Received: July 3, 2023. Revised: September 8, 2023.

International Journal of
Intelligent Engineering & Systems

http://www.inass.org/

NOMA-NR-FOFDM Performance Enhancement-Based Sub-band Filtering

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Abstract: The orthogonal multiple access (OMA) used in fifth generation (5G) is suffered from limited resources. Due to the increasing number of users and ultra-high data rate requirements for user applications, non-orthogonal multiple access (NOMA) is a promising scheme for future communication systems. NOMA suffered from inter-user interference due to non-orthogonal resource sharing. This paper proposes the enhanced NOMA technique to be employed in the 5G system to satisfy the data rate requirements for Beyond 5G (B5G). The performance improvement is achieved through incorporating the filtering techniques with the new-radio orthogonal frequency division multiplexing (NR-OFDM) in 5G used waveform. The limitation in high out of band emission (OOBE) in the existing waveforms can also be reduced through the proposed method. Performance evaluation of the proposed system is demonstrated, and the results proved an improvement in bit error rate (BER) and power spectral density (PSD). As compared with the literature, the proposed system provides almost the same error floor with a benefit of approximately 11dB and 17dB SNR for full-band and sub-band-based filtering techniques, respectively. The achieved side lobe gain is up to 257dB for the Kaiser-Chebyshev-based filtering method.

Keywords: Filtered OFDM (FOFDM), Multicarrier modulation (MCM), Multiple access (MA), OOBE.

1. Introduction

Next-generation wireless communication systems should satisfy extreme performance requirements regarding high data rate, massive connectivity, and low latency. To achieve such requirements, a variety of enabling techniques are considered. The MA schemes and the MCM algorithms are some of the creative solutions that help to achieve the mentioned goals [1, 2].

The evolution of wireless communication depends significantly on the development of MA technologies. Orthogonal frequency division multiple access (OFDMA), the used MA in 5G NR, is a form of OMA. In OMA, the same resource (frequency or time) can be exploited by only one user at a time. It is considered the conventional MA in wireless standards but it may not be adequate to support the increasingly massive number of users and ultra-high data rate requirements in B5G [3, 4]. On the other hand, NOMA is a possible solution for the upcoming wireless systems. To achieve higher spectral efficiency (SE), sum rate, and throughput, NOMA allows many users to share the same resource block employing time slots or subcarriers. Due to enhancing the overall capacity as compared with OMA, it has been considered a powerful MA technique for the continuous expansion of wireless communication networks [5, 6].

By adding the non-orthogonality into the physical layer design, the performance of the mobile communication system can be improved in terms of a massive number of users, SE, and latency at the expense of inter-user interference and implementation complexity [7]. Such interference, which is occurred as a result of nonorthogonal resource allocation, results in low signal to interference and noise ratio (SINR) which is the main drawback of the NOMA technique [8]. The performance can be enhanced by incorporating a MCM technique with NOMA which is one of the main goals of this paper.

To meet the various application requirements in 5G and B5G, variable multi-numerology is employed with the MCM waveforms. To achieve such requirements and according to the traffic type, the used waveform should be configured flexibly [9]. Using dynamic subcarrier spacing (SCS), variable cyclic prefix (CP), and slots duration, the used MCM waveforms in 5G can provide faster transmission speed as compared with the traditional OFDM waveform in 4G [3]. The used waveform in 5G will be denoted as NR-OFDM in this paper.

There are some limitations in the NR-OFDM waveform including high OOBE which results in strong interference into neighbouring frequency bands. For maintaining the carrier orthogonally which keeps a low level of intercarrier interference, strict frequency, and time synchronization are required [10]. To overcome these drawbacks, there are several alternative candidate waveforms for upcoming wireless systems, such as FOFDM, generalized frequency division multiplexing (GFDM), universal filtered multicarrier (UFMC), and filter bank multi-carrier (FBMC). The filter design plays an effective role in these techniques [11, 12]. Among these MCM techniques, FOFDM is the best candidate waveform for B5G air interface due to many reasons. It keeps the OFDM advantages in terms of flexibility, simplicity of equalization, multiple input multiple output (MIMO) compatibility, and simplest implementation. It also supports asynchronous communication, and different numerology, and improves the bandwidth efficiency by suppressing OOBE specification [13].

The FOFDM can provide the need for B5G waveforms due to its flexibility by employing the sub-band-based filtering on existing OFDM. The total bandwidth is divided into many sub-bands which will be filtered independently. A group of subcarriers is made for each sub-band, SCS, CP length, and fast fourier transform (FFT) size can be different for each one [2].

To meet the increasing demand in the system capacity and user data rates requirements for B5G, this paper proposes a NOMA-NR-FOFDM technique to be employed in the 5G system. The proposed system focuses on integrating three emerging techniques to achieve the best results. These techniques include; NOMA, NR-OFDM, and filtering. Such a proposal overcomes the OOBE drawbacks by applying the FOFDM flexible technique in the system design. A modification to the existing NR-OFDM waveform is proposed based on employing both full-band and sub-band filtering. The sub-band-based filtering to the NR-OFDM-based NOMA has not been considered previously, as to the best knowledge of the authors.

The remainder of this paper is structured as follows: the related work is reviewed in section 2. Section 3 describes the proposed NOMA-NR-FOFDM model. Section 4 presents the results and discussions. Section 5 includes the mathematical modeling for the NOMA-NR-FOFDM system over AWGN. Finally, the paper is concluded in section 6.

2. Related work

The authors in [11] considered a combination of a polar encoder with FOFDM to meet the 5G requirements. They evaluate the system simulation results over an additive white gaussian noise (AWGN) channel in terms of BER, error vector magnitude (EVM), and peak-to-average-power-ratio (PAPR) as a comparison with polar-coded OFDM. They did not consider a MA technique; they designed a polar-coded FOFDM technique for one user.

Various windowing-based filter designs for the FOFDM system were introduced in [13] to improve the existing MCM waveforms utilizing time-frequency localization. The used windowing methods in filter design were: Hanning, Hamming, Kaiser, Chebyshev, and a hybrid combination of these windows. It was proved from the obtained results that the used filters outperform the previous design in SE by releasing the synchronization overhead. As compared with traditional OFDM, the BER results of the proposed system had a comparable performance using different modulation orders, while the PSD was improved dramatically. This work also considered single-user transmission; no MA technique had been employed.

In [14], the authors combined the NOMA technique with FOFDM for both uplink and downlink transmissions. The system was evaluated using PSD, and BER for AWGN, Rayleigh, and Nakagami-m fading channels. The results achieved an enhancement in BER of about 2dB and 1dB for uplink and downlink systems respectively as compared with NOMA-based OFDM. However, the MCM technique used in this work did not consider the frame structure of wireless slandered. Also, the multi-numerology was not taken into account.

A comparative analysis in OOBE, latency, complexity, and PAPR of several 5G candidate waveforms was made in [15]. The evaluated waveforms were: GFDM, FBMC, UFMC, and FOFDM. The results proved that all these waveforms have better OOBE as compared with OFDM. The authors recommend the FOFDM over the other waveforms since it has enhanced OOBE, low latency, and moderate complexity. Although the FBMC has the best OOBE, its high latency and complexity made it unsuitable to be considered in 5G and B5G.

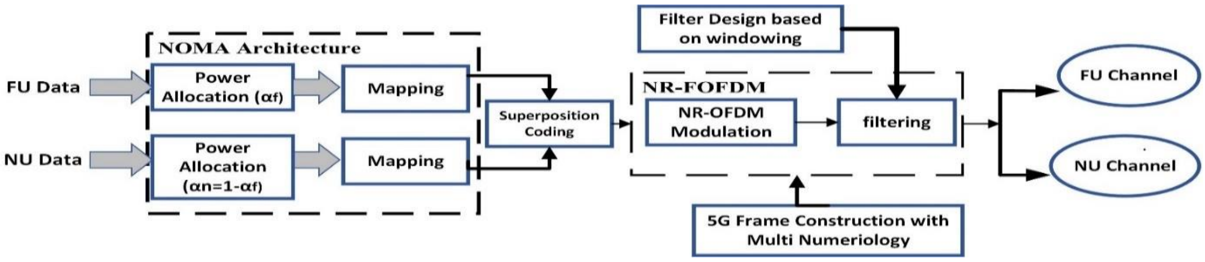


Figure. 1 General transmitter architecture of the proposed NOMA-NR-FOFDM system

The authors in [16] analyse a system model for LTE advanced by employing the 3rd Generation Partnership Project (3GPP) MCM waveforms proposed for 5G systems. The model explored the windowed OFDM (w-OFDM), and FOFDM as 5G contenders in resource with MIMO element mapping. As compared with the OFDM-based system model, the simulation results provided performance enhancement in system sum rate, SE, and throughout. According to the obtained results in OOBE and spectral confinement, the authors recommended the FOFDM as the most promising candidate waveform for 5G systems.

However, most of the above literature constrains using the FOFDM technique to meet the 5G requirements. The authors in [11] & [13] made their design analysis for single-user transmission, i.e., they did not consider a multiple access technique. While [15] & [16] included a breakdown of all the candidate waveforms for the 5G system, the authors recommended FOFDM as the best waveform among all contenders. The authors in [14] considered NOMA multiple access with FOFDM-based full-band filtering. All the mentioned literature made their analysis without considering the flexibility of the 5G frame structure.

For the above reasons, the main contribution of this paper is incorporating the NOMA technique in 5G MA to enhance the overall system performance. The NOMA limitation in users' interference is reduced through the proposed NR-FOFDM MC technique. The improved filtering-based technique significantly reduces the OOBE drawback in the existing waveform. The frame construction of the 5G systems is also considered.

3. The proposed NOMA-NR-FOFDM model

The transmitter block diagram of the proposed NOMA-NR-FOFDM downlink system is shown in Fig. 1. It consists of one base station (BS) and two users. Far and near users will be denoted as FU and NU respectively. Initially, data bits are generated randomly according to the available band for 5G frame in terms of the used number of RBs and SCS.

According to NOMA concept architecture, for each user, power allocation, and symbol mapping are performed. The users' symbols are joined using NOMA superposition coding (SC). To reduce the NOMA restriction in terms of low SINR due to the effect of inter-user interference, the proposed system processed the superimposed NOMA signal to a MCM to increase the SINR.

The proposed MCM technique is a combination between NR-OFDM and filtering, to overcome the limitation in the existing NR-OFDM waveform. The resulting waveform is denoted as NR-FOFDM which is generated by processing the NR-OFDM signal through a spectrum-shaping filter to improve the OOBE suppression of the signal.

The NR-FOFDM MCM process is applied using two different scenarios, full-band, and sub-band-based filtering. Fig. 2 displays the MCM with a sub-band-based filtering scenario. In this paper, four sub-bands are used to compromise between complexity and performance.

As shown in Fig. 2, the NOMA superposition-coded signal is divided into four parts to process each part to a MCM and filtering separately. In each part, a group of sub-carriers with fixed or variable SCS is available for transmission. The achievable rates of FU and NU in the proposed NOMA-NR-FOFDM system are as follows:

$$R_{FU} = Blog_2\left(1+\gamma\,\frac{p\alpha_1|h_1|^2}{p\alpha_2|h_1|^2+\sigma_1^2}\right) \quad (1)$$

$$R_{NU} = Blog_2(1+\gamma\,\frac{p\alpha_2|h_2|^2}{\sigma_2^2}) \quad (2)$$

Where B is the system bandwidth, p is the transmit power from the BS, $\alpha_1, \alpha_2, h_1, h_2, \sigma_1^2, \sigma_2^2$ are the power allocation factors, Rayleigh fading coefficients, and the noise variance assigned to FU and NU respectively, γ is a factor related to the used NR-FOFDM MCM as follows:

$$\gamma = \mathrm{No_{Sub}} \times \frac{\mathrm{nFFT}}{\mathrm{RBs\times 12}} \quad (3)$$

Received: July 3, 2023. Revised: September 8, 2023.

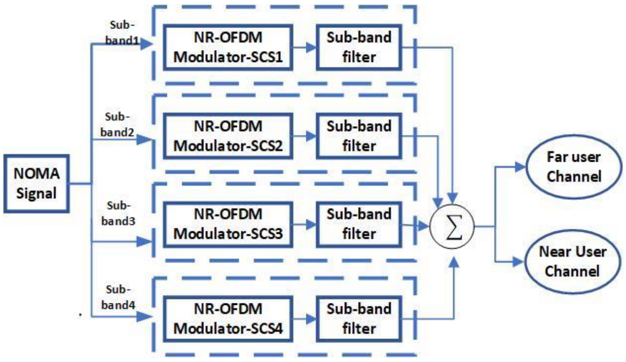
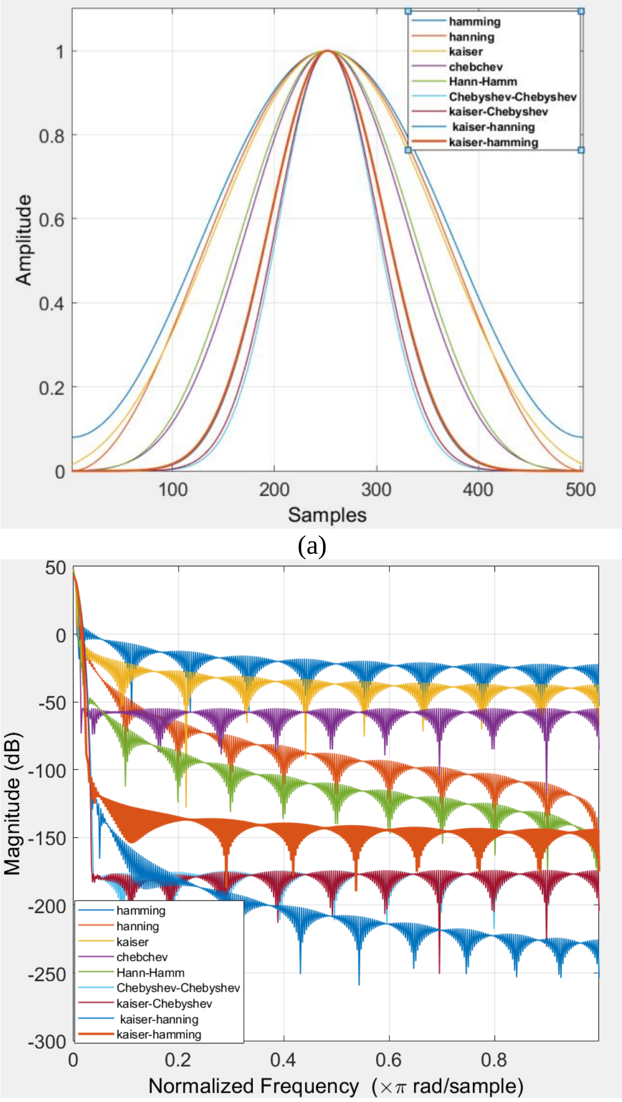


Figure. 2 The sub-band based MCM process for the proposed system



(a)

(b)

Figure. 3 The response representation of the used windows: (a) Time domain, and (b) Frequency domain

Where No_{Sub} is the number of used sub-bands, RBs is the number of resource blocks used for data transmission, and nFFT is the FFT size.

The number of used subcarriers for data transmission is equal to RBs×12, based on the 3GPP report [17]. It's clear from Eq. (2) that the NU will perform successive interference cancelation (SIC) to the FU signal.

To improve the SE of the proposed system, with better time and frequency localization, the filter design has an effective role in the NR-FOFDM performance. The primary objective of filter usage is to provide adequate stopband attenuation to ensure minimal interference with neighboring subcarriers, allowing the filter to handle interference with another nearby spectrum.

In this paper, different windows are analyzed to determine a window with a lower side lobe level and a narrower main lobe as possible. Traditional and modified windows are used, traditional ones include Hanning, Hamming, Kaiser (β=16), and Chebyshev (ρ=140).

The modified used windows are based on combining two windows. The combination achieves by multiplying the windows in the time domain. The used modified windows are Hanning-Hamming, Kaiser-Hamming, Chebyshev-Chebyshev (ρ_1=120, ρ_2=140), and Kaiser-Chebyshev (β=16, ρ=100). The time domain of the traditional and the combined window are shown in Fig. 3 (a).

It's clear from the comparison with the traditional windows, the combined windows have a narrower main lobe. The frequency domain realization of the used windows is shown in Fig. 3 (b). As compared with the traditional windows; it can be shown that the combined windows have the lowest levels of side lobes.

By taking into account the window function-based soft truncation of a filter with rectangular frequency response, mathematically, the process is as follows:

$$h(n) = g(n).w(n) \tag{4}$$

Where *g(n)* is the time domain correspondence to rectangular filter, *w(n)* can be any one of previously mentioned windows.

The receiver block diagram of the proposed NOMA-NR-FOFDM system is shown in Fig. 4. At the receiving section, equalization will be performed at each user, zero-forcing equalizers are used. Then, the received signals will be processed to the same filter that is used at the transmitter side (*g*(-n)*). According to the NOMA concept, FU will detect its signal directly considering NU's signal as interference as described in Eq. (1). While NU will perform SIC to mitigate the interference with FU's signal.

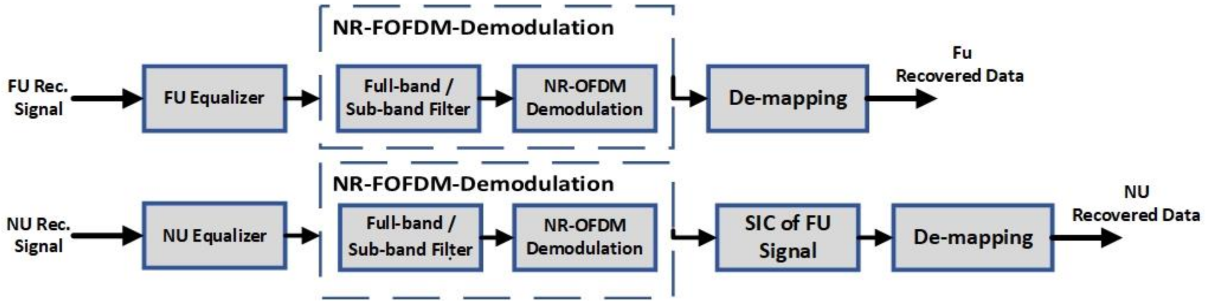


Figure. 4 The receiver block diagram of the proposed NOMA-NR-FOFDM system

Table 1. System simulation parameters

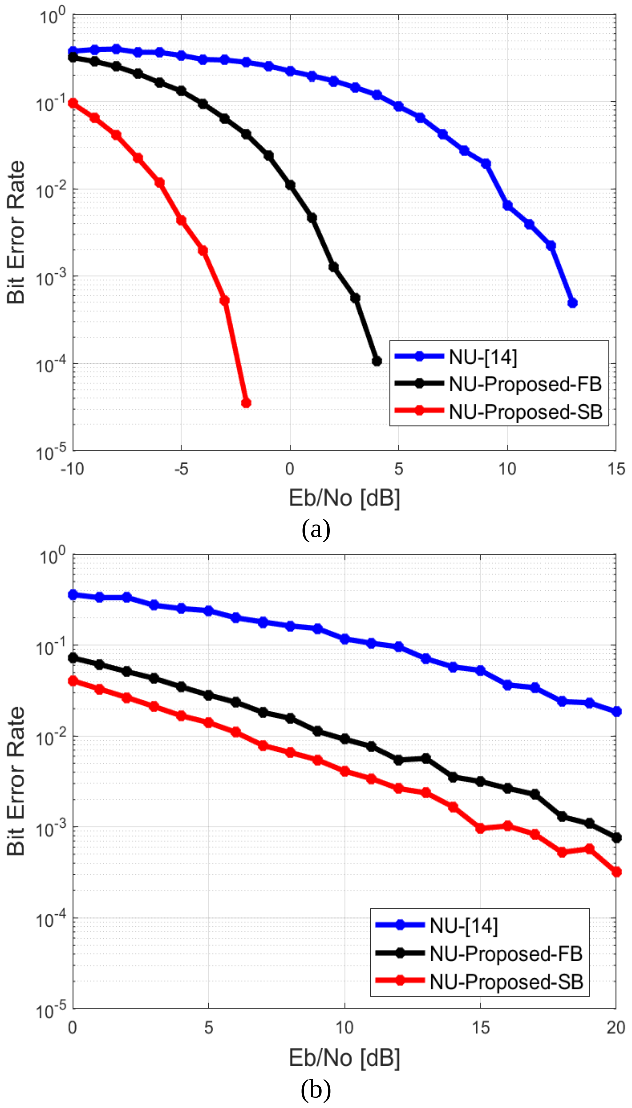
Parameter	Scenario-I	Scenario-II
nFFT	1024	2048
Filter Length	513	1025
RBs	84	100
Power a_1,a_2	0.8.0.2	0.75,0.25
Window	Hanning	All
Modualtion order	BPSK (FU) & QPSK (NU)	QPSK (for both users)
SCS	15 KHz	30KHz (for all sub-bands)

When sub-band-based filtering is used, each user will split the received signal into sub-bands to perform the NR-FOFDM demodulation process individually for each sub-band. Then demodulation and interference cancellation are performed on the reconstructed NOMA signal.

4. Results and discussions

The BER results of the proposed NOMA-NR-FOFDM system are evaluated over AWGN and Rayleigh fading channels. Table.1 displays the simulation parameters of the proposed system considering two scenarios. Since the work in [14] considered combining NOMA technique and full-band based F-OFDM, equivalent parameters are considered in scenario-I for performance comparison. As in [14], Binary Phase Shift Keying (BPSK) modulation is used for FU while Quadrature Phase Shift Keying (QPSK) is used for NU due to channel conditions.

The NU's BER results in full-band and sub-band based filtering for NOMA-NR-FOFDM system are shown in Figs. 5 (a-b) over AWGN and Rayleigh fading channels respectively. As compared with the results get in [14], the full-band-based filtering scenario provides almost the same error floor with a benefit of approximately 11dB SNR, while the sub-band-based filtering scenario achieves almost the same error floor with a benefit of approximately 17dB SNR.



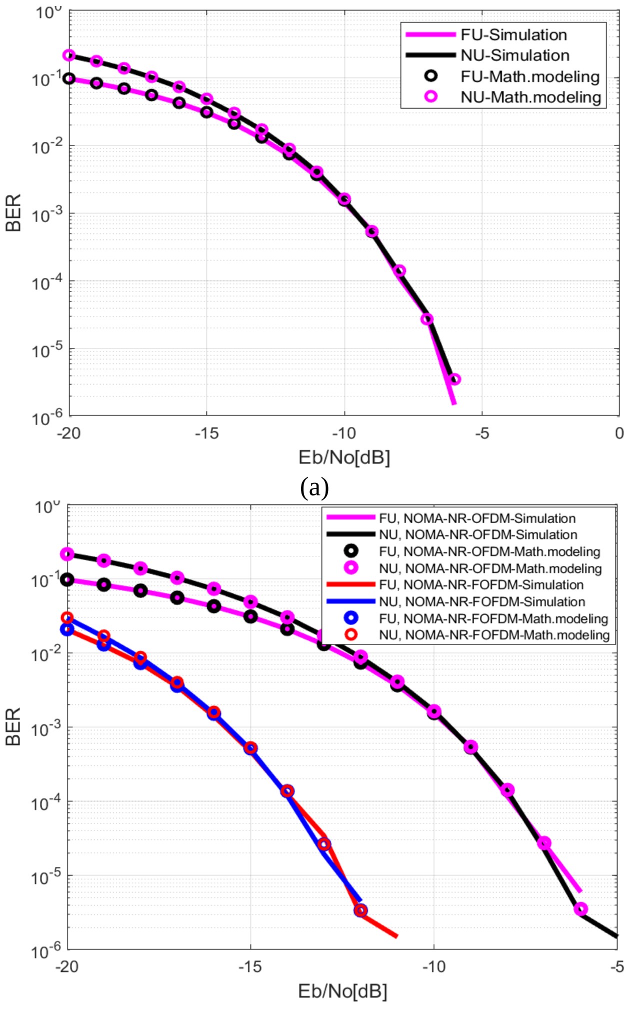
(a)

(b)

Figure. 5 BER simulation performance for the NU in the proposed system: (a) over AWGN channel, and (b) over Rayleigh fading channel

The BER better performance of the proposed system as compared with ref [14] is due to SINR gain through employing the 5G frame structure.

These results proved that the NOMA performance is successfully enhanced in the proposed system by the used subcarriers and sub-bands in the NR-FOFDM MCM technique.



(a)

(b)

Figure. 6 BER Results theoretical and practical simulation for NOMA-NR-FOFDM system: (a) full-band filtering scenario, and (b) sub-band filtering scenario

Another set of simulation parameter is illustrated as displayed in Table.1-scenario-II. In this case, the 5G frame is constructed using 1200 subcarriers (100 RBs) in the frequency domain and 20 slots in the time domain by using 30KHz SCS for all sub-bands.

5. Mathematical modelling for NOMA-NR-FOFDM system over AWGN

To prove the correctness of the proposed system in terms of BER results, mathematical modeling has been derived for FU and NU over the AWGN channel. The derived formula for FU is as follows:

$$P_{FU} = \frac{1}{2}Q\left(\sqrt{\lambda_1 SNR_e}\right) + \frac{1}{2}Q\left(\sqrt{\lambda_2 SNR_e}\right) \tag{5}$$

Where λ_1 and λ_2 are power enhancement and power attenuation factors respectively, these factors are expressed using the power coefficient assigned to FU and NU (α_{FU} and α_{NU}) as follows:

$$\lambda_1 = \left(\sqrt{\alpha_{FU}} + \sqrt{\alpha_{NU}}\right)^2 \tag{6}$$

$$\lambda_2 = \left(\sqrt{\alpha_{FU}} - \sqrt{\alpha_{NU}}\right)^2 \tag{7}$$

SNR_e is the enhanced SNR value ($\gamma P/\sigma^2$) where γ is described in Eq. (3). When full band filtering is used, the parameter No_{Sub} in Eq. (3) is set to 1. Since the decoding of the NU signal is based on applying SIC to the FU signal, the derived formula for NU is as follows, with the assumption of imperfect decoding:

$$P_{NU} = Q(\lambda_3) + \frac{1}{2}Q(\lambda_4) + \frac{1}{2}Q(\lambda_5) + \frac{1}{2}Q(\lambda_6) + \frac{1}{2}Q(\lambda_7) \tag{8}$$

Where λ_3, λ_4, λ_5, λ_6 and λ_7 are descibed as follows:

$$\lambda_3 = \sqrt{\alpha_{NU} SNR_e} \tag{9}$$

$$\lambda_4 = 2\sqrt{\alpha_{FU} SNR_e} + \sqrt{\alpha_{NU} SNR_e} \tag{10}$$

$$\lambda_5 = \sqrt{\alpha_{FU} SNR_e} - \sqrt{\alpha_{NU} SNR_e} \tag{11}$$

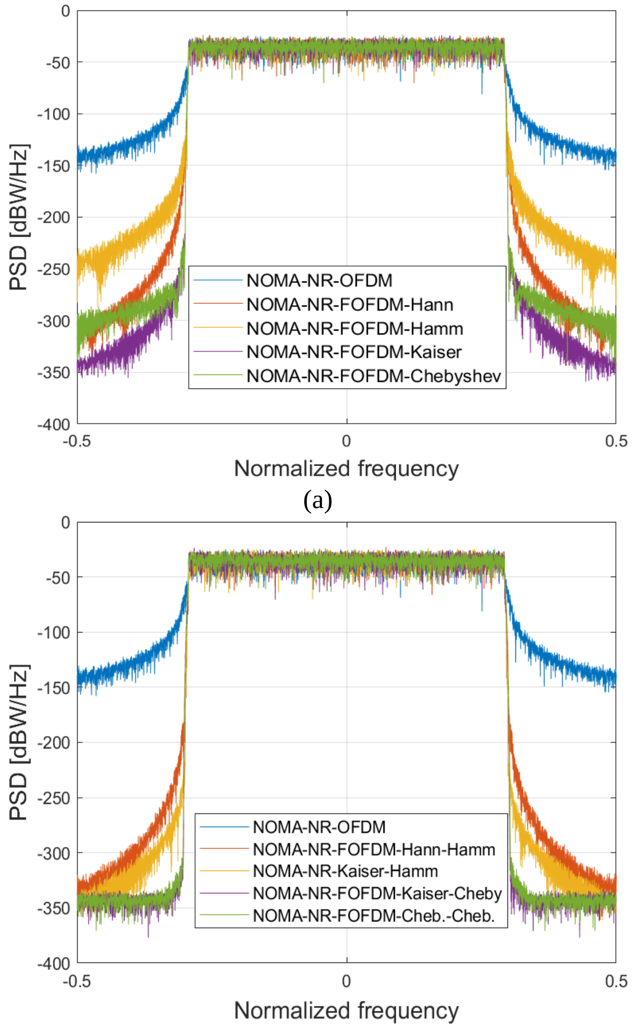
$$\lambda_6 = \sqrt{\alpha_{FU} SNR_e} + \sqrt{\alpha_{NU} SNR_e} \tag{12}$$

$$\lambda_7 = 2\sqrt{\alpha_{FU} SNR_e} - \sqrt{\alpha_{NU} SNR_e} \tag{13}$$

The obtained mathematical formulas described in Eq. (5) and Eq. (8) are proved through a comparison with the obtained results in practical simulation as shown in Fig. 6. The BER results of practical simulation and mathematical modeling over AWGN for scenario-II with full-band-based filtering are shown in Fig. 6 (a). Compared with the BER results for the NOMA system obtained in [18], it can be observed that the proposed system successfully reduced the effect of inter-user interference by the number of subcarriers and the improved filtering-based technique.

There is also a significant enhancement in the SINR values by demonstrating 5G flexible frame construction. In Fig.6 (b), a comparison of BER mathematical and simulation result is made considering two systems, NOMA-NR-OFDM, and NOMA-NR-FOFDM with sub-band filtering, the system is simulated with and without filtering.

The results proved that the sub-band-based filtering scenario outperforms that of the full-band-based one which has a comparable performance to the NOMA-NR-OFDM system.



(b)

Figure. 7 PSD Performance of NOMA-NR-FOFDM system: (a) using traditional windows and (b) using combined windows

The PSD results of the proposed system are evaluated to analyse the effect of filtering on OOBE suppression. Fig. 7 (a) illustrates the results with traditional-windows-based filtering scenarios. In this case, the sidelobe levels show an enhancement of about, 68dB,100dB, 170dB, and 172dB for Hamming, Hanning, Chebyshev, and Kaiser-based filtering respectively. While Fig. 7 (b) shows the results with combined-windows-based filtering scenarios.

The enhancement in the side lobe levels for these scenarios is about 127, 174, 254, and 257 for Hanning-Hamming, Kaiser-Hamming, Chepyshev-Chepyshev, and Kaiser-Chebyshev-based filtering respectively.

It's clear from Fig. 7 that all the proposed waveforms enhanced the spectrum localization and bandwidth efficiency as compared with NOMA-NR-OFDM. As compared with the PSD results achieved in [11, 13], Fig. 7 proves that the obtained results outperform those achieved in previous works.

6. Conclusion

In this paper, NOMA based 5G MCM is designed which is a promising candidate MA with a flexible waveform that meets the requirements for next-generation wireless systems. The proposed system incorporates, NOMA, filtering techniques, and NR-OFDM 5G waveform. Simulation results proved that the proposed NR-FOFDM waveform provides the advantages of better PSD due to reducing the OOBE with the designed windowing scenarios. The side lobe of the proposed waveform achieves up to 80% enhancement as compared with NOMA-NR-OFDM.

The SINR of the proposed system for users is also enhanced due to decreasing the noise effect by the sub-band filtering technique. The sub-band-based filtering scenario has a SINR gain of about 6dB as compared with the full-band-based filtering scenario when four sub-bands are assumed.

As compared with the literature, the SINR gain is about 11dB and 17dB for full-band and sub-band-based filtering respectively. The BER mathematical modelling for the proposed system is derived and proved its correctness as compared with practical simulation. The proposed system enhances the BER and PSD at the cost of PAPR and the complexity, which are out of the scope of this paper and can be considered in future works.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, N.N.K and R.K.M; methodology, R.K.M; software, R.K.M; validation, N.N.K and R.K.M; formal analysis, R.K.M; investigation, N.N.K and R.K.M; resources, R.K.M; data curation, R.K.M; writing—original draft preparation, R.K.M; writing—review and editing, N.N.K; visualization, N.N.K and R.K.M; supervision, N.N.K.

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