Hindawi
Wireless Communications and Mobile Computing
Volume 2021, Article ID 8876026, 11 pages
https://doi.org/10.1155/2021/8876026

Research Article

Mitigation of Imperfect Successive Interference Cancellation and Wavelet-Based Nonorthogonal Multiple Access in the 5G Multiuser Downlink Network

Muneeb Ahmad,[1] **Sobia Baig**,[1,2] **Hafiz Muhammad Asif**,[3] **and Kaamran Raahemifar**[3,4,5]

[1] *Electrical and Computer Engineering Department, COMSATS University Isb, Lahore Campus, Lahore 54000, Pakistan*
[2] *Energy Research Center, COMSATS University Isb, Lahore Campus, Lahore 54000, Pakistan*
[3] *Department of Electrical and Computer Engineering, Sultan Qaboos University, Al-Khoud 123, Muscat Sultanate of Oman, Oman*
[4] *College of Information Sciences and Technology (IST), Data Science and Artificial Intelligence Program, Penn State University, State College, Pennsylvania, PA 16801, USA*
[5] *School of Optometry and Vision Science, Faculty of Science, Department of Chemical Engineering, Faculty of Engineering, University of Waterloo, 200 University Ave W, Waterloo, ON, N2L 3G1, Canada*

Correspondence should be addressed to Muneeb Ahmad; muneeb.ahmad72@gmail.com

Received 3 August 2020; Revised 30 November 2020; Accepted 23 December 2020; Published 21 January 2021

Academic Editor: Sujan Rajbhandari

The fourth Industrial Revolution is expected to lead to an era of technological innovation and digitization that would require connectivity by the users, anywhere and anytime. The fifth generation of wireless communication systems and the technologies therein are being explored to cater to high connectivity needs that encompass high data rates, very low latencies, energy-efficient systems, etc. A multiuser environment is anticipated that would require multiple access techniques, such as Nonorthogonal Multiple Access (NOMA). The user data in the power domain NOMA is superimposed, at the transmitter base station, which is in turn subjected to Successive Interference Cancellation at the user end. In the multiuser downlink, the desired user's signal is subjected to imperfect SIC due to incomplete cancellation of the undesired user's signal. Pulse-shaping of NOMA symbols using wavelet transform is proposed to mitigate the multiuser interference due to imperfect SIC. Closed-form symbol error rate (SER) expression is derived for the wavelet NOMA system for a three-user scenario. Analytical results show that wavelet transform pulse-shaped NOMA performs better compared to Fourier transform pulse-shaped NOMA symbols in mitigating SIC and thereby minimize the residual error due to imperfect SIC.

1. Introduction

The number of wireless devices connected to the network is growing to billions, and the fifth-generation mobile communication networks (5G) is envisaged to cater to massive connectivity, high data rate with high reliability [1]. Moreover, most of the data traffic from mobile subscribers is video streaming that requires higher bandwidth and lower latency. These requirements call for an upgrade of current mobile communication networks. To meet the requirements, there are several types of technologies have been presented in the literature [2], the use of millimetre-wave (mmWave) spectrum and Nonorthogonal Multiple Access (NOMA), where suboptimal power allocation and hybrid beamforming problems are solved to meet the minimum rate requirements of each user [3, 4].

Although, mmWave frequencies are yet to be standardized, still 30 to 300 GHz spectrum could be the best option for 5G mobile networks [4]. On the other hand, NOMA is considered a promising multiple access technique to boost the current wireless communication network. NOMA allows the optimization of multiuser operation and allocates the same frequency resources to all the users in the downlink, where no spatial separation is needed. This can be achieved by using a superposition technique [5]. In the power domain NOMA, the user's data is superimposed based on power level, while sharing the same frequency channel at the same time. At the receiver side, successive interference cancellation (SIC) is applied to retrieve a signal.

2. Prior Works and Contribution

In downlink NOMA, most of the researchers consider Fast Fourier transform-based Orthogonal Frequency Division Multiplexing (FFT-OFDM) as a pulse shaping technique [6–8]. However, a few works have focused on wavelet transform based OFDM pulse shaping in NOMA that offers greater bandwidth, low latency, and higher spectral efficiency [9]. Due to the presence of cyclic prefix (CP), the FFT-NOMA system lacks the ability to counter intersymbol interference (ISI) and intercarrier interference (ICI) for multicarrier NOMA system. Moreover, the wavelet-based NOMA system offers improved SER performance if the channel conditions are not fully known at the receiver and greater immunity to channel noise for its spectrally confined side lobes. A great amount of work has been presented to solve the mathematical framework which quantifies the performance of multicarrier NOMA [10]. In single carrier NOMA, users with high channel gain need to decode all the other user's signals; hence, it magnifies the complexity and decoding delay [11]. Therefore, wavelet transform-based NOMA is a key to counter each shortcoming of FFT-NOMA, related to interference suppression, and can be implemented in a 5G mobile communication system to accommodate greater connectivity demands [12].

To the best of our knowledge, none of the works in literature has evaluated wavelet NOMA performance for more than two users. Moreover, perfect SIC conditions are considered in the prior works for wavelet NOMA, which implies that undesired user's signals are completely subtracted until the desired signal is recovered [13]. However, if the undesired user's Channel State Information (CSI) is incomplete, then all such user's signals cannot be subtracted from the composite signal to retrieve the desired user's data. This results in imperfect SIC and thus gives rise to a residual error in addition to the desired user signal. In this paper, closed-form SER expressions are formulated for a three-user scenario by considering the effect of channel noise through FFT-NOMA as well as wavelet NOMA. While deriving the expressions, imperfect channel state information is considered, which leads to imperfect SIC at the receiver. Therefore, some residual error is produced as a result of imperfect SIC. Our work highlights the issue targeting more than two users in NOMA system, along with the channel impairments and imperefct SIC at the reciever. Because of the imperfect SIC, residual error will occur at every SIC performing user. We give a comparison of residual error at User 2 and User 3 using FFT and wavelet NOMA.

2.1. Organization. The rest of the paper is organized as follows: Section 2 presents the system model of FFT and wavelet NOMA, and interference mitigation using wavelet NOMA is described in Section 3. Section 4 explains the formulation of SER expression for three users with imperfect channel conditions at the receiver. Results are presented and explained in Section 5. Section 6 concludes the paper and elaborates the future research challenges for the proposed research work in 5G mobile communication networks.

2.2. System Model of FFT-NOMA and W-NOMA. The selection of a suitable pulse-shape plays an important role in the system's complexity and other communication-related problems such as channel dispersion. Communication systems based on the OFDM technique possess many features, including receiver design with lower complexity, robustness to multipath delay spread, compatibility of MIMO systems, and simple equalizers.

In the cited literature, a typical NOMA system model comprises of two users in which User 1 is considered as the far user while the other is near to the base station (BS). In this research work, three user NOMA system model is considered that includes an intermediate user in addition to the far and the near user. By applying a superimposed algorithm, each user's data is allocated with different power levels and converted into a single data stream, authorizing multiplexing of all the three users in a nonorthogonal way over the wireless communication channel as shown in Figure 1.

The focus of this work is the influence of interference between User 2 and User 3 on their communication error rate. In the case of imperfect estimation of User 3 and User 1 channel, incomplete SIC at the receiver will result in a residual error. To mitigate this effect of incomplete SIC, wavelet filter banks are proposed in our system model. The three-user system model for both FFT-NOMA and W-NOMA is presented in this section. Figure 2 shows the transceiver structure for wavelet NOMA. The input data symbol is subjected to source coding and baseband modulation at the transmitter side. Variable power is assigned based on channel conditions for all three users. A superposition coding algorithm is applied at the transmitter. Each user's signal is termed as $x_1(t)$, $x_2(t)$, and $x_3(t)$, respectively. Mathematically, this superimposed signal can be expressed as $x(t)$:

$$x(t) = \sqrt{\alpha_1 P}x_1(t) + \sqrt{\alpha_2 P}x_2(t) + \sqrt{\alpha_3 P}x_3(t), \qquad (1)$$

where P is the total available transmit power, while α_1, α_2, and α_3 are the allocated power factors to symbols of User 1, User 2, and User 3, respectively. Multicarrier modulation using Fast Fourier Transform (FFT) for FFT-NOMA and wavelet transform for wavelet NOMA allows multiple low symbol error rate data streams to be communicated over nonorthogonal subcarriers. At the receiver side, after the Minimum Mean-Square Error (MMSE) equalization, the received data is transformed using DFT filter banks for FFT-NOMA, while wavelet filter banks are used for wavelet

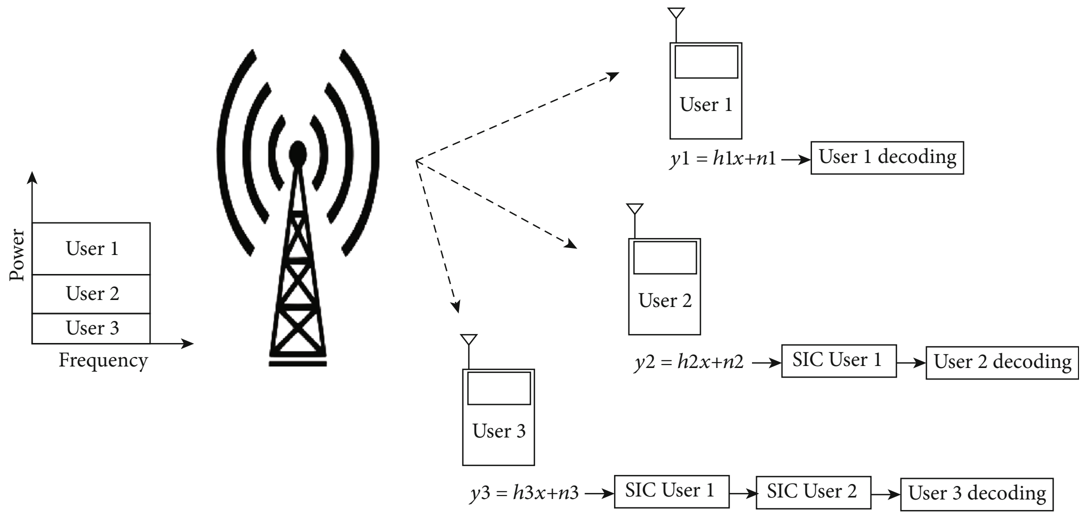

Figure 1: System model for wavelet pulse-shaped NOMA.

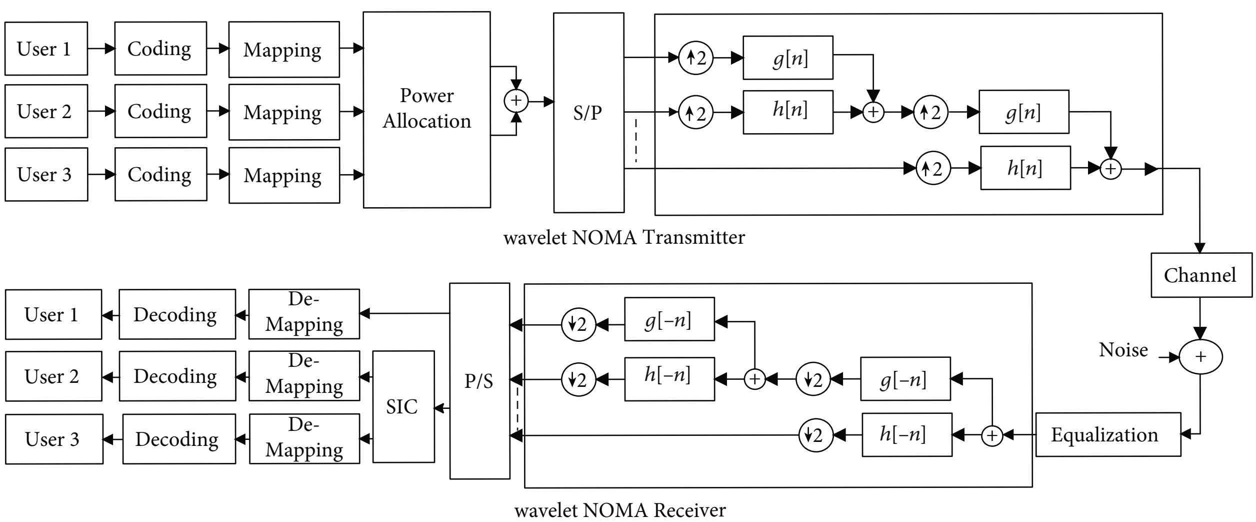

Figure 2: Transceiver design for wavelet pulse-shaped NOMA.

NOMA. User 3 and User 2's interference is cancelled out using SIC, whereas for User 1, the interference is treated as noise and each user's signal is thus recovered after baseband demodulation and decoding. Since this research work has proposed wavelet NOMA for interference mitigation between users, the following section presents the effect of interference between users.

2.3. Interference Mitigation Using Wavelet Transform-Based NOMA. In this article, researchers have analysed the performance of the wavelet-based wireless communication system because it inherits some useful advantages compared to OFDM. Wavelet uses short waveforms to form an orthogonal base in comparison with OFDM applications that make it robust to suppress the ISI and ICI. Usually, wavelets are used for the multiresolution analysis of signals or images. Our focus is to reduce the power of interferences that have to be calculated according to the definition of ISI and ICI [14]. As described in [15], ISI occurs when delayed waves of subchannel j affect the reception of the currently transmitted symbol of the same subchannel, where ICI occurs if the currently transmitted symbol is affected by the delayed waves of all the other channels. Therefore, the interference power due to ISI and ICI for the j subchannel can be described as [15]:

$$\mathrm{ISI}_j(n) = \sum_{r=-\infty}^{\infty} x_j(r) h_{jjp}\left(n_j(n-r)\right), \tag{2}$$

$$\mathrm{ICI}_j(n) = \sum_{k=0,k\neq j}^{M-1} \sum_{r=-\infty}^{\infty} x_k(r) h_{jkp}\left(n_j n - r n_k\right), \tag{3}$$

where,

$$h_{jkp}(n) = h_k(n-p) * h_j^*(-n) = \sum_{m=-\infty}^{\infty} h_k(m-p)h_j^*(m-n), \quad (4)$$

and

$$h_{jjp}(n) = h_j(n-p) * h_j^*(-n) = \sum_{m=-\infty}^{\infty} h_j(m-p)h_j^*(m-n). \quad (5)$$

These interferences occur because of imperfect SIC and CSI at the receiver side, and it can be reduced to the minimum as wavelets offer additional flexibility in signal reconstruction. The data x_j is first modulated and converted to a parallel data stream by a multiplexer and then unsampled by the factor n_k. Subsequently, the data stream is then filtered by the subchannel impulse responseh_k to retrieve the data, where h_{jkp} is the channel coefficient having excess delay p of the former subchannel k to the followed subchannel j, and this justifies the ICI occurrence among the delayed waves of all the other channels to the current detection of the transmitted data. It is important to notice that p is the additional delay subjected by the channel and affecting the SIC process for every user performing SIC to subtract the high power user's data from the received composite signal. For the conventional OMA system that implies OFDM, the sampling factor for all the subchannels is the same, whereas the power of ISI and ICI is represented as n_j and n_k respectively. However, for the increased number of subchannels, the power of ISI and ICI reduced intensely because of the inherited nature of wavelets to less sensitive to offsets in both time and frequency domain. Hence, it prunes the delayed symbols of other subchannels to prevent ICI. Furthermore, customizable transceiver characteristics of wavelets give an edge over the conventional OFDM system to adapt channel conditions in a better way to overcome ISI. Figure 3 shows the responses of FFT and wavelet filter banks, which annotates the low side-lobe attenuation of wavelet compared to FFT filter bank which prevents spectral leakage and results in a reduced interference scenario. In Figure 3, it can also be seen that lower power requirements towards frequency offsets from interferences and reduced Peak-to Average-Power-Ratio (PAPR) make our wavelet-based system model more robust towards interferences from imperfect SIC and help in the better reconstruction of the signal, hence increasing SER of the system.

In the literature [16–18], ideal channel conditions are considered for two users for NOMA-based communication system. In this research work, more than 2 users are considered, and multiuser interference using a wavelet filter bank is described in detail. Three users are presented, and SER expressions are derived for each user in wavelet NOMA. These expressions will help in the evaluation of imperfect SIC on multiuser data. In [16, 19], the symbol error rate (SER) expression of QPSK-modulated downlink NOMA system for User 1 and User 2 is given as,

$$\begin{aligned} \mathrm{SER}_{U_1} &= Q\left(\sqrt{\frac{2}{N_0}}D_1\right) + \frac{1}{2}\left[Q\left(\sqrt{\frac{2}{N_0}}\left(D'\right)\right)\right], \\ \mathrm{SER}_{U_2} &= \frac{1}{2}\left[Q\left(\sqrt{\frac{2}{N_0}}D'\right) + Q\left(\sqrt{\frac{2}{N_0}}\left(D' + 2D_1\right)\right)\right], \end{aligned} \quad (6)$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-u^2/2}du$, N_0 is the AWGN noise, and D' is the distance between two users and given as,

$$\begin{aligned} D' &= D_1 - D_2, \\ D_1 &= \sqrt{\alpha \mathrm{E}_{s_1}}, \\ D_2 &= \sqrt{(1-\alpha)E_{s_2}}, \end{aligned} \quad (7)$$

here, D_1 and D_2 are the terms including the product of power factor and symbol energy. E_{s1} and E_{s2} are the average symbol energy of User 1 and User 2; α and $1-\alpha$ are the power factors assigned to User 1 and User 2, respectively. Substituting values of D_1, D_2, and D' in (2) and (3) gives us,

$$\begin{aligned} \mathrm{SER}_{U_2} &= Q\left(\sqrt{2(1-\alpha)\frac{E_{s_2}}{N_{0,2}}}\right), \\ \mathrm{SER}_{U_1} &= Q\left(\sqrt{2\alpha\frac{E_{s_1}}{N_{0,1}}}\right) + Q\left(\sqrt{2(1-\alpha)\frac{E_{s_2}}{N_{0,1}}}\right), \end{aligned} \quad (8)$$

where $N_{0,i}$ represents the noise variance at the output of the i_{th} user for FFT or wavelet filter bank for near and far users, respectively. In the literature, perfect SIC is assumed [20, 21]. However, in this research work, the case of three users is considered. It is also assumed that SIC is imperfect and interference is caused due to high power user's signal either at near user or intermediate user.

In the following discussion, assumptions of contribution are briefly explained to assess the SER performance of near, intermediate, and far users with perfect and imperfect CSI conditions in the downlink NOMA. Assuming QPSK modulation, power factors are allocated to each user based on the channel gains $|h_1|^2 < |h_2|^2 < |h_3|^2$. Channel is assumed to be imperfect, which leads to imperfect SIC and residual error due to interference during demodulation of the received signal. The distance among the users is assumed to be equal. Furthermore, Additive White Gaussian Noise (AWGN) channel conditions are assumed; therefore, channel equalization is not considered in either FFT-NOMA or Wavelet-NOMA. At the receiver, SIC is applied to recover the data from the superimposed signal. In literature, closed-form SER expressions are derived for a two-user case using NOMA [22]. However, in this research, the wavelet-transform-based NOMA technique is proposed, which includes wavelet as a pulse shaping technique and NOMA as a multiple access technique. The basis of the research work is focused on interference created by User 2's data on User 1 and User 3. In

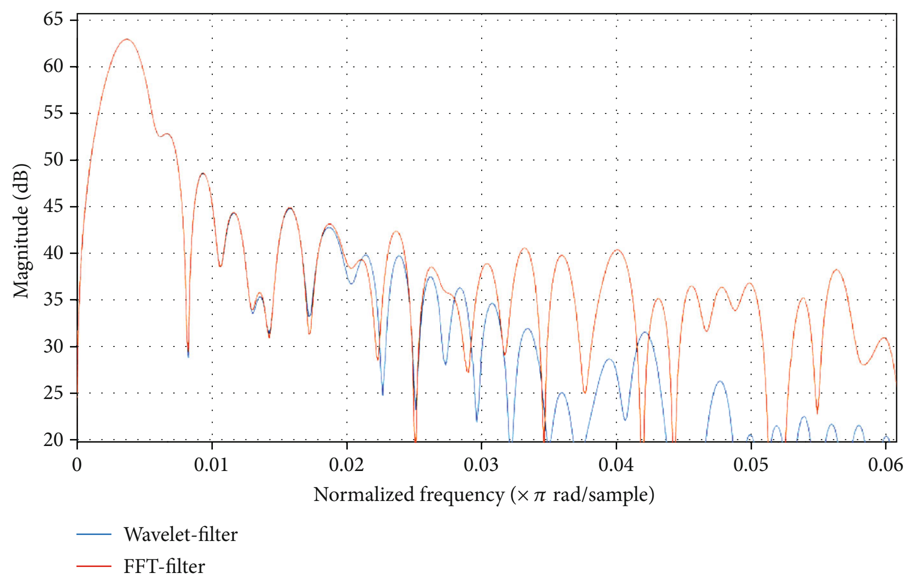

Figure 3: Magnitude response of FFT and wavelet filters.

Figure 4, signal space for three users is shown which explains the effect of high transmits power users on relatively low power users that are performing SIC. For the ease of understanding of interference from User 1, constellation points are rotated 45° for the third user. User 3 has its constellation at the centre, and User 2 has its constellation around User 3. We have assumed that User 1 has its constellation 45° tilted around User 2, for simplicity. In this way, all users can easily be identified due to the isolation of each user from the other. Moreover, each user is interfering with the other two users, which is the scenario presented in this research work. In Figure 4, the circle at the centre shows User 3, which has the effect of the other two high-power users in the received superposed signal. User 2 is shown by the cross sign, and it will have the effect of User 1 only. User 1 is shown by an asterisk sign, and it will treat other user's signals as noise.

User 1 and User 2 constellations are grouped, shown by the elliptical circles in Figure 4. Hence, interference between User 1 and User 2 can easily be recognized. It is assumed that the minimum distance between constellation points of User 3, User 2, and User 1 is $2d$, $2d\sqrt{A1}$, and $2d\sqrt{A2}$, respectively, and A is the ratio of SNR_s of two users under consideration. Assume that all user's data is equally likely to be transmitted simultaneously. Due to Inter User Interference (IUI), each user's received data consists of a constellation point that after rotation transferred to four different possible constellation points. Users are considered at equidistance from each other, where User 1 will decode its data by considering near (User 3) and intermediate user's (User 2) data as noise. However, at User 2, SIC is applied. Due to imperfect CSI, User 2 will not be able to completely subtract User 3's data. Thus, the incomplete cancellation of undesired data results in a residual error in the signal, after imperfect SIC. As a similar case for User 3, imperfect CSI produces a residual error. We have focused on the mitigation of this residual error due to incomplete channel state information, at the receiver. To mitigate this effect, the wavelet-transform-based pulse-shaping technique is considered. This research evaluates the downlink wavelet NOMA for the three users' case. We present a closed-form expression of SER for three users in FFT-NOMA and wavelet-NOMA and numeric results for SER vs. E_s/N_o. The numeric values for residual error are also presented for FFT-NOMA and wavelet-NOMA.

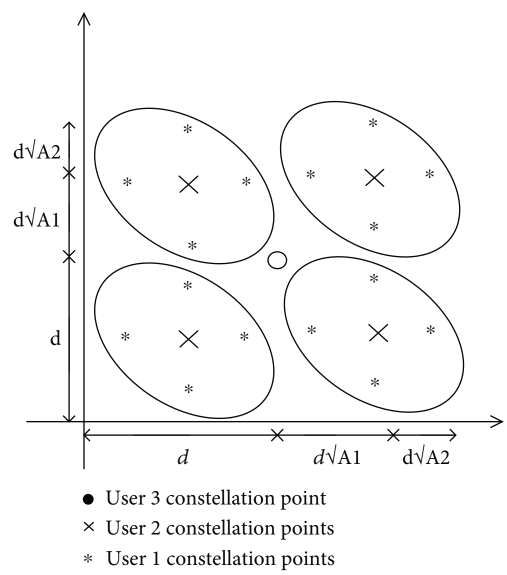

Figure 4: Signal-space diagram for three users (QPSK).

3. Closed-Form SER Expression for 3 Users with Imperfect Channel Estimation

The closed-form SER for traditional NOMA is a function of symbol energy to noise ratio. To evaluate the exact form of SER, it is essential to find the value of noise, i.e., channel noise and multiuser interference that affects the demodulation process. Consider a three-user case, where users are equally spaced, and the channel gain of three users are in the order that User 1 is with the worst channel condition, and User 2 interfere with User 1 and User 3 both. The channel conditions are expressed as $|h_1|^2 < |h_2|^2 < |h_3|^2$. The α_i is the variable power allocated to the i_{th} user. The power allocated to each user can be considered magnitude wise ($\alpha_1 P > \alpha_2 P > \alpha_3 P$).

3.1. Residual Error. Most of the literature work assumes a perfect SIC scenario, which is one of the key aspects in realizing the performance gain of NOMA technology [7, 23, 24]. However, the imperfect SIC in a three-user case implies that the signal information of User 3 is distorted due to the presence of a relatively greater power signal from undesired users since User 3 does not have complete information about User 1 and User 2 signal. The composite signal received at the l_{th} user is expressed as [24] ($l = 1, 2, 3$),

$$y_l = H_l \sum_{i=1}^{l} s_i \sqrt{\alpha_i P} + n_l, \tag{9}$$

where y is the composite received signal, $\alpha_i P$ is the transmit power assigned, H is the channel coefficient between the i^{th} user and the BS, s_i is the i^{th} user's desired signal, and n_l is the zero-mean complex additive Gaussian noise of the i^{th} channel link comprising σ^2as variance. From equation (9), the composite signal can be expressed as,

$$y = y_1 + y_2 + y_3 + n, \tag{10}$$

where n is the overall channel noise. The desired received signal at User 1 is retrieved by considering User 2 and User 3 signal as noise because of the lesser power and will simply be subtracted out to retrieve y_l,

$$\begin{aligned} y_1 &= y - y_2 - y_3 - n_1, \\ y_1 &= H_1 \sqrt{\alpha_1 P} s_1 + H_1 \sqrt{\alpha_2 P} s_2 + H_1 \sqrt{\alpha_3 P} s_3 \\ &\quad - H_1 \sqrt{\alpha_2 P} s_2 - H_1 \sqrt{\alpha_3 P} s_3 - n_1, \end{aligned} \tag{11}$$

since User 1 is the far user and can decode its data by treating User 2 and User 3 signal as noise. The desired signal is expressed as,

$$y_1 = H_1 \sqrt{\alpha_1 P} s_1 - n_1. \tag{12}$$

While for the SIC performing users, due to imperfect channel conditions, the SIC leads to the residual error, affecting the SER of the intended user. Thus, User 2 will perform SIC to decode User 1 data from the composite signal, and there will remain some residual data of User 1 which can be expressed as,

$$\begin{aligned} y_2 &= y - y_1 - y_3 - n_2, \\ y_2 &= H_2 \sqrt{\alpha_1 P} s_1 + H_2 \sqrt{\alpha_2 P} s_2 + H_2 \sqrt{\alpha_3 P} s_3 \\ &\quad - \tilde{H}_2 \sqrt{\alpha_1 P} s_1 - H_2 \sqrt{\alpha_3 P} s_3 - n_2. \end{aligned} \tag{13}$$

After performing SIC, the signal at User 2 can be expressed as,

$$y_2 = \left(H_2 - \tilde{H}_2\right) \sqrt{\alpha_1 P} s_1 + H_2 \sqrt{\alpha_2 P} s_2 - n_2, \tag{14}$$

where $H^{\sim}{}_2 \sqrt{\alpha_1 P} s_1$ represents the interference of User 1 due to the imperfect CSI of this user. This interference thereby results in a residual error in the desired signal of User 2. Similarly, if the intended user is User 3 that is performing SIC again, there will be a residual signal from User 1 and User 2 after performing SIC. User 3 signal can be expressed as,

$$\begin{aligned} y_3 &= y - y_1 - y_2 - n_3, \\ y_3 &= H_3 \sqrt{\alpha_1 P} s_1 + H_3 \sqrt{\alpha_2 P} s_2 + H_3 \sqrt{\alpha_3 P} s3 \\ &\quad - \tilde{H}_3 \sqrt{\alpha_1 P} s_1 - \tilde{H}_3 \sqrt{\alpha_2 P} s_2 - n_3. \end{aligned} \tag{15}$$

So, if we consider the three users' case, then the signal after SIC at the User 3 will be given as,

$$y_3 = \left(H_3 - \tilde{H}_3\right) \sqrt{\alpha_1 P} s_1 + \left(H_3 - \tilde{H}_3\right) \sqrt{\alpha_2 P} s_2 + H_3 \sqrt{\alpha_3 P} s_3 - n_3. \tag{16}$$

From (14) and (16), the expression for residual error in the User 2 and User 3 due to the imperfect SIC is expressed as,

$$\begin{aligned} e_{s_2} &= \left(H_2 - \tilde{H}_2\right) \sqrt{\alpha_1 P} s_1, \\ e_{s_3} &= \left(H_3 - \tilde{H}_3\right) \sqrt{\alpha_1 P} s_1 + \left(H_3 - \tilde{H}_3\right) \sqrt{\alpha_2 P} s_2, \end{aligned} \tag{17}$$

where e_{s_2} and e_{s_3} are the residual error terms present in the desired user's signal due to imperfect CSI. The case of User 1 is slightly different from the other two SIC-performing users. As User 1 is not performing SIC, there will only be the channel interference. After receiving the signal from the BS, User 1 will cancel out all the other user's signals because these low power signals are now treated at the noise level. The application of FFT and DWT is a linear transformation process of a signal. By applying either FFT or DWT transformation on the received signal, $Y(t)$ is given as,

$$\begin{aligned} Y(t) &= \mathrm{FFT}[x(t) + N(t)], \\ Y(t) &= X(t) + N_{\mathrm{FFT}}(t), \end{aligned} \tag{18}$$

where $N_{\mathrm{FFT}}(t)$ is the noise output from the FFT filter bank and can be manifested as

$$N_{\mathrm{FFT}}(t) = \frac{1}{\sqrt{N}} \sum_{l=0}^{N} \omega_t(t) e^{-j2\pi n(1/N)}, \tag{19}$$

The output of the DWT filter bank is given as,

$$Y(t) = \mathrm{DWT}[x(t) + N(t)],$$
$$Y(t) = X(t) + N_W(t), \tag{20}$$

where $N(t)$ comprises the interference e_{s2}, e_{s3}, and channel noise n. $N_W(t)$ is the noise output from the wavelet filter bank. The use of DWT means simply passing the received signal from the low pass and high pass filters with impulse response g_n and h_n, respectively [8, 25, 26]. The SER expression of QPSK-modulated downlink NOMA system can now be formulated as,

$$D_1' = D_2 - D_1,$$
$$D_2' = D_2 - D_3, \tag{21}$$
$$D_3' = D_3 - D_2,$$

where D_1', D_2', and D_3' are the distances between the three users. We evaluated D_1, D_2, and D_3 as,

$$D_1 = \alpha_1 E_{s_1},$$
$$D_2 = \sqrt{\left(1 - (\alpha_1 + \alpha_3)E_{s_2}\right)}, \tag{22}$$
$$D_3 = \sqrt{\left(1 - (\alpha_1 + \alpha_2)E_{s_3}\right)},$$

where E_{s_1}, E_{s_2}, and E_{s_3} are the energy assigned to the three users. For a three-user case, the SER expressions for wavelet NOMA are given as,

$$\mathrm{SER}^W_{\mathrm{User}_1} = Q\left(\sqrt{2\alpha_1 \frac{E_{s_1}}{N_W}}\right) + \frac{1}{2}\left[Q\left(2\sqrt{(2 - 2(\alpha_1 + \alpha_3))\frac{E_{s_2}}{N_W}}\right)\right] + \frac{1}{2}\left[Q\left(2\sqrt{(2 - 2(\alpha_1 + \alpha_2))\frac{E_{s_3}}{N_W}}\right)\right],$$
$$\mathrm{SER}^W_{\mathrm{User}_2} = Q\left(-2\sqrt{2\alpha_1 \frac{E_{s_1}}{N_W}}\right) + \frac{1}{2}\left[Q\left(s\sqrt{(2 - 2(\alpha_1 + \alpha_3))\frac{E_{s_2}}{N_W}}\right)\right] + \frac{1}{2}\left[Q\left(\sqrt{(2 - 2(\alpha_1 + \alpha_2))\frac{E_{s_3}}{N_W}}\right)\right],$$
$$\mathrm{SER}^W_{\mathrm{User}_3} = Q\left(-\sqrt{2\alpha_1 \frac{E_{s_1}}{N_W}}\right) + \frac{1}{2}\left[Q\left(4\sqrt{(2 - 2(\alpha_1 + \alpha_3))\frac{E_{s_2}}{N_W}}\right)\right] + \frac{1}{2}\left[Q\left(\sqrt{(2 - 2(\alpha_1 + \alpha_2))\frac{E_{s_3}}{N_W}}\right)\right]. \tag{23}$$

On similar lines, SER expressions are derived for FFT as $\mathrm{SER}^{\mathrm{FFT}}_{\mathrm{User}_i}$ $(i = 1, 2, 3)$, while the symbol energy to noise ratio will consider N_{FFT}.

4. Results and Performance

In this article, the authors presented the work including mathematical analysis of three users for NOMA system under imperfect SIC constraint and thus preference is given to the numerical results. Specifications for the system of a three user NOMA are described in Table 1. The residual error values of User 2 and User 1 are shown with FFT and wavelet noise in Tables 2 and 3, respectively. Error due to imperfect CSI is also added, but overall noise will be lower due to good channel conditions of the users located near the BS. Hence, the residual error minimizes as the distance from the BS is reduced.

Comparing Tables 2 and 3, it can be seen that for wavelet NOMA and FFT-NOMA, three different types of channel conditions are used. Residual error due to imperfect CSI for User 2 and User 3 for FFT noise is shown in Table 2. At 0 dB, the residual error value for User 3 is 0.0565 that is the minimum compared to the User 2 for FFT-NOMA, while for User 2, the error value at 0 dB is 0.0781 that is a bit higher than the User 3 because of the placement of it is near to the base station. The channel has the minimum error for User 3 since the channel conditions are better compared to User 2. Similarly, Table 2 shows the effect of wavelet filter banks for the NOMA system, and at the 0 dB, the residual error value for User 2 and User 3 is 0.0625 and 0.0255, respectively. The error values for both the users from Table 3 are significantly less than the error value from Table 2 because of the potential of wavelet filter banks to perform better for imperfect SIC at the receiver side.

Furthermore, for relatively poor channel conditions where channel gains at 10 dB with FFT-noise, the absolute value of the residual error for User 3 is 2.61×10^{-7}, and for User 2, the residual error is 3.68×10^{-6}. On the other hand, at 10 dB with wavelet-noise, the residual error for User 3 is 1.36×10^{-12}, and for User 2, the residual error value at 10 dB is 4.01×10^{-8}. This is verified from the residual error values shown in Table 3 for wavelet NOMA. The cyclic prefix in FFT-NOMA helps to avoid ISI, but these redundant bits reduce the spectral efficiency. The length of the cyclic prefix depends on the bandwidth, but maximum, it could be 25% of the symbol length. However, the wavelet filter banks due to the ability of energy confinement of the transmitted symbols have a greater impact in reducing interference compared to the FFT filters. Thus, the wavelet NOMA improves the overall signal to noise ratio after passing through the high-quality wavelet filters. Therefore, the wavelet noise level is lower than the FFT noise level for both User 2 and User 3. That is the reason with the imperfect SIC, a user can perform better in terms of SER by implementing wavelet-based NOMA instead of the FFT-based NOMA system.

Moreover, Figure 5 shows the trend of three NOMA users for SER on the y-axis and the symbol to noise ratio on the x-axis without implying any filter at this stage. Conventionally, with ideal conditions for two users, the near user performs better in terms of SER compared to the far user. The behaviour of the NOMA users for the assumptions made in the presented work for three users with imperfect SIC is presented in Figure 5. The SER of User 3 has the least

Table 1: Parameters for the simulation of wavelet-OFDM and FFT-based NOMA.

Parameters	Value	Parameters	Value
Wavelet levels	4	Number of subchannels	512
Wavelet family	Daubechies	Cyclic prefix	25%
Available BW (wavelet)	100%	Available BW (FFT)	75%
Modulation scheme	QPSK	SIC	Imperfect
Number of users	3	Near user channel gain	0, -5 dB
Intermediate user channel gain	-5, -10 dB	Far user channel gain	-10, -15 dB

Table 2: Residual error at the intermediate and near user using FFT-NOMA.

SNR in dB	-10	-5	0	5	10
Residual error (intermediate user)	0.2023	0.1504	0.0781	0.0058	3.68×10^{-6}
Residual error (near user)	0.1452	0.1106	0.0565	0.0024	2.61×10^{-7}

Table 3: Residual error at the intermediate and the near user using wavelet NOMA.

SNR in dB	-10	-5	0	5	10
Residual error (intermediate user)	0.1736	0.1195	0.0625	0.0055	4.01×10^{-8}
Residual error (near user)	0.0814	0.0511	0.0255	6.7×10^{-5}	1.36×10^{-12}

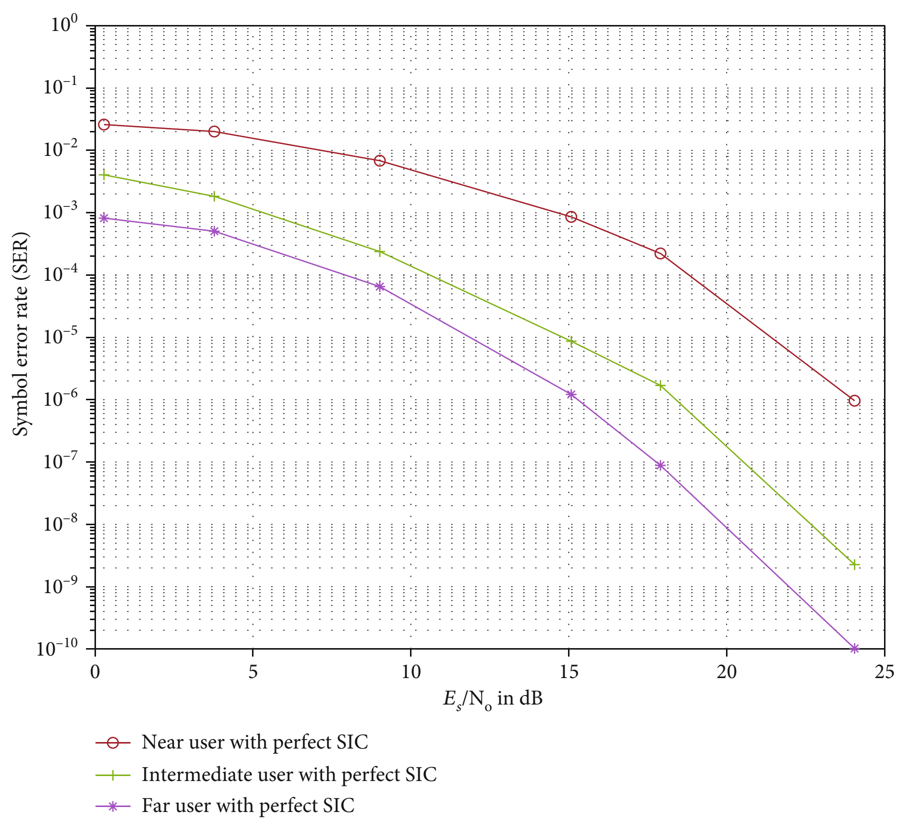

Figure 5: SER comparison of three users without FFT or wavelet filters.

performance compared to User 2 because of the suitable combination of the constellation presented in Figure 4. Also, User 2 has greater power allocation as compared to User 3, hence resulted in a better SER performance. User 1 subtracts both User 2 and User 3 signals by treating them as noise. For imperfect SIC, Figure 6 shows the SER performance of User

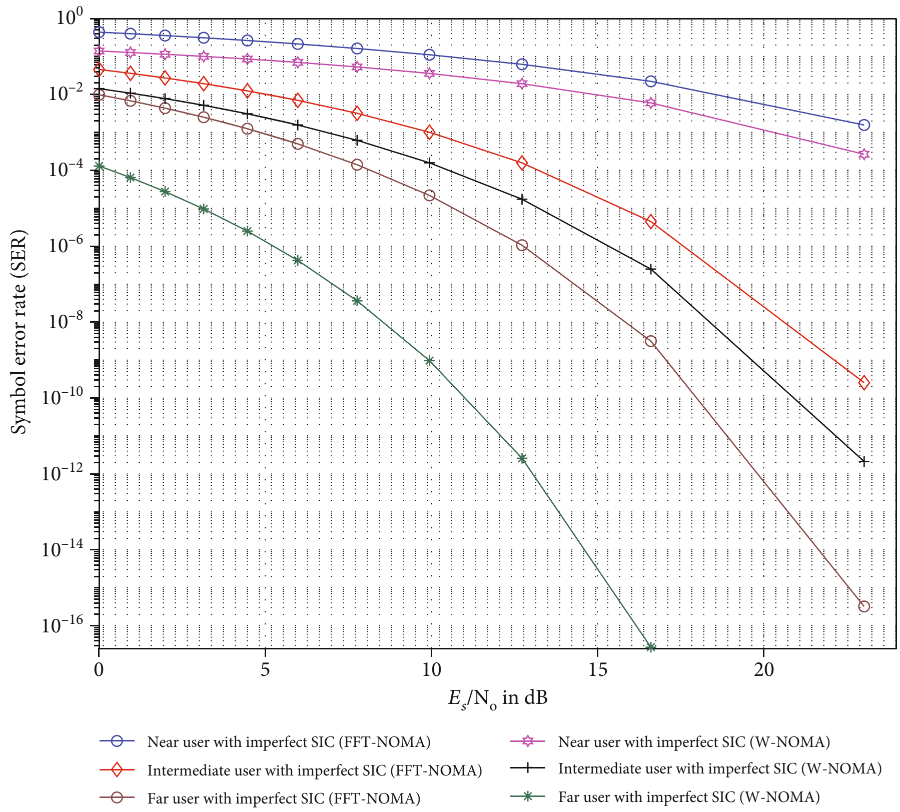

Figure 6: SER comparison of three users with imperfect SIC for wavelet NOMA and FFT-NOMA.

3, User 2, and User 1 in the presence of both FFT and wavelet filter banks. As we do not have complete information about the channel, interference will be strong at User 3 because of the interference from other users. These interferences add up in the form of noise and affecting the SER performance of the SIC-performing users. User 1 will treat other users' signal as noise due to the low power levels of the users. This is the scenario which also implies that User 2 will treat User 3 signal as noise. But the residual error due to User 1 will occur after SIC at User 2. Out of the band noise due to poor response of IFFT or FFT filters for imperfect SIC makes it worse for User 2 to detect and demodulate its data. As the SER performance degrades, the overall system's performance and throughput also deteriorate. Therefore, wavelet NOMA performs better than FFT-NOMA either for perfect channel conditions or imperfect CSI due to its high-quality filter banks.

5. Future Applications and Challenges

For future wireless communication networks, wavelet is gaining popularity in communication system design [20]. Due to spectral efficiency and user fairness with QoS, 5G has attracted the attention of communication system designers. In future works, in addition to NOMA, several other multiple access schemes can be analysed such as Generalized Frequency Division Multiplexing (GFDM) and Universal Filtered Multicarrier (UFMC) for the 5G network. Using adaptive modulation schemes such as Index Modulation (IM), we can manage to retrieve near user and far user data with more realistic results for more than two users assuming imperfect SIC. This work can be extended to a multicarrier NOMA system, where radio frequency front-end impairments are ignored in the literature. Security is the perspective of multiple access techniques and is also a significant area that remains to be explored. To perform SIC, users must decode other user's data which is a real security concern. The security threat also occurs with other multiple access schemes like TDMA where users can switch on during a time slot not allocated to it and attempt to decode another user's signal. Furthermore, all the research work is based on half-duplex NOMA, either uplink or downlink case has been presented in the literature. Thus, it is critical to consider full-duplex (FD) NOMA and analyse its performance. To improve the performance of the 5G cellular system, FD-NOMA is a potential approach than a half-duplex system.

6. Conclusion

For the next-generation (5G/B5G) wireless communication technology, NOMA is presented in the literature as a promising multiple access scheme. In 5G, limited bandwidth can be efficiently used by implementing NOMA utilizing the user's channel conditions and QoS requisites, while for channel impairments and imperfect SIC, current research has already proved the ability of wavelet NOMA to increase system throughput and efficiency. Closed-form SER expressions for three users, that are equally spaced with each other, are already shown. Numeric results show that wavelet filter banks help to detect and demodulate the signal better than the FFT-based NOMA system for imperfect CSI conditions. Further studies can be carried out to validate the mathematical model of the assumption to compare the analytical and theoretical findings using a cooperative relay sharing network. MIMO NOMA and FD-NOMA can be studied for the most suitable wavelet filter banks to improve 5G system performance.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to acknowledge the Energy Research Center, COMSATS University Islamabad, Lahore Campus, and SQU for their support and encouragement throughout. The research reported in this publication was partly funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) of Canada and the in-kind support of the University of Waterloo, Ontario, Canada.

References

[1] S. Islam, M. Zeng, O. A. Dobre, and K. S. Kwak, "Resource allocation for downlink NOMA systems: key techniques and open issues," *IEEE Wireless Communication*, vol. 25, no. 2, pp. 40–47, 2018.

[2] L. Zhu, J. Zhang, Z. Xiao, X. Cao, D. O. Wu, and X. Xia, "Millimeter-wave NOMA with user grouping, power allocation and hybrid beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5065–5079, 2019.

[3] L. Zhu, Z. Xiao, X.-G. Xia, and D. O. Wu, "Millimeter-wave communications with non-orthogonal multiple access for B5G/6G," *IEEE Access*, vol. 7, pp. 116123–116132, 2019.

[4] Z. Xiao, L. Zhu, J. Choi, P. Xia, and X. Xia, "Joint power allocation and beamforming for non-orthogonal multiple access (NOMA) in 5G millimeter wave communications," *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2961–2974, 2018.

[5] H. Marshoud, V. M. Kapinas, G. K. Karagiannidis, and S. Muhaidat, "Non-orthogonal multiple access for visible light communications," *IEEE Photonics Technology Letters*, vol. 28, no. 1, pp. 51–54, 2016.

[6] Q. He, C. Schmitz, and A. Schmeink, "BEP of Fourier transform and discrete wavelet transform based OFDM," in *ISWCS 2013; The Tenth International Symposium on Wireless Communication Systems*, pp. 1–5, Ilmenau, Germany, 2013.

[7] A. S. Marcano and H. L. Christiansen, "Performance of non-orthogonal multiple access (NOMA) in mmWave wireless communications for 5G networks," in *2017 International Conference on Computing, Networking and Communications (ICNC)*, Santa Clara, CA, USA, 2017.

[8] V. Kumbasar and O. Kucur, "Performance comparison of wavelet based and conventional OFDM systems in multipath Rayleigh fading channels," *Digital Signal Processing*, vol. 22, no. 5, pp. 841–846, 2012.

[9] V. K. Trivedi, K. Ramadan, P. Kumar, M. I. Dessouky, and F. E. A. El-Samie, "Enhanced OFDM-NOMA for next generation wireless communication: a study of PAPR reduction and sensitivity to CFO and estimation errors," *AEU - International Journal of Electronics and Communications*, vol. 102, pp. 9–24, 2019.

[10] A. A. Boulogeorgos, N. D. Chatzidiamantis, and G. K. Karagiannidis, "Non-orthogonal multiple access in the presence of phase noise," *IEEE Communications Letters*, vol. 24, no. 5, pp. 1133–1137, 2020.

[11] W. Xu, X. Li, C.-H. Lee, M. Pan, and Z. Feng, "Joint sensing duration adaptation, user matching, and power allocation for cognitive OFDM-NOMA systems," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1269–1282, 2018.

[12] S. Baig, M. Ahmad, H. M. Asif, M. N. Shehzad, and M. H. Jaffery, "Dual PHY layer for non-orthogonal multiple access transceiver in 5G networks," *IEEE Access*, vol. 6, pp. 3130–3139, 2018.

[13] S. Baig, U. Ali, H. M. Asif, A. A. Khan, and S. Mumtaz, "Closed-form BER expression for Fourier and wavelet transform-based pulse-shaped data in downlink NOMA," *IEEE Communications Letters*, vol. 23, no. 4, pp. 592–595, 2019.

[14] K. Baker, *Implementation of physical layer security for multiple-input, multiple-output communications via a wavelet packet modulated software-defined radio system with noise masking [M.S. thesis]*, Naval Postgraduate School, Calhoun, MS, USA, 2019, http://hdl.handle.net/10945/64039.

[15] B. Negash and H. Nikookar, "Wavelet based OFDM for wireless channels," in *IEEE VTS 53rd Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No.01CH37202).*, Rhodes, Greece, 2001.

[16] E. C. Cejudo, H. Zhu, and O. Alluhaibi, "On the power allocation and constellation selection in downlink NOMA," in *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*, Toronto, ON, Canada, 2017.

[17] F. Kara and H. Kaya, "BER performances of downlink and uplink NOMA in the presence of SIC errors over fading channels," *IET Communications*, vol. 12, no. 15, pp. 1834–1844, 2018.

[18] G. Niharika, "Performance comparison of modulation schemes for downlink NOMA," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, Coimbatore, India, 2018.

[19] M. R. Usman, A. Khan, M. A. Usman, Y. S. Jang, and S. Y. Shin, "On the performance of perfect and imperfect SIC in downlink non orthogonal multiple access (NOMA)," in *2016 International Conference on Smart Green Technology in Electrical and Information Systems (ICSGTEIS)*, Bali, Indonesia, 2016.

[20] K. Higuchi and A. Benjebbour, "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access," *IEICE Transactions on Communications*, vol. E98.B, pp. 403–414, 2015.

[21] Q. He, Y. Hu, and A. Schmeink, "Closed-form symbol error rate expressions for non-orthogonal multiple access systems," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 7, pp. 6775–6789, 2019.

[22] L. Dai, B. Wang, Y. Yuan, S. Han, I. C-L, and Z. Wang, "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 74–81, 2015.

[23] X. Dai, S. Chen, S. Sun et al., "Successive interference cancelation amenable multiple access (SAMA) for future wireless communications," in *2014 IEEE International Conference on Communication Systems*, Macau, 2014.

[24] Y. Wu, E. Attang, and G. E. Atkin, "A novel NOMA design based on steiner system," *2018 IEEE International Conference on Electro/Information Technology (EIT)*, 2018, pp. 846–850, Rochester, MI, 2018.

[25] F. J. Perez-Macias, C. A. Perez-Ramirez, M. Valtierra-Rodriguez, A. Dominguez-Gonzalez, and J. P. Amezquita-Sanchez, "Wavelet transform-fractal dimension-based methodology for damage assessment in truss type structures," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, China, 2017.

[26] Q. Wang, Y. Liu, X. Yan, and H.-C. Wu, "An innovative pulse-shaping scheme using multiwavelets for non-orthogonal multiple-access," *IEEE Communications Letters*, vol. 23, no. 12, pp. 2376–2380, 2019.