A Low-Complexity Coding Scheme for NOMA

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***Abstract*—This work focuses on exploiting the constructive interference among different users' data waveforms to introduce new coding and decoding techniques, which are specifically designed for non-orthogonal multiple access (NOMA) systems. In this paper, a structured coding scheme is devised. In essence, the proposed technique focuses on finding a relationship between the sent users' data waveforms and then uses this relationship in the decoding process at the receiving destination. It is worth pointing out that the proposed coding and decoding techniques exhibit better performance and reduced the complexity compared with the conventional uncoded NOMA. The complexity order evaluation shows that the proposed scheme attains a reduction in the required number of the floating point operations (FLOPs) of $5N$ and $6N$ at the second and third users, respectively, compared with that of the uncoded NOMA. Moreover, we have derived a closed-form expression for the bit-error rate (BER), which is verified using the Monte Carlo simulation. To demonstrate the practicality of the proposed system, the obtained results are compared with those of the uncoded and convolutional coding NOMA systems. Finally, the performance of the proposed system outperformed conventional systems by an average of 5 dB in the case of two users and an average of 15 dB in the case of three users in the same work environment.**

***Index Terms*—NOMA, constructive interference, destructive interference, BER, performance analysis, low-complexity, convolutional codes, AWGN, error detection and correction.**

I. Introduction

THE rapidly increased number of users in the nowadays wireless communication networks has increased the necessity of providing techniques that can maximize spectral efficiency [1], [2]. One of these spectral efficiency enhancement techniques that has gained much attention recently is non-orthogonal multiple access (NOMA) [3], [4]. The main idea behind NOMA is to apply the superposition concept at the transmitter, where different users' data waveforms are superimposed together by assigning different power levels for each user [5]. At the receiver side, successive interference cancellation (SIC) is utilized to successfully decode the desired data [6]–[10]. Hence, much research attention has been shifted towards NOMA schemes. In [11], the reliability of integrating the NOMA scheme with a dual-hop cooperative system in the presence of an eavesdropper was investigated. Moreover, Tian et. al. studied the trade off between spectral efficiency and power efficiency in NOMA systems and formulated an optimization problem based on the required rate and the allocated power for each user, which was solved using the bisection method [12]. The impact of imperfect channel state information (CSI) on the performance of a two-way relay network (TWRN) NOMA system was investigated in [13]. Furthermore, a downlink NOMA system in which a base station (BS) is communicated with multi-antenna users over Nakagami-m fading channels is considered in [14]. The authors of this work have investigated the reliability of the considered network in the presence of a multi-antenna eavesdropper.

However, one of the main drawbacks of the NOMA is the superimposition of the data waveforms for different users will introduce extra interference. Consequently, the system will be prone to BER performance degradation. The BER degradation of the NOMA system has motivated researchers to consider error detection and correction techniques, to effectively improve the BER performance. A polar-coded NOMA system was proposed in [15], which recognized the NOMA from the perspective of the channel polarization. Then, multi-dimensional TCM (MD-TCM) techniques were incorporated with the NOMA system to effectively improve the BER performance [16]. Moreover, a resource-pattern-aided bit-interleaved NOMA was proposed in [17], where the LDPC code was integrated with this NOMA system. The authors in [18] has investigated the performance of the NOMA system when different coding schemes are utilized and they deducted that the LDPC code outperforms the Turbo and convolutional codes. Despite the efficiency of these coding schemes in orthogonal multiple access (OMA) communication systems, they are not designed to deal with particularity of NOMA, i.e. having interference from the superimposed users' data. Hence, their efficiency is reduced, and their ability to detect and correct errors compared to the proposed system in this research paper, which took into account the particularity of NOMA.

While in [19]–[23], the researchers were keen on the integration of the NOMA with the reflecting intelligent surface (RIS) to improve the system BER and secrecy performance but at the cost of the added complexity of the system. In [24] the authors have developed two algorithms for scheduling power allocation and user selection, whilst in our case, the need for such additional techniques has been eliminated, since the interference between users' signals is either constructive or can be mitigated using the proposed decoding method. Next, the authors in [25] investigated the feasibility of integrating the NOMA scheme with a multi-layer cooperative network. This

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network comprises a high-altitude platform (HAP) and several unmanned aerial vehicles (UAVs) to improve the spectral utilization of the IoT networks. Moreover, in [26], the authors investigated combining the NOMA scheme with a full-duplex (FD) unmanned aerial vehicle (UAV) that was employed as a relay node to connect the base stations (BSs) with the users with no direct path with these due to obstacles and shadowing fading. This work has investigated the feasibility of utilizing half-duplex (HD) and FD relaying and evaluated the outage probability performance of the proposed system. Also, the results of this work have shown that the SIC is one of the major performance degradation sources for NOMA systems. Hence, in this work will introduce a coding method that can dramatically reduce the impact of the SIC on the performance of the NOMA system.

To the best of our knowledge, the research work that considered coding with NOMA has not addressed the fact that superimposing multiple users' data waveforms in the NOMA system will introduce extra noise to each user's signal. Hence, these algorithms can work properly up to a certain number of users and then will not be able to detect and correct errors. Moreover, the majority of the coded NOMA research work has focused only on performance enhancement achieved by the utilized coding scheme without investigating the complexity of these schemes, which does have a direct impact on the latency of the network. Also, as shown in the literature review the imperfect SIC induces extra noise in the NOMA systems, which can dramatically degrade the performance of these systems. Motivated by these facts, we propose a novel low-complexity coding algorithm, which is specifically designed for the NOMA scheme. The introduced scheme will dramatically reduce the utilization of the SIC in the decoding process, which will reduce the resulting interference from the imperfect SIC. The main contributions of this work can be summarized as follows:

- Unlike the existing work, we present a coding scheme that is specifically designed for NOMA systems. In essence, in this coding scheme we exploit the interference resulting from superimposing multiple users' data waveform.
- Moreover, we present a theoretical BER formula for the introduced coded NOMA system and this formula is validated using simulation results.
- Next, we present the complexity evaluation of the proposed scheme, which shows that our scheme exhibits less complexity order than that of the conventional uncoded NOMA. Thus, it is fair to say that the time and computational requirements for the introduced algorithm are less than that of the existing algorithms.
- The obtained results suggest that the performance of the proposed coded NOMA system is much better than that of the conventional uncoded NOMA system, with less complexity.

Although the proposed system greatly improves the performance, it reduces the transmission rate to half, also when the number of users increases, we will need the SIC process, even if it is less than the number of times required by conventional NOMA systems.

The idea of the proposed system may open the door to other ideas for developing a coded NOMA system. For instance, it is possible to develop the current system using a more efficient coding scheme than the one deployed and take advantage of the constructive interference. Also, it is possible to find and develop a relationship between users' data that always allows data retrieval without the need for SIC operations which will further reduce the complexity. In addition, since the transmitted signal in NOMA system always contains the data of all users, this feature can be exploited and employed in cooperative coded NOMA communication.

The rest of the paper is organized as follows: the proposed coded-NOMA system is introduced in Section II. Then, the closed-form formula of the BER performance and the complexity analysis of that system is presented in Section III. Moreover, Section IV illustrates the obtained results of the proposed system along with the discussion of these results. Finally, the conclusions of this work are given in Section V.

II. Proposed Coded-NOMA System

The left side of Fig. 1 presents the transmitter of the proposed coded-NOMA system and it starts with $[n,k]$ elementary encoders for two users structured coded NOMA system with code rate of $R=\frac{k}{n}$, where n is codeword length and k is the length of message bits. The first encoder will act like a repetitive code with [2,1] and the codeword of the $user_1$ will be:

$$\mathbf{C}_1=\left\{c_1^1,c_1^2\right\}=\left\{u_1,u_1\right\}, \quad (1)$$

where u_1 is the message bit of the far user. In other words, the codeword of the first encoder will be [0 0] if the transmitted message bit is 0 and [1 1] if the transmitted bit is 1. The second encoder will encode the $user_2$ data u_2 to $\mathbf{C}_2$. The first bit of $\mathbf{C}_2$ will be u_2 and the flipped version of it is the parity check or redundancy bit. Hence, $\mathbf{C}_2$ is given by:

$$\mathbf{C}_2=\left\{c_2^1,c_2^2\right\}=\left\{u_2,\bar{u}_2\right\}, \quad (2)$$

where $\bar{u}_2=1-u_2$. In particular, every 0 of the second user's message will be mapped to [0 1] and every 1 will be [1 0] as the output of the second encoder. It is very clear that the design of the encoders is very simple but the main idea of the design is to build a relationship between their outputs, so that one element must always be identical in the codewords of the encoders and it can be expressed mathematically as:

$$\mathbf{C}_1\cap\mathbf{C}_2=\left\{u_1\right\}. \quad (3)$$

The overlapping set in (3) plays the key role to take advantage of the users' interference, which ensures that one bit from each user is always in the same phase as the other user and this will lead to constructive interference [27]. It is worth noting that this is one of the most important strengths of the proposed system, because other systems will have an equal proportion of constructive and destructive interference, and this leads to low efficiency in detecting and correcting errors.

After encoding, the binary phase-shift keying (BPSK) is used for the two users to modulate $\mathbf{C}_1$ and $\mathbf{C}_2$ to $\mathbf{X}_1$ and $\mathbf{X}_2$,

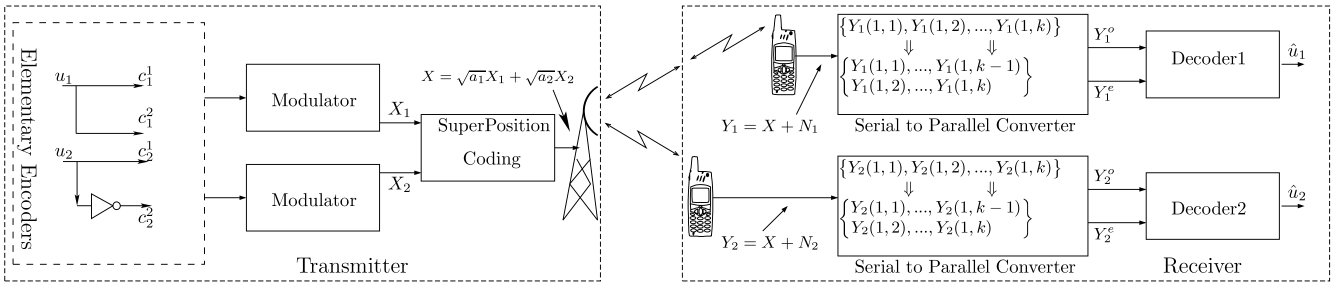

Fig. 1. Proposed coded-NOMA system model.

respectively. Where every 0 is mapped to -1 and every 1 to 1. Then, the superposed signal is given as:

$$\mathbf{X} = \sqrt{a_1 E_c}\mathbf{X}_1 + \sqrt{a_2 E_c}\mathbf{X}_2, \tag{4}$$

where E_c is the coded bit energy and it is equal to $E_b R$, where E_b is the uncoded bit energy, a_1 and a_2 are the allocated power coefficients for the first and second user, respectively, and $a_1 + a_2 = 1$.

The right side of Fig. 1 shows the receiver of the proposed system. The received signal of two users can be expressed as:

$$\mathbf{Y}_1 = \mathbf{X} + \mathbf{N}_1, \tag{5}$$

$$\mathbf{Y}_2 = \mathbf{X} + \mathbf{N}_2, \tag{6}$$

where $\mathbf{Y}_1 = \left[y_1^1, y_1^2, ..., y_1^N\right]$, $\mathbf{Y}_2 = \left[y_2^1, y_2^2, ..., y_2^N\right]$ are the far and near user received signal vectors, respectively, and N is the length of transmitted data, y_1^i and y_2^i are the i-th received signal of $user_1$ and $user_2$, respectively; where $\mathbf{N}_1 = \left[n_1^1, n_1^2, ..., n_1^N\right]$ and $\mathbf{N}_2 = \left[n_2^1, n_2^2, ..., n_2^N\right]$ are the additive white Gaussian noise (AWGN) vectors, respectively, n_1^i, n_2^i are the i-th noise element that has zero mean and variance σ^2 of $user_1$ and $user_2$, respectively.

With our proposed coding scheme, a simple decoding processes can be used to recover the $user_1(\hat{u}_1)$ as we can see in Fig. 1, first, the received sequence Y_1 is divided into two sub-sequences, Y_1^o and Y_1^e, where $Y_1^o = [y_1^1, y_1^3, ...]$, and $Y_1^e = [y_1^2, y_1^4, ...]$, then a simple decoding processes can be used to recover the i-th bit of $user_1$'s message as:

$$\hat{u}_1(i) = \begin{cases} 1, & \text{if } Y_1^o(i) + Y_1^e(i) > 0 \\ 0, & \text{else.} \end{cases} \tag{7}$$

Using the same mechanism, by dividing the received signal of the near user into odd and even sub-sequences, i-th bit of $user_2$'s received message can be retrieved as follows:

$$\hat{u}_2(i) = \begin{cases} 1, & \text{if } Y_2^o(i) - Y_2^e(i) > 0 \\ 0, & \text{else.} \end{cases} \tag{8}$$

Note that our proposed scheme can also be extended to more than two users. For instance, the decoders of coded NOMA system with 3 users can be, two encoders are used the same as in the case of a two-user system and a third encoder will be added with the same mechanism as the first encoder, given by:

$$\mathbf{C}_3 = \left\{c_3^1, c_3^2\right\} = \left\{u_3, u_3\right\}. \tag{9}$$

In this matter the first encoder is used for the first and third user to represent the proposed system. For more users case, the proposed system can be extended similarly.

III. Performance Analysis

A. BER for two users

1) BER of two Uncoded BPSK NOMA users: In this section, we start from the analysis of uncoded BPSK BER for two users NOMA system, and then extend to our proposed coded-NOMA system. It is possible to graphically and numerically represent all possible points of two users BPSK modulated NOMA system, as shown in table I and Fig. 2, respectively. This table includes all the numerical possibilities of decoding processes of the proposed coded NOMA and uncoded NOMA system for various values of a_1 and a_2, assuming that there is no noise, in order to clarify the effect of users' interference with each other. In this figure, all the possible constellation of two users are shown, taking into account the superposition coding and free noise scenario, where U_1 and U_2 refer to first and second user various constellations, respectively and the superposed points defined as; $U_1(u_1^1, u_1^2)$ and $U_2(u_2^2, u_2^2)$ for far and near user, respectively. The graphic also clearly shows the boundaries that, if crossed, will cause errors in the detection and retrieval of transmitted data.

In addition to a graphical illustration, this can be represented mathematically, for uncoded NOMA system with BPSK modulation, the received signal can be written in a simple form as:

$$Y_1 = \sqrt{a_1}x_1 + \sqrt{a_2}x_2 + n_1, \tag{10}$$

$$Y_2 = \sqrt{a_1}x_1 + \sqrt{a_2}x_2 + n_2, \tag{11}$$

where n_1 and n_2 follow a Gaussian distribution $\mathcal{N}(0, \sigma^2)$. Let's assume that the $user_1$ sent a bit of 1, Fig. 2 and Table **??** clearly illustrate that the error will occur when the noise exceed the boundary. Hence, according to the decision boundary given in Fig. 2, we can obtain the probability that u_1 is in error as:

$$P_{u_1} = \frac{P(n_1 \geq \sqrt{a_1} + \sqrt{a_2}) + P(n_1 \geq \sqrt{a_1} - \sqrt{a_2})}{2}. \tag{12}$$

Since n_1 is Gaussian distributed $\mathcal{N}(\mu, \sigma^2)$ with zero mean and variance σ^2. Because BPSK was used, only the real part of n influences decision making, so the value of n_{real} will be following the the distribution of $\mathcal{N}(0, \sigma^2/2)$ [28]. The

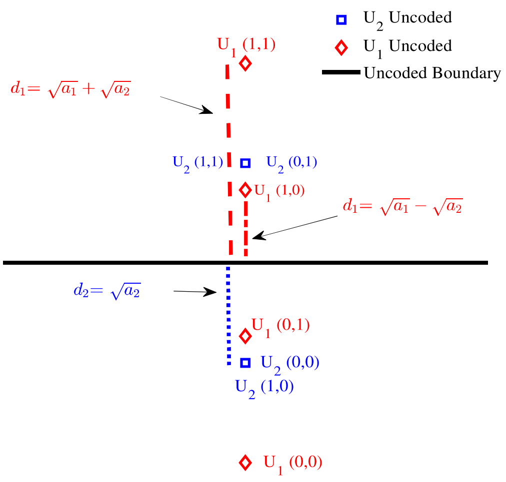

Fig. 2. Uncoded decision boundary for 2-user BPSK NOMA system.

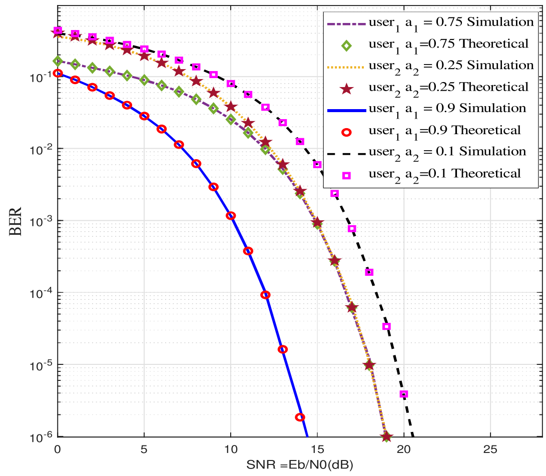

Fig. 3. Theoretical and simulated BER performance of uncoded 2-user BPSK NOMA system.

above $P(n_1 \geq \sqrt{a_1} + \sqrt{a_2})$ and $P(n_1 \geq \sqrt{a_1} - \sqrt{a_2})$ can be calculated by integrating the Gaussian PDF (probability density function) as

$$P(n \geq \sqrt{a_1} + \sqrt{a_2}) = \frac{1}{\sqrt{2\pi\sigma^2/2}} \int_{\sqrt{a_1}+\sqrt{a_2}}^{\infty} e^{\frac{-v^2}{2\sigma^2/2}} dv. \quad (13)$$

$$P(n \geq \sqrt{a_1} - \sqrt{a_2}) = \frac{1}{\sqrt{2\pi\sigma^2/2}} \int_{\sqrt{a_1}-\sqrt{a_2}}^{\infty} e^{\frac{-v^2}{2}} dv. \quad (14)$$

By substituting $\frac{v}{\sigma}$ with t, then $dt = \sigma dv$ and equation (14) will be [29]:

$$P(n \geq \sqrt{a_1} + \sqrt{a_2}) = \frac{1}{\sqrt{2\pi}} \int_{\frac{\sqrt{a_1}+\sqrt{a_2}}{\sigma^2/2}}^{\infty} e^{\frac{-t^2}{2}} dt. \quad (15)$$

$$P(n \geq \sqrt{a_1} - \sqrt{a_2}) = \frac{1}{\sqrt{2\pi}} \int_{\frac{\sqrt{a_1}-\sqrt{a_2}}{\sigma^2/2}}^{\infty} e^{\frac{-t^2}{2}} dt. \quad (16)$$

Note that, (15) and (16) are $Q(\frac{\sqrt{a_1}+\sqrt{a_2}}{\sigma^2/2})$ and $Q(\frac{\sqrt{a_1}-\sqrt{a_2}}{\sigma^2/2})$ respectively, where the Q function is: $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{\frac{-t^2}{2}} dt$. Hence, P_{u1} can be rewritten as:

$$P_{u_1} = \frac{Q\left(\sqrt{\frac{2A^2 E_b}{\sigma^2}}\right) + Q\left(\sqrt{\frac{2B^2 E_b}{\sigma^2}}\right)}{2}, \quad (17)$$

where $A = \sqrt{a_1} + \sqrt{a_2}$, $B = \sqrt{a_1} - \sqrt{a_2}$ and $E_b/\sigma^2 = \text{SNR}$ then (17) can be written as:

$$P_{u_1} = \frac{Q\left(\sqrt{2A^2 \text{SNR}}\right) + Q\left(\sqrt{2B^2 \text{SNR}}\right)}{2}. \quad (18)$$

By following same procedure, we can calculate the probability of error in u_2. The erroneous of the received codeword would occur only if the u_1 is in error and if the SIC process has an error. Since recovering u_2 is depending on u_1 and on the error that occur on the u_2 data itself, thus we have:

$$P_{u_2} = P_{u_1} + P_{e_2}, \quad (19)$$

where P_{e_2} is the SIC error and it can be estimated easily in the same way, equation (18) was calculated. It is clear that, the error will happen only if the level of the received modulated signal is less than the level of the noise that impact on the second user and it can be evaluated as:

$$P_{e_2} = P(n_2 \geq \sqrt{a_2}), \quad (20)$$

thus, the total error probability for the second user in equation (19) can be written as:

$$P_{u_2} = P_{u_1} + Q\left(\sqrt{\frac{2a_2 E_b}{\sigma^2}}\right) = P_{u_1} + Q\left(\sqrt{2a_2 \text{SNR}}\right). \quad (21)$$

The concord of the theoretical and practical results of equations (18) and (21) proves the correctness of the mathematical calculations of different power allocation coefficients, and this is very clear, as can be seen in Fig. 3.

2) BER of the Proposed Two Coded NOMA Users: For the proposed coded-NOMA system, the received signal of each bit in $\mathbf{Y}_1$ is given as:

$$y_1^1 = \sqrt{a_1 E_c} x_1^1 + \sqrt{a_2 E_c} x_2^1. \quad (22)$$

$$y_1^2 = \sqrt{a_1 E_c} x_1^2 + \sqrt{a_2 E_c} x_2^2. \quad (23)$$

Let assume $\mathbf{X}_1$ is modulated as 11 (i.e. the input of the first encoder is considered to be 1) then $\mathbf{X}_2$ can take the modulated values of $\{1, -1\}$ or $\{-1, 1\}$ (i.e. the input of the second encoder is considered as either 1 or 0), therefore, the above equations (22), (23) can be written as follows to consider all possible combinations:

$$y_1^1 = \sqrt{a_1 E_c} \pm \sqrt{a_2 E_c}, \quad (24)$$

$$y_1^2 = \sqrt{a_1 E_c} \mp \sqrt{a_2 E_c}. \quad (25)$$

$\sqrt{a_1}$ and $\sqrt{a_2}$ are: $\sqrt{0.75}$ and $\sqrt{0.25}$ respectively.																					
Proposed														**Uncoded**							
u_1	u_2	X_1		X_2		X		d_1	$\hat{u_1}$	X_2		d_2	$\hat{u_2}$	u_1	u_2	X_1	X_2	d_1	$\hat{u_1}$	d_2	$\hat{u_2}$
0	0	-1	-1	-1	1	-1.36	-0.36	-1.73	0	-0.5	0.5	-1	0	0	0	-1	-1	-1.36	0	-0.5	0
0	1	-1	-1	1	-1	-0.36	-1.36	-1.73	0	0.5	-0.5	1	1	0	1	-1	1	-0.36	0	0.5	1
1	0	1	1	-1	1	0.36	1.36	1.73	1	-0.5	0.5	-1	0	1	0	1	-1	0.36	1	-0.5	0
1	1	1	1	1	-1	1.36	0.36	1.73	1	0.5	-0.5	1	1	1	1	1	1	1.36	1	0.5	1
$\sqrt{a_1}$ and $\sqrt{a_2}$ are: $\sqrt{0.5}$ and $\sqrt{0.5}$ respectively.																					
Proposed														**Uncoded**							
u_1	u_2	X_1		X_2		X		d_1	$\hat{u_1}$	X_2		d_2	$\hat{u_2}$	u_1	u_2	X_1	X_2	d_1	$\hat{u_1}$	d_2	$\hat{u_2}$
0	0	-1	-1	-1	1	-1.41	0	-1.41	0	-0.70	0.70	-1.4	0	0	0	-1	-1	-1.41	0	-0.41	0
0	1	-1	-1	1	-1	0	-1.41	-1.41	0	0.70	-0.70	1.4	1	0	1	-1	1	0	0	1	1
1	0	1	1	-1	1	0	1.41	1.41	1	-0.70	0.70	-1.4	0	1	0	1	-1	0	0	1	1
1	1	1	1	1	-1	1.41	0	1.41	1	0.70	-0.70	1.4	1	1	1	1	1	1.41	1	0.41	1

TABLE I
DECODING TABLE OF THE PROPOSED CODED AND UNCODED NOMA SYSTEM FOR VARIOUS POWER ALLOCATION COEFFICIENTS.

The simple decoding process that estimate the transmitted u_1 can be carried out by adding the equations (24) and (25) and comparing the result with zero as:

$$\hat{u}_1 = \begin{cases} 1, & \text{if } y_1^1 + y_1^2 > 0 \\ 0, & \text{else} \end{cases}, \tag{26}$$

and the sum of the above equations will be:

$$y_1^1 + y_1^2 = 2\sqrt{a_1 E_c}. \tag{27}$$

Thus, the error will occur only if the noise level exceeds the value of $(2\sqrt{a_1 E_c})$ and this is also shown in the Fig. 4 where the visual representation of all possible constellations of two users with the proposed NOMA-coded BPSK system, which was extracted from the table I. In other words, the probability that the far user will received data in error P_{e1} can be calculated as:

$$P_{e_1} = Q\left(\sqrt{\frac{2a_1 E_c}{\sigma^2}}\right) = Q\left(\sqrt{4a_1 R E_b \text{SNR}}\right). \tag{28}$$

While the error probability for u_2 can be estimated similarly. Let assume the $\mathbf{X}_2$ take the modulated values of $\{1, -1\}$ (i.e. the input of the second encoder is considered to be 1), and X_1 can take the modulated symbols of $\{1, 1\}$ or $\{-1, -1\}$ (i.e. the input of the first encoder is considered as either 1 or 0). So, the mathematical representation of the first and second bits of the received signal at the second user can be formulated as:

$$y_2^1 = \sqrt{a_2 E_c} \pm \sqrt{a_1 E_c}. \tag{29}$$

$$y_2^2 = -\sqrt{a_2 E_c} \pm \sqrt{a_1 E_c}. \tag{30}$$

The decoding decision on u_2 can be estimated by subtracting (29) and (30) and then comparing the outcome with zero as follows:

$$\hat{u}_2 = \begin{cases} 1, & \text{if } y_2^1 - y_2^2 > 0 \\ 0, & \text{else,} \end{cases} \tag{31}$$

and the output of this subtraction will be:

$$y_2^1 - y_2^1 = 2\sqrt{a_2 E_c}. \tag{32}$$

Hence, the the error probability P_{e2} for the second user can be evaluated as:

$$P_{e2} = Q\left(\sqrt{\frac{2a_2 E_c}{\sigma^2}}\right) = Q\left(\sqrt{4a_2 R E_b \text{SNR}}\right). \tag{33}$$

To prove the correctness of the theoretical results in the equations (28) and (33) with the simulation results, Fig. 5 showed a great match in the results. Furthermore it is noticeable in (33) that the process of decoding the data of u_2 does not require SIC process, that is why it depends on the power allocation that assigns to the u_2 itself.

However, this is not the case if more users are added to the system and this instance will be explained in the next section.

B. BER for Three Users

1) BER for Three Uncoded BPSK NOMA Users: By following the same steps used in calculating the BER performance of the two-user NOMA system in section III-A1, it is possible to derive a closed-form BER performance analysis of three uncoded BPSK NOMA users easily, as shown in the following equations:

$$P_{e_1} = \frac{1}{4}(Q(\sqrt{2A^2\text{SNR}}) + Q(\sqrt{2B^2\text{SNR}}) + Q(\sqrt{2C^2\text{SNR}}) + Q(\sqrt{2D^2\text{SNR}})), \tag{34}$$

where P_{e_1}, A, B, C and D are the probability of error for the first user, $\sqrt{a_1} - \sqrt{a_2} - \sqrt{a_3}$, $\sqrt{a_1} - \sqrt{a_2} + \sqrt{a_3}$, $\sqrt{a_1} + \sqrt{a_2} - \sqrt{a_3}$ and $\sqrt{a_1} + \sqrt{a_2} + \sqrt{a_3}$, respectively.

$$P_{e_2} = P_{e_1} + \frac{1}{2}(Q(\sqrt{2E^2\text{SNR}}) + Q(\sqrt{2F^2\text{SNR}})), \tag{35}$$

where P_{e_2}, E and F are the probability of error for the second user, $\sqrt{a_2} - \sqrt{a_3}$ and $\sqrt{a_2} + \sqrt{a_3}$, respectively.

$$P_{e_3} = P_{e_2} + Q(\sqrt{2a_3^2\text{SNR}}), \tag{36}$$

where P_{e_3} is the probability of error for the third user. To examine the above three equations (34), (35) and (36), Fig. 6 shows the theoretical and simulated BER performance vs. SNR of three user BPSK modulated NOMA system for various values of the power allocation coefficients and has shown an exact match between the simulated and theoretical results.

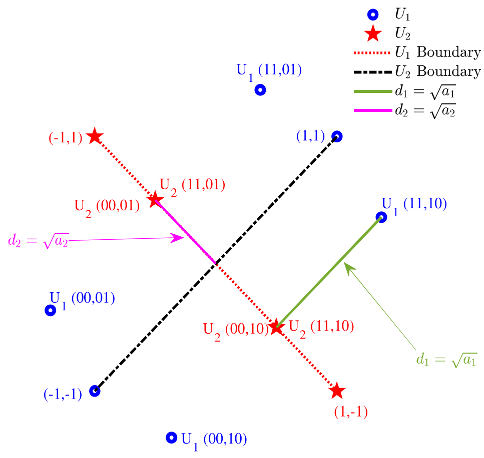

Fig. 4. Proposed coded decision boundary for 2-user NOMA system.

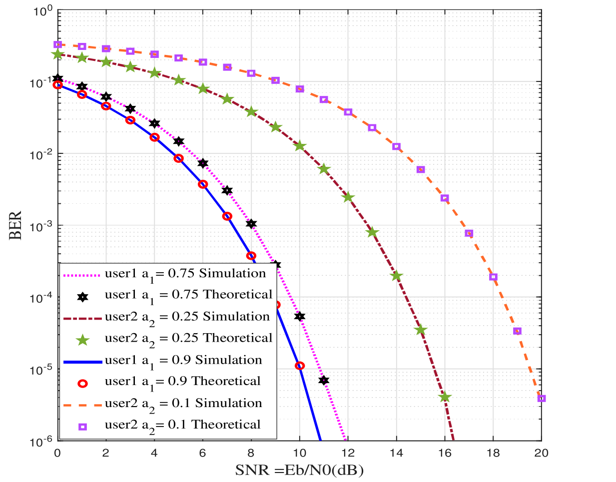

Fig. 5. Theoretical and simulated BER performance of the proposed coded 2-user NOMA system.

2) BER of the Proposed Three Coded NOMA Users: Additional user of the proposed system will be considered in this section. Let assume $user_3$ will use the encoder1 for the encoding process of u_3, see equation (9). In case of the proposed system is applied to three users scenario, and the input of the encoder of the far user is considered to be 1 the received signal of each bit in $\mathbf{Y}_1$ is given as:

$$y_1^1 = \sqrt{E_c a_1} \pm \sqrt{E_c a_2} \pm \sqrt{E_c a_3}. \quad (37)$$

$$y_1^2 = \sqrt{E_c a_1} \mp \sqrt{E_c a_2} \pm \sqrt{E_c a_3}. \quad (38)$$

As is known by now, in the proposed system, the decoding decision based on the addition of the two signals and the sum will lead to:

$$y_1^1 + y_1^2 = \sqrt{E_c a_1} \pm \sqrt{E_c a_3}. \quad (39)$$

Thus, the P_{e_1} can be evaluated as:

$$P_{e_1} = \frac{1}{2}(Q(\sqrt{4E^2 RE_b \text{SNR}}) + Q(\sqrt{4F^2 RE_b \text{SNR}})), \quad (40)$$

where E and F are $\sqrt{a_1} - \sqrt{a_3}$ and $\sqrt{a_1} + \sqrt{a_3}$, respectively.

While the decoding process for u_2 can be achieved by subtracting the received two bits of each codeword and that will lead to:

$$y_2^1 - y_2^2 = \sqrt{E_c a_2}. \quad (41)$$

Therefore, the P_{e_2} can be estimated as:

$$P_{e_2} = Q\left(\sqrt{4a_2^2 RE_b \text{SNR}}\right). \quad (42)$$

It is worth noting that the decoding of the second user did not require the SIC process, but it was done immediately after the interference with the first and third user was eliminated by a simple subtraction process, and this is what (42) illustrated.

In the case of the third user, since the same encoder will be used for u_1 and u_3, the decoding process will require a one-time use of the SIC process because the interference with the second user will be eliminated by the simple addition, and the result of this summation will be:

$$y_3^1 + y_3^2 = \sqrt{E_c a_3} \pm \sqrt{E_c a_1}. \quad (43)$$

Since $\sqrt{a_1} > \sqrt{a_3}$ (i.e. the signal of u_1 is dominant over the signal of u_3) the SIC need to be applied to remove u_1 from the received signal at u_3 side. Thus, P_{e3} can be evaluated as follows:

$$P_{e_3} = P_{e_1} + Q(\sqrt{4a_3^2 E_b \text{SNR}}). \quad (44)$$

To validate the three equations (40), (42) and (44), see Fig. 7 which shows an excellent match between the practical and theoretical results of the proposed coded NOMA system for three users and for different power allocation coefficients.

C. Complexity Analysis

This section investigates the complexity of the proposed coding scheme by evaluating the number of floating point operations (FLOPS). Low latency is one of the key goals of the 5G and 6G communications systems. Hence, determining the number of the required FLOPS for each proposed algorithm and/or scheme is of great importance, as less number of FLOPS means less processing time and less latency. This fact has motivated us to introduce a low complexity coding scheme to improve the performance of the conventional uncoded NOMA system. Without the loss of generality, each mathematical operation between any two real-valued number are treated as a single FLOP in this work [30]–[32]. A closer look at (7) and (8) show that the decoding of the received signal at $user_1$ and $user_2$ is done as follows:

- First, we divide the received sequence into odd and even sub-sequences. Consequently, we will have two sub-sequences with a size of $\frac{N}{2}$, one for the odd signals and one for the even signals.

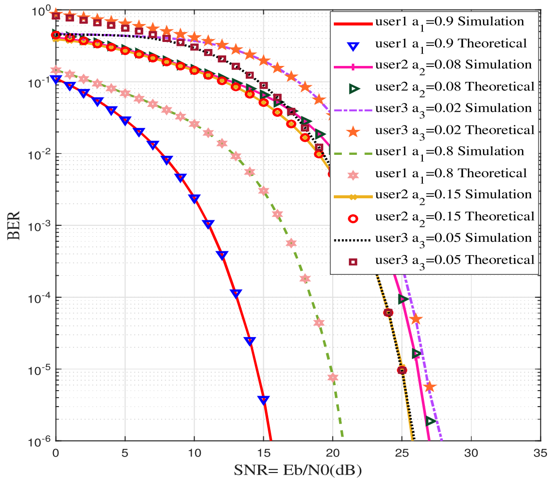

Fig. 6. Theoretical and simulated BER performance of uncoded 3-user BPSK NOMA system.

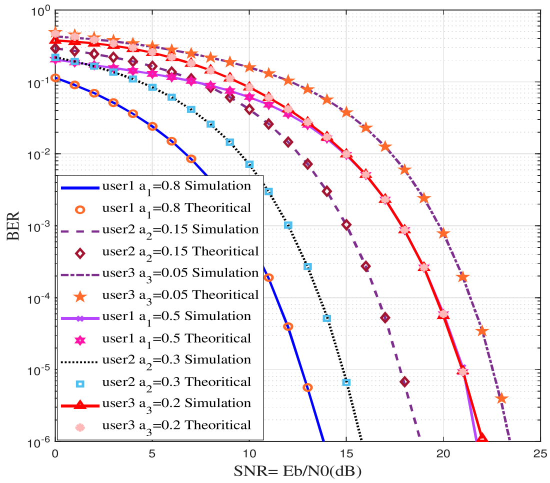

Fig. 7. Theoretical and simulated BER performance of the proposed coded 3-user NOMA system.

- Then, we preform addition between these sub-sequences at $user_1$ and subtraction between them at $user_2$ to obtain the decision sequence of size $\frac{N}{2}$, which is used to decode the received signals.
- Finally, we compare each element of the decision frame with zero to decide whether the received signal is demodulated as "1" or "0".

So, the demodulation of the received signal frame will require performing $\frac{N}{2}$ additions or subtractions, followed by $\frac{N}{2}$ comparison with zero. Hence, the complexity order of the proposed algorithm can be expressed as

$$\mathrm{CPLX}_{\mathrm{u}_1,\mathrm{u}_2} = \mathcal{O}(N). \tag{45}$$

Extending our NOMA system to three users will require extra arrangements for demodulating and decoding the third user's data. First, the proposed decoding algorithm is used to eliminate the effect of $user_2$ by simple addition process as illustrated by equation (43), and then $user_1$ data can be obtained which is then remodulated and multiplied by $\sqrt{a_1}$ to mimic $user_1$ signal. Next, this signal is removed from the total received signal by subtracting it from that signal. After that, the proposed scheme is performed again to obtain the data of the third user. Hence, the complexity order of the proposed approach will increase to be:

$$\mathrm{CPLX}_{\mathrm{u}_3} = \mathcal{O}(5N). \tag{46}$$

On the other hand, for the uncoded NOMA system and for the first user, i.e, the user that has been assigned the higher power allocation factor, the demodulation of the received frame is done by comparing each signal with zero to decide whether this signal is demodulated as "0" or "1". Thus the complexity order of obtaining the data of $user_1$ can be given as:

$$\mathrm{CPLX}_{\mathrm{u}_1} = \mathcal{O}(N). \tag{47}$$

For $user_2$, we need to detect the data of $user_1$, then, we remodulate the data to BPSK symbols. After that these BPSK symbols will be multiplied the power allocation factor assigned for $user_1$ and subtract the resulting signal from the received signal to obtain the signal of $user_2$. The obtained signal is demodulated using the comparison operation with zero to obtain the data of $user_2$. Hence, the complexity order of demodulating the data of $user_2$ can be presented as:

$$\mathrm{CPLX}_{\mathrm{u}_2} = \mathcal{O}(6N). \tag{48}$$

Analogous to $user_2$, the third user performs SIC to obtain its data. First, the data intended for the first user is detected and demodulated and then used to generate a copy of the first user's signal. Next, we subtract this signal from the received signal and use the subtraction output to detect and obtain user two data. Then, this data will be used to mimic the signal of user two, which will be subtracted from the total received signal. Finally, the remainder signal after the two stages of SIC will be utilized to obtain the data of the third user. Consequently, the complexity order of detecting the data of user 3 can be expressed as:

$$\mathrm{CPLX}_{\mathrm{u}_3} = \mathcal{O}(11N). \tag{49}$$

Fig. 8 shows the complexity order of the proposed scheme and that of the conventional uncoded NOMA. Moreover, a closer look at Fig. 8 reveals that the complexity order of the proposed scheme at $user_2$ is $5N$ less than that of the uncoded NOMA with SIC. Furthermore, this gap is increased at $user_3$ to $6N$. Consequently, it is fair to say that our scheme provides higher efficiency, less latency, and better BER performance, which were the main motivations for our work.

IV. Results and Discussion

In this section the results of the proposed system will be presented in different scenarios and compare them with the uncoded and convolutional coded NOMA system on AWGN

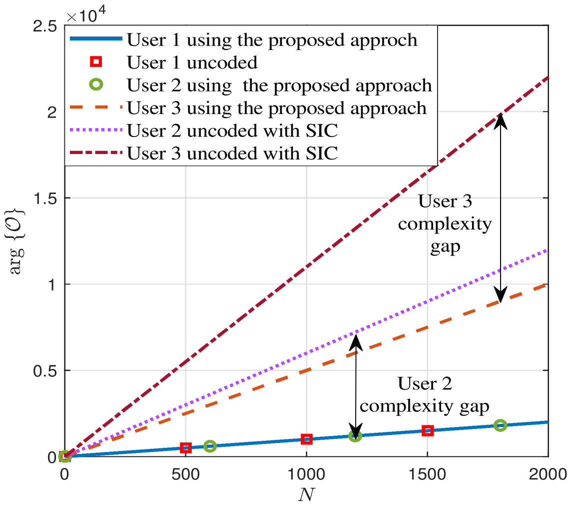

Fig. 8. The complexity of the proposed scheme and that of the SIC vs. frame size N.

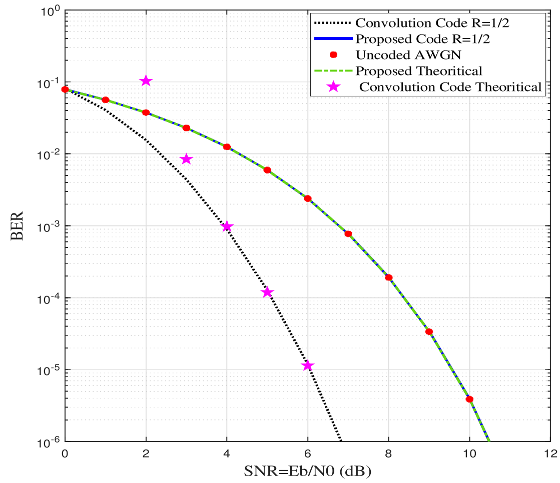

Fig. 9. BER Performance comparison between the proposed code, uncoded and convolutional code in the case of the conventional communication system.

channel. Before starting the comparison, the performance of the comparative systems need to be clarified in the conventional communication system in order to have a fair comparison to determine their efficiency in detecting and correcting errors when employed in NOMA.

Fig. 9 illustrates the BER Performance comparison between the proposed code, uncoded and convolutional code in the case of the conventional communication system and clearly the convolutional codes achieve very low BER at 6 dB while the proposed one performes just like the uncoded system in this scenario and the gain in power will be about 4 dB in the advantage of convolutional code over the proposed code. For more information about the performance of the convolutional code that used in this paper can be found in the following sources [33], [34]. Although the potential and ability of convolutional code to detect and correct errors on the OMA communication system is much more than the proposed code, the proposed system will outperform the NOMA convolutional system as it is specifically designed for this type of communication, and this is clearly shown in the following figures.

Fig. 10 shows the BER performance of the proposed coded NOMA, the uncoded NOMA system and convolutional coded NOMA versus SNR, when the power allocation coefficients a_1 and a_2 are 0.75 and 0.25 respectively. In this figure, the gain in BER for both users of the proposed system over the uncoded users about 7.5 dB and 2.3 dB for $user_1$ and $user_2$ respectively. Since $a_1 \gg a_2$, in other words when the difference in user power allocation coefficients are huge the proposed system is performing better than the convolutional coded system for the far user and the gain in performance over the convolutional NOMA is about 2 dB. In contrast, the convolutional coded NOMA system with such values will perform better for the second user by 2 dB as well.

Adding more users to the system will clearly show the difference in performance of the proposed coded system from the rest of the conventional coded and uncoded NOMA systems. Fig. 11 displays the BER curves for three users coded NOMA and uncoded system. Obviously, the proposed system has a huge gain in performance over the uncoded one, by roughly 17.5 dB, 15.5 dB and 13 dB for user 1,2 and 3 respectively. Even though the BER of the proposed system of $user_2$ in Fig. 10 is worse than the convlutional coded NOMA system, the difference in overall performance will be in the interest of the suggested system when the number of users increased and also when the values of the power allocation coefficients are very close. Fig. 11 carries the idea of the comparison between the proposed coded NOMA and convolutional coded NOMA for three users. The proposed system outperforms the convolutional coded NOMA system in error detection and correction, so the gain in favor of the proposed system about 10 dB,7.5 dB, and 5 dB for user 1,2, and 3 respectively.

Furthermore, to show the impact of the power allocation factors on the performance of the coded NOMA systems, Fig. 12 will carry out the effect of different values of the power allocation coefficients on the overall system performance. It is absolutely clear that if the $a_1 = a_2$ the convolutional coded NOMA systems is unable to detect and/or correct errors. While the proposed system can provide an excellent performance in detecting and correcting errors even when a_1 is close or equal to a_2.

To find a relationship between the performance of the NOMA system and the power allocation factors in order to chose the optimum parameters, Fig. 13 presents the relationship between the BER performance of two users coded and uncoded NOMA systems on fixed SNR (10 dB) versus a_1. Since $a_2 = 1 - a_1$ and $a_1 > a_2$, this figure is considering the values of $a_1 \in [0.5, 1]$ and $a_2 \in [0.5, 0]$.

Fig. 13, also shows that the lowest BER (3.4×10^{-2}) for both users of the uncoded NOMA system can be achieved when the $a_1 = 0.8$ (i.e. $a_2 = 0.2$ and $a_1 >> a_2$), while the lowest BER of the proposed system was (7.8×10^{-4}) when $a_1 = a_2 = 0.5$. This clearly demonstrates the ability

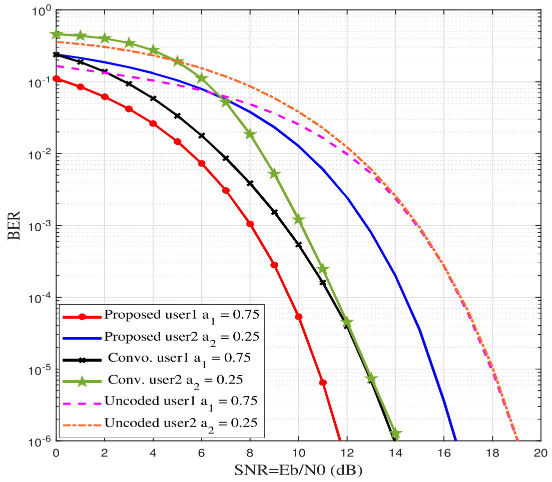

Fig. 10. BER Performance comparison between uncoded, convolutional and the proposed coded two users' NOMA system.

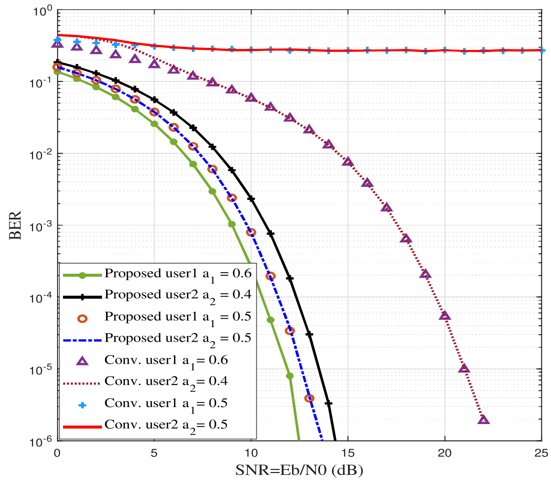

Fig. 12. BER Performance comparison between the proposed and the convolutional coded NOMA for various power allocation coefficients.

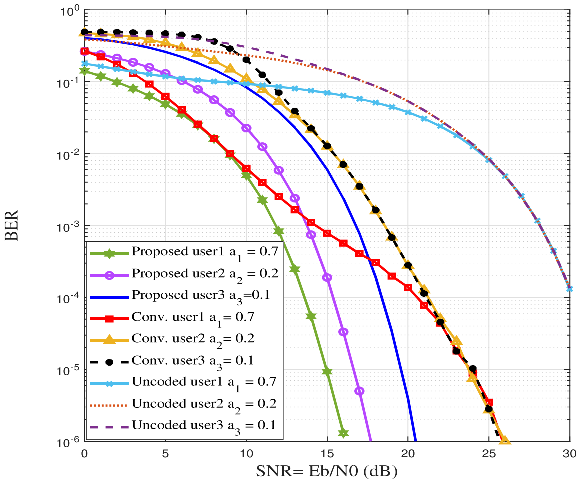

Fig. 11. BER Performance comparison between uncoded, convolutional and the proposed coded three users' NOMA system.

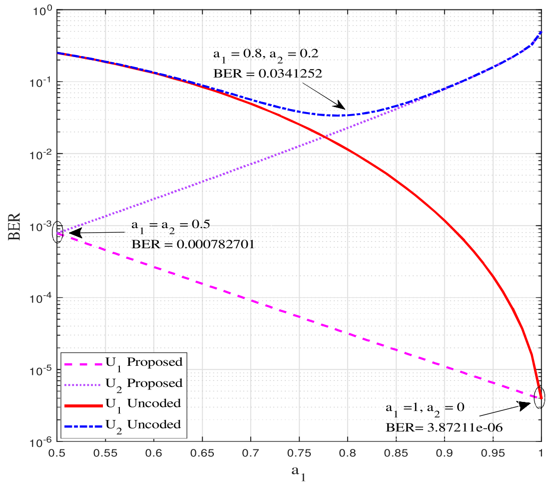

Fig. 13. NOMA power allocation coefficients for the proposed coded NOMA and uncoded NOMA when the SNR is fixed to 10 dB.

of the proposed system to recover the transmitted data more efficiently, and does not require a large difference in power allocation factor between users, and this gives more freedom to increase the number of users or assign close values of power allocation coefficients unlike the conventional system which requires a large difference in power allocation factor between users so that the system can function.

V. Conclusion

Taking into account the various characteristics of the NOMA system to think of coding and decoding methods that suit these features, it is possible to gain better performance with lower complexity. This is what was considered and implemented in this research paper, and the results were worthwhile to some extent compared to the simplicity of the proposed system. The proposed system outperformed the traditional systems that were compared, such as uncoded NOMA and convolutional coded NOMA systems in many cases and scenarios that were practically implemented and mathematically proven. Comparison with the classical NOMA system and the proposed system when using the same power allocation parameters showed a significant performance superiority of the proposed system by 7.5 dB and 2.3 dB for $user_1$ and $user_2$, respectively, in the case of a two-user system while in the case of a three-user system, the gain was 17.5 dB, 15.5 dB, and 13 dB in favor of the proposed system and for the first, second, and third users, respectively. In addition, this superior performance was achieved without adding complexity to the system, on the contrary, the proposed scheme needs the same number of FLOPs at $user_1$ and achieves a reduction in the number of FLOPs by $5N$ and $6N$ at $user_2$ and $user_3$, respectively. Moreover, the research has proven the validity and conformity of the obtained results for the proposed system mathematically, and accurate mathematical equations were derived to estimate the performance of the system. Finally, the theoretical and practical results in this paper were congruent.

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