free SM-NOMA is evaluated and compared with the conventional NOMA, and SIC-based SM-NOMA. The results show that the SIC-free SM-NOMA outperforms conventional NOMA in terms of spectral efficiency, energy efficiency, and BER. © 2021 The Author(s). Published by Elsevier B.V. on behalf of The Korean Institute of Communications and Information Sciences. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Channel state information; Non-orthogonal multiple access; Spatial modulation; Successive interference cancellation

1. Introduction

Massive machine-type communications (mMTC) are expected to play an essential role in future 5G and 6G networks. One of the important features of mMTC is to enable energy efficient uplink transmission for a massive number of IoT (Internet of Things) devices sending very short packets, which is not possible in cellular systems designed for human-type communications (HTC) [1,2]. Therefore, finding an efficient uplink transmissions scheme for a large number of IoT devices with minimum energy constraints is an open research challenge.

Spatial Modulation (SM) is one of the promising techniques for future wireless networks that transmits additional information along with the M -ary modulation symbols [3]. SM provides high energy efficiency by simply utilizing the multiple-input multiple-output (MIMO) antenna settings and exploiting the spatial gain with a single radio frequency (RF) chain [4]. With SM, extra information bits are transmitted through the index information of a single active antenna, and the antenna index changes according to the spatial information bits to be transferred.

Recently, the integration of SM with non-orthogonal multiple access (NOMA) has gained attention [5–13]. A downlink NOMA in MIMO-SM with finite alphabet inputs was proposed in [5] where the information of the users was simultaneously transmitted by utilizing two active transmit antennas. However, only two users in a pair were grouped together to reduce the SIC complexity at the users. Furthermore, the SM-NOMA in multi-antenna settings [6] and MIMO systems [7] were introduced to enhance the ergodic sum rate. The proposed scheme in [6] reduced the intra-cluster interference and improved the user fairness in downlink communication. Moreover, to avoid the use of SIC and to reduce the computational complexity the transmit antenna was selected according to one of the users' data and the M -ary modulated symbol of the other user was transmitted on that selected antenna. However, only the ergodic sum-rate simulations are provided in both schemes [6,7]. Later, a detailed performance analysis of a similar scheme like [7] was presented in [8] and [9] where instead of SM, the generalized space-shift keying (GSSK) and space-shift keying (SSK) was used, respectively, in combination with NOMA to increase the number of served users but still performing SIC to decode the superposed signal at the users end in a downlink communication. Recently, a joint user detection scheme for an uplink grant-free SM based multi-carrier (MC)-NOMA was proposed to support massive connectivity in mMTC [10]. Moreover, there are some existing works which investigated SM in vehicular networks [11,12]. However, most of the

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previous research works on SM have considered downlink NOMA and have used SIC-based detection techniques which leads to high BER and an error floor [13] and joint maximum likelihood (JML) detection technique is only exploited in conventional NOMA.

Considering the above research analysis gap, in this paper, an uplink SIC-free SM-NOMA is proposed for mMTC that successfully recovers the information bits along with the modulated symbol bits, improves the bit-error-rate (BER), and eliminates the error floor which cannot be avoided using existing SIC-based detection techniques. Moreover, the proposed system operating under both perfect and imperfect channel state information (CSI) is investigated to highlight the performance gain. Additionally, the complexity analysis of the proposed scheme is performed to highlight the tradeoffs between BER and complexity. Finally, the performance of the proposed SIC-free SM-NOMA system in terms of spectral and energy efficiency is evaluated and compared with the conventional NOMA, and SIC-based SM-NOMA.

2. System model and transmission scheme

In this paper, uplink NOMA transmission is considered where U users, $u \in \{1, \dots, U\} = \{UE_1, \dots, UE_U\}$, transmit their modulated signal using transmit antennas N_t and transmit powers P_1 and P_2 , where $P_1 > P_2$. This transmitted signal is received as a superimposed signal at the receiver with receive antennas N_r . At each communication interval, each user (u) selects a single transmit active antenna (n) based on the information bits of that user to be transmitted. Therefore, transmit active antennas of U users at each transmission could be same or different depending on their individual information bits. The channel gains of near and far users are represented as $|h_1|^2 > \dots, |h_u|^2 > \dots, |h_U|^2$. Furthermore, the transmitted signal x_u of U users over the same time-frequency resource block (RB) is received as a superposed signal at the BS, and is given by

$$y = \sum_{u=1}^U h_u \sqrt{P_u d_u^{-\alpha}} x_u + w, \quad (1)$$

where d_u is the distance of each user (u) from the BS, the term α represents the path-loss exponent, $h_u \in \mathbb{C}^{N_r \times N_t}$ is the channel vector from user (u) to the BS and it is assumed that all the elements of h_u follow identically and independently distributed (i.i.d.) complex Gaussian distribution with zero mean and unit variance, i.e., $h_u \sim \mathcal{CN}(0, \mathbf{I}_N)$. The additive white Gaussian noise at the BS is denoted by $w \sim \mathcal{CN}(0, \sigma_w^2)$, each element of which is i.i.d. complex Gaussian random variable with zero mean and variance of σ_w^2 . Additionally, least squares (LS) method is used for the channel estimation where the estimated channel is \hat{h}_u and the estimation error is $e = \hat{h}_u - h_u$ [14]. The estimated channel coefficient \hat{h}_u follows $\hat{h}_u \sim \mathcal{CN}(0, \sigma_u^2 + \sigma_e^2)$ where $\sigma_u^2 = d_u^{-\alpha}$ is the channel variance for the UE_u -BS link and σ_e^2 is the variance of the disruptive effects occurred in the channel estimation.

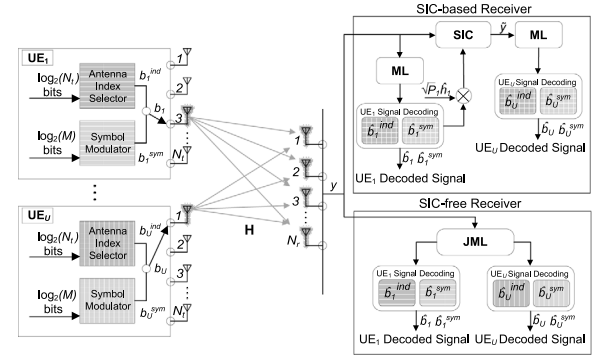


Fig. 1. Proposed system model of SIC-based and SIC-free uplink SM-NOMA.

2.1. Conventional spatial modulation

In this paper, two users ($U = 2$) are considered in a pair, each user ($u \in \{1, 2\}$) wants to transmit $b_u = b_u^{ind} + b_u^{sym}$ bits in each SM data block where $b_u^{ind} = \log_2(N_t)$ bits represent the active transmit antenna index. While $b_u^{sym} = \log_2(M)$ is the M -ary modulated symbol to be transmitted using the active transmit antenna (n) [3,4]. Moreover, given the number of transmit antennas N_t and signal constellation (M) the spectral efficiency of SM is

$$\eta_{SM} = \log_2 N_t + \log_2 M \text{ [bpcu]} \quad (2)$$

where bpcu represents the total transmit bits per channel use.

2.2. Uplink SM-NOMA system

Similar to [15,16], SIC-based SM-NOMA is used without any power control mechanism and a maximum likelihood (ML) detection scheme is used at the receiver for SIC-based SM-NOMA. For more details uplink transmission model of SM-NOMA is shown in Fig. 1. The information bits b_u ($u \in \{1, 2\}$) of each user transmitted to the BS using SM, consist of symbols from a predefined M -ary constellation and the information bits of the transmit antenna indices to be activated for the transmission. Consider that $\mathbf{x}_1 = \{0 \ 0 \ x_1 \ 0\}^T$ is the output vector of UE_1 that contains x_1 symbol to be transmitted using antenna with index bits $b_1^{ind} = 10$ following the given transmit antenna bits to indices mapping as $00 \rightarrow n_1, 01 \rightarrow n_2, 10 \rightarrow n_3, 11 \rightarrow n_4$ for a given number of $N_t = 4$ transmit antennas having indices $\{n_1, n_2, n_3, n_4\}$. Similarly, $\mathbf{x}_2 = \{x_2 \ 0 \ 0 \ 0\}^T$ represents the output vector for UE_2 that contains x_2 symbol to be transmitted using antenna index $b_2^{ind} = 00$. Considering that N is the number of transmit N_t and receive N_r antennas then the channel matrix \mathbf{H} over the MIMO channel is given as

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & \dots & \dots & h_{1,N_t} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ h_{N_r,1} & \dots & \dots & h_{N_r,N_t} \end{bmatrix} \quad (3)$$

where each $\mathbf{h}_{r,t} = \{h_{1,t} \ h_{2,t} \dots h_{N_r,t}\}^T$ is the complex channel response vector between receive antennas ($r = [1 \dots N_r]$) and

Algorithm 1 SIC-free SM-NOMA Algorithm

Transmitter: Users (U) transmit using same RB
 Input: $\log_2 N_t + \log_2 M$ \triangleright Information bits of each user
 Output: \mathbf{x}_u \triangleright Output vector of user (u) containing n_u, x_u
Receiver: Receives superposed SM-NOMA signal
 Input: $\hat{\mathbf{h}}, \mathbf{y}, M, U, N_r, N_t$
 Output: \hat{n}_u, \hat{x}_u
SIC-free Detection: Initialize $M \times N_r \times N_t$ matrix \mathbb{C} to store all possibilities

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1: Calculate  $\mathbb{C}$  for all users  $u=1$  to  $U$ 
2: for  $r=1$  to  $N_r$  do
3:   for  $t=1$  to  $N_t$  do
4:     for  $i=1$  to  $M$  do
5:        $\mathbb{C}(i, r, t) \leftarrow \left\| \mathbf{y}(r, t) - \sqrt{P_u} \hat{\mathbf{h}}_u(r, t) \mathbf{x}_u(i) \right\|^2$ 
6:     end for
7:   end for
8: end for
9:  $[\hat{n}_u, \hat{x}_u] = \min(\mathbb{C})$   $\triangleright$  Finds minimum Euclidean distance
    
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an active transmit antenna ($t = 1$) while the size of \mathbf{H} is $N_r \times N_t$. Therefore, the received vector \mathbf{y} with AWGN noise vector $\mathbf{w} = \{w_1, w_2, \dots, w_N\}^T$ at the receiver can be written as

$$\mathbf{y} = \sum_{u=1}^U \sqrt{P_u} \mathbf{H} \mathbf{x}_u + \mathbf{w}. \quad (4)$$

2.3. Conventional SIC-based detection for SM-NOMA

In a conventional SIC-based NOMA detection scheme, the receiver first decodes high-power signal while considering the low power signal as noise. Then, the decoded signal is subtracted from the received signal to decode the low-power signal. For uplink SM-NOMA, the receiver follows the same decoding strategy and at the first step of decoding the signal of low power signal user (UE_2) will be treated as interference due to which the overall signal-to-noise-interference ratio (SINR) of high power signal user (UE_1) saturates at high transmit power [13]. This results in an error floor for both users which is the main drawback of SIC-based detection schemes for SM-NOMA [16]. Because in SM-NOMA, if the information bits of the high power signal user (UE_1) are not correctly decoded then it may cause high BER at the low power signal user (UE_2). Therefore, a SIC-free detection technique is proposed to overcome the above problem.

In the proposed SM-NOMA, for $U = 2$ users with $P_1 > P_2$, the BS first decodes the received signal of UE_1 using ML detection scheme by checking all possibilities of \mathbf{x}_1 and treats the UE_2 signal as noise. The ML detection for UE_1 is performed as

$$[\hat{n}_1, \hat{x}_1] = \arg \min_{\mathbf{x}_1 \in \mathcal{X}} \left\| \mathbf{y} - \sqrt{P_1} \hat{\mathbf{h}}_1 \mathbf{x}_1 \right\|^2. \quad (5)$$

After recovery of antenna index \hat{n}_1 and symbol \hat{x}_1 , the BS subtracts the recovered \hat{x}_1 from \mathbf{y} during the SIC process and

gets $\tilde{\mathbf{y}}$ after eliminating the impact of UE_1 from \mathbf{y} . Then, BS decodes UE_2 signal and checks all possibilities of \mathbf{x}_2 by applying ML operation on $\tilde{\mathbf{y}}$ which is given as

$$[\hat{n}_2, \hat{x}_2] = \arg \min_{\mathbf{x}_2 \in \mathcal{X}} \left\| \tilde{\mathbf{y}} - \sqrt{P_2} \hat{\mathbf{h}}_2 \mathbf{x}_2 \right\|^2. \quad (6)$$

2.4. Proposed SIC-free detection for SM-NOMA

To avoid the error floor and information lost in uplink SM-NOMA a SIC-free algorithm (**Algorithm 1**) is proposed. In Algorithm 1, the SM-NOMA transmission and the SIC-free detection of SM-NOMA signal is presented. The SIC-free detection is based on joint maximum likelihood (JML) technique [17]. In JML, the BS jointly decodes the high and low power signals of both NOMA users by performing an exhaustive search. However, the computational complexity of the JML detection is higher than the SIC-based detection scheme as it simultaneously recovers the symbols of both users by checking all possibilities but it provides optimal BER than the conventional SIC-based technique. The JML operation on the received signal vector \mathbf{y} for given $U = 2$ users is written as

$$[\hat{n}_1, \hat{n}_2, \hat{x}_1, \hat{x}_2] = \arg \min_{\mathbf{x}_1, \mathbf{x}_2 \in \mathcal{X}} \left\| \mathbf{y} - \sqrt{P_1} \hat{\mathbf{h}}_1 \mathbf{x}_1 - \sqrt{P_2} \hat{\mathbf{h}}_2 \mathbf{x}_2 \right\|^2, \quad (7)$$

where \mathcal{X} is the symbols vector based on a pre-defined constellation scheme. Similarly, for any U number of users, the JML operation can be written as

$$\{\hat{n}_u, \hat{x}_u\}_{u=1}^U = \arg \min_{\mathbf{x}_u \in \mathcal{X}} \left\| \mathbf{y} - \sum_{u=1}^U \sqrt{P_u} \hat{\mathbf{h}}_u \mathbf{x}_u \right\|^2. \quad (8)$$

In this work, the goal of exploiting uplink SM-NOMA is to achieve high spectral efficiency by transmitting additional information using active transmit antenna index in mMTC. Therefore, an efficient detection scheme like SIC-free scheme is used that can correctly decode the transmitted symbol and the additional information bits as much as possible to achieve its target goal. That is why unlike the other research works on SM-NOMA the aim is to provide energy efficient and reliable uplink transmission in mMTC at the cost of computational complexity which is mostly at the receiver side.

3. Complexity

To analyze the complexity, the number of complex operations required for the detection process of SIC-based and SIC-free detection schemes will be considered. According to [9], the number of multiplications required for SM detection are $N_r N_t + M$ and $N_t M$. Additionally, complexity of ML-detection for U users is $4N_r M$. Therefore, the complexity of the SIC-based detection on performing SM and ML detection (in Eq. (5)) for high power signal of UE_1 can be written as

$$\gamma_1 = \underbrace{2N_r N_t + N_t M + M}_{SM} + \underbrace{4N_r M}_{ML}. \quad (9)$$

On the other hand, SIC will be performed for low signal power users UE_U at the receiver in SIC-based SM-NOMA

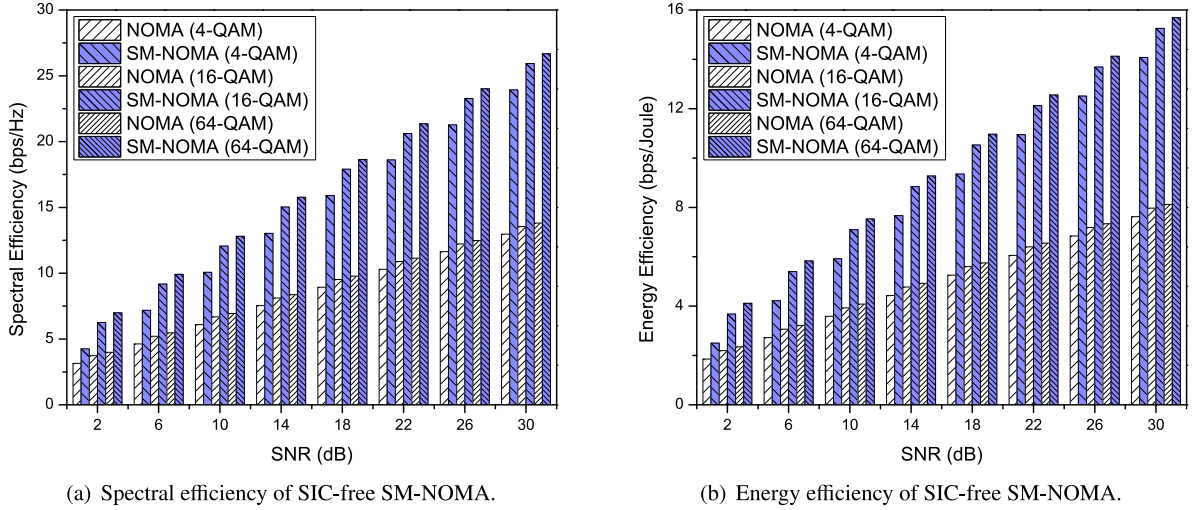


Fig. 2. Spectral and energy efficiency of SIC-free SM-NOMA and conventional NOMA for $U = 2$, $N_t = 4$, $N_r = 4$, and $M = \{4, 16, 64\}$.

and the number of iterations of SIC process depends on the number of users having higher power than UE_U . Therefore, for any U number of users case, the SIC process iterations for a user UE_U with the lowest signal power will be $U - 1$. Then, after subtracting the interference of the other users, ML-detection given in Eq. (6). will be applied. Therefore, the overall complexity for UE_U is given as

$$\gamma_U = \underbrace{2N_r N_t + N_t M + M}_{SM} + \underbrace{4N_r M}_{ML} + \underbrace{U - 1}_{SIC}. \quad (10)$$

Thus, the total receiver complexity for SIC-based SM-NOMA is $\gamma_{SM-NOMA}^{SIC} = \gamma_1 + \gamma_U$.

Furthermore, it is noted that the complexity of the SIC-based detection is lower than the SIC-free detection given in [17] as $\gamma_{SM-NOMA}^{SIC-free} = M^2(3N_r N_t - 1) + 3M^2 N_r N_t + M^2 - 1$ where the first, second and third term represent the computational complexity in terms of adder, multiplier, and comparator operations, respectively. Moreover, the complexity of both detection schemes can be compared by assuming the numeric values $U = 2$, $N_t = 4$, $N_r = 4$, and $M = 4$. As a result, the SIC-based scheme requires overall 233 complex operations while the SIC-free scheme requires 752 adder operations, 768 multiplier operations, and 15 comparator operations. However, SIC-free SM-NOMA achieves high spectral and energy efficiency along with better BER performance gain.

4. Performance evaluation

This section presents performance evaluation of the proposed SIC-free SM-NOMA scheme in terms of spectral efficiency, energy efficiency and BER.

4.1. Spectral and energy efficiency

To calculate the spectral efficiency of SIC-free SM-NOMA Eq. (2) can be utilized like in [8,9]. Additionally, the spectral efficiency depends on the error performance (P_e) of users at the given signal-to-noise ratio (SNR) ρ , the number of transmit

antennas (N_t), and the modulation technique (M). Therefore, the spectral efficiency of SIC-free SM-NOMA can be written as

$$\eta_{SM-NOMA} = \log_2(\rho \log_2(\log_2(M))) + (1 - P_e) \lfloor \log_2(N_t) \rfloor. \quad (11)$$

Furthermore, energy efficiency of SM is comprehensively analyzed in [18] and it is shown that SM is more energy efficient compared to conventional MIMO transmission. Let us say the number of bits transmitted in SIC-free SM-NOMA system using number of transmit antennas N_t and QAM modulation of size M are $\eta_{SM-NOMA}$. While the number of bits transmitted in conventional NOMA are η_{NOMA} . Therefore, the energy efficiency of SM-NOMA transmission is given as

$$\epsilon_{SM-NOMA} = \frac{\eta_{SM-NOMA}}{P_T}, \quad (12)$$

where P_T is the total transmit power required for each transmission. For instance, in the SIC-free SM-NOMA system if $U = 2$ users with $N_t = 4$ transmit antennas using signal modulation of size $M = \{4, 16, 64\}$ transmit $\eta_{SM-NOMA}$ per transmission while in conventional NOMA η_{NOMA} bits per transmission. Then, the energy efficiency of SIC-free SM-NOMA system with normalized transmit powers $P_1 = 1$, $P_2 = 0.7$ where $P_T = P_1 + P_2$ [13] can be compared to the conventional NOMA system. The results of spectral and energy efficiency of SIC-free SM-NOMA are shown in Fig. 2(a) and Fig. 2(b), respectively which show the efficacy of the SIC-free SM-NOMA scheme for uplink transmission which is the key requirement in mMTC.

4.2. BER performance of SM-NOMA

For the BER performance evaluation, firstly a case with users $U = 2$, $N_r = N_t = 4$ transmit and receive antennas, and 4-QAM signal modulation scheme is considered. The other system parameters are set as $d_1 = 0.5$, $d_2 = 1$ as normalized distances between users and the BS, $P_1 = 1$, $P_2 = 0.7$ as transmit powers of UE_1 and UE_2 , respectively. Additionally,

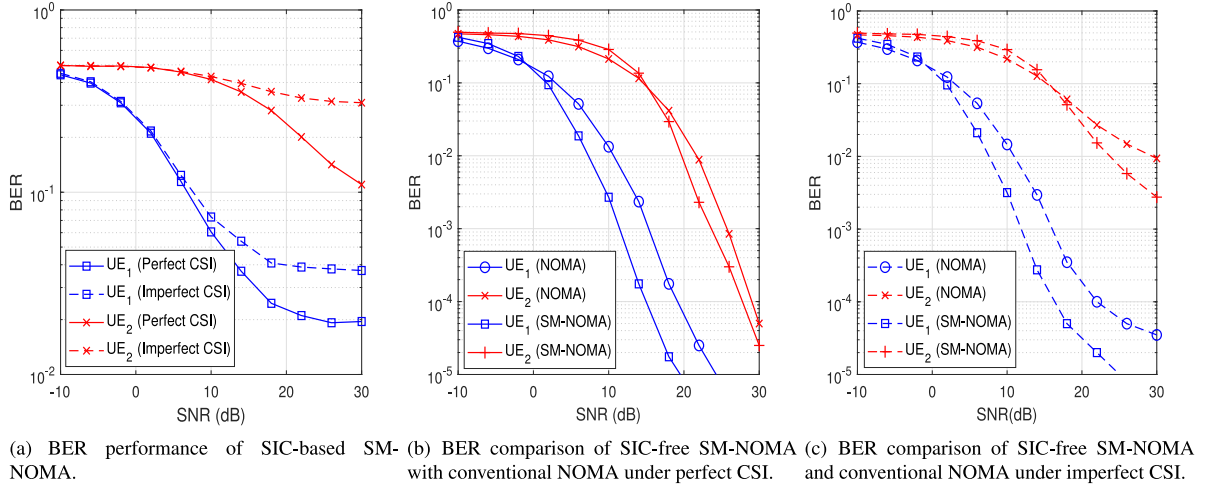


Fig. 3. BER comparison of the proposed SIC-free SM-NOMA, the conventional NOMA, and SIC-based SM-NOMA under perfect and imperfect CSI ($\sigma_e = 0.05$).

for a fair comparison bpcu of the proposed SM-NOMA and conventional NOMA scheme is the same.

In Fig. 3(a), the BER performance of SIC-based SM-NOMA is shown under both perfect CSI with $\sigma_e = 0$ and imperfect CSI with $\sigma_e = 0.05$. The BER of SIC-based SM-NOMA suffers from the error floor at high SNR regime because in SIC-based detection the UE_2 signal is treated as interference while decoding UE_1 signal which is the root cause of the error floor. Furthermore, the results in Fig. 3(b) show BER performance of the proposed SIC-free SM-NOMA where both conventional uplink NOMA and SM-NOMA overcome the error floor and achieves high BER by utilizing JML detection scheme which simultaneously decodes the signals of both users and provides better BER for both conventional NOMA and SM-NOMA. In Fig. 3(c), it can be seen that the near user (UE_1) with SIC-free SM-NOMA achieves SNR gain of 8 dB at 10^{-4} than the conventional NOMA while far user (UE_2) achieves 4 dB SNR gain at 10^{-2} than the conventional NOMA under imperfect CSI ($\sigma_e = 0.05$). Thus, the SIC-free SM-NOMA outperforms conventional NOMA and SIC-based SM-NOMA under both perfect and imperfect CSI.

5. Conclusion

This paper presents SIC-free SM-NOMA to evaluate the performance gain of SM and power domain NOMA for uplink communication in mMTC. Importantly, in this work, both SIC-free and SIC-based detection schemes for uplink SM-NOMA are implemented and their performance is evaluated. Moreover, the performance of the proposed system is analyzed under both perfect and imperfect CSI. Performance in terms of spectral efficiency and BER is evaluated and compared with the conventional NOMA. The results show that the SIC-free SM-NOMA outperforms the conventional NOMA and SIC-based SM-NOMA in terms of BER, spectral efficiency and energy efficiency.

CRediT authorship contribution statement

Irfan Azam: Conceptualization, Methodology, Investigation, Writing – original draft. **Soo Young Shin:** Supervision, Resources, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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