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A NOMA-UFMC Precoded System for 6G

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Abstract

Multi-Carrier Waveform (MCW) modeling and design are envisioned as one of the most important and challenging for the 6th generation (6G) communication networks. In oppose to Orthogonal Frequency Division Multiplexing (OFDM) waveforms, new and innovative design techniques for MCWs have been designed and proposed in recent literature because of their performance superiority. The typical OFDM waveforms have dominated the previous generation of communication systems and proven their potential in many real-time communication environments, but it may not be sufficient to meet the ambitious target of 6G communication systems. Hence, need for new solutions like flexible MCWs and relevant technological advancements in waveform design are needed. This paper proposes designing and evaluating a new MCW design to meet the 6G requirements for spectral efficiency, throughput, and overall system capacity. On the transmitter side, the MCW design proposed in this article employs power domain multiplexing, such as Non-Orthogonal Multiple Access (NOMA), and phase-rotations of the input signal to the Universal Filtered Multi-Carriers (UFMC) modulations, where the Base-Station (BS) assigns different power levels to each user while using the same frequency resources. MATLAB® simulations were performed to assess the proposed MCW performance. Detailed simulation data are employed for comparative performance analysis of the proposed MCW. The results have shown the superior performance of the proposed MCW approach compared to the conventional 5th generation (5G) NOMA-UFMC waveform.

Keywords: 6G, MCW, OFDM, PAPR, UFMC, NOMA.

1. Introduction

The 6th generation (6G) is a technology capable of having a more real and positive impact on our lives. The previous decade has attracted significant research attention and eventual architectural advancements for 5G networks, which are now in the standardization and deployment stages. Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (MMTC), and Ultra-Reliable and Low Latency Communications (URLLC) were the primary design concerns and technology advancements of 5G networks (Series, M., 2017; 3GPP, 2017).

These targeted applications and use cases demanded stringent requirements like reliability, low latency, increased throughput, ubiquitous connectivity, and optimum spectral efficiency (Popovski, P., Trillingsgaard, K. F., Simeone, O., & Durisi, G., 2018). To meet the targets and address upcoming challenges in the 6G communication networks, novel solutions are being investigated for the physical layer challenges (Matthaiou, M., et al., 2021). The regulation process of the 5G is almost over, and now it is the deployment period. The conceptualization of the 6G communication network has begun to sustain the viable superiority of wireless networks, manufacturing, and academia interaction to cope with the stratification of the communication requirements of the 2030s (Yang, P., Xiao, Y., Xiao, M., & Li, S., 2019).

In recent years, significant research efforts have been made to assess the appropriateness of the Universal Filtered Multi-Carriers (UFMC) waveform for 5G cellular networks (Schaich, F., Wild, T., & Chen, Y., 2014, May). The main idea behind the UFMC-based waveforms concept is to divide the whole bandwidth into a number of small groups where each group would be termed a sub-band. Each of these sub-bands has a further number of orthogonal sub-carriers. The Out-of-Band Emissions are then reduced by filtering these sub-bands (OBE). The aforementioned filter procedure reduces the filter length compared to similar approaches in 5G networks. Sub-band filtering also provides more design freedom, resulting in reduced Inter-Symbol Interference (ISI). As a result, the UFMC waveform is a good fit for short-burst communications (Vakilian, V., et al., 2013, December). In addition, the UFMC waveform has a higher spectrum efficiency. However, the performance limitation in spectral efficiency is a silent major shortcoming of standard UFMC waveform that limit its scope to continue its role for 6G communications. Because of its multi-carrier structure, the Peak Average Power Ratio (PAPR) is another severe issue with the UFMC waveform (Rani, P. N., & Rani, C. S., 2016, December). Therefore, the standard 5G waveforms need to be investigated more rigorously and develop an improved design to cope with the upcoming 6G requirements (Wikström, G., et al., 2020, March).

This article extends the work presented by the authors in (Baig, I., et al., 2020, April); however, the precoding matrix is different, and PAPR is analyzed at higher-order modulations. This paper selected Walsh–Hadamard Transform (WHT) precoding matrix due to its maturity and simplicity. The proposed waveform employs Selective Mapping (SLM) and WHT precoding to rotate the phase. The phase rotation reduces the autocorrelation relationship amongst the modulation symbols; hence the chances of in-phase additions at IFFTs are reduced, which results in high PAPR reduction. Additionally, the power domain multiplexing technique is used to increase the system capacity in terms of users while utilizing the same frequency band. The proposed waveform's fundamental idea is that k users can be multiplexed in the power domain, similar to Non-Orthogonal Multiple Access (NOMA), to boost system capacity and serve enormous 6G users. It is also demonstrated that each k user utilizes the same frequency band but at various power, levels to maximize system capacity and throughput. The following are the themes covered in this paper: Section II contains a brief overview of the literature, and Section III has a brief explanation of the suggested waveform design. The mathematical equations are also developed and thoroughly discussed in Section III. Section IV then presents and discusses the numerical and simulation results, while Section V brings the work close.

2. Related Work

A large number of multi-carrier waveforms are proposed in the literature for upcoming modern communication systems (Schaich, F., Wild, T., & Chen, Y., 2014, May; Al-Dulaimi, A., Wang, X., & Chih-Lin, I. (Eds.)., 2018; Basar, E., et al., 2017). The Cyclic Prefix-based Orthogonal Frequency Division Multiplexing (CP-OFDM) waveform (Schaich, F., Wild, T., & Chen, Y., 2014, May). Many 4G communication technologies utilize it, such as LTE-A and the IEEE 802.11 family. This modulation technique can handle frequency selective fading channels is the main reason for its popularity. This is a feature that not all single carrier-based systems possess. In CP-OFDM, the data stream is divided into parallel streams, each modulated with narrow subcarriers. There is no coherence across the transmission channels since each sub-bandwidth carrier is modified. This function aids in the equalization of flat fading channels by using a simple multiplication algorithm. Furthermore, the OFDM waveform's orthogonal overlap of sub-carriers allows for highly flexible frequency assignment, resulting in efficient frequency spectrum utilization. The OFDM waveform may be generated using the Inverse Fast Fourier Transform (IFFT).

The CP characteristic of OFDM is established by deleting the final element of IFFT and putting it to the beginning. This copy-append approach adds a cyclic component to the OFDM waveform while simultaneously acting as an interval guard. The guard interval is determined by the length of the cyclic component being added. Inter-Symbol interference is reduced with the use of this approach (ISI). The CP-OFDM waveform has several disadvantages, including a high Peak-to-Average Power Ratio (PAPR), high Out-of-Band Emissions (OBE), and a higher sensitivity to synchronization failures. Some remedies have been proposed in the literature to address and correct the aforementioned flaws. Two of the countermeasures include increased flexibility and improved time-frequency localization. In CP-OFDM, the external guard period should also be replaced by an internal guard interval. This replacement will increase flexibility while improving spectral efficiency. Although CP-OFDM is a significant player in new and developing standards because of its low implementation complexity, simplicity of MIMO integration, and backward compatibility, its stringent character and poor coexistence with other standards and the limitations already mentioned further damage its argument. As a result, standard CP-OFDM-based waveforms may not fulfill stringent application and use case requirements, such as MMTC, which is primarily targeted at 5G networks.

Another extensively utilized waveform in 4G LTE is OFDM (Discrete Fourier Transform Spread) (DFT-s-OFDM). It has become a standard for uplink communications because of its low PAPR and resistance to multipath fading (Myung, H. G., Lim, J., & Goodman, D. J., 2006). The DFT-s-OFDM waveform inherits some benefits from its predecessor, the CP-OFDM waveform, including restricted flexibility and good spectrum efficiency. The IDFT has a high variance in the CP-OFDM waveform, which can be reduced by introducing a DFT operation before the IDFT. Furthermore, in DFT-s-OFDM, the inclusion of a cyclic prefix simplifies the handling of the multipath channel effect. It also features a simple implementation, changeable spectrum assignment, and strong MIMO adaptability. The DFT-s-OFDM waveform, like the CP-OFDM waveform, suffers from excessive OBE and cannot satisfy 5G standards (Ebrahimi, H., 2012, October). Several waveforms have been presented in the state-of-the-art literature to address these concerns and challenges. These waveforms are designed to address the new issues that 5G cellular networks and beyond provide. Filter Bank Multicarrier (FBMC) (Farhang-Boroujeny, B., 2011), Multi-Carrier NOMA(MC-NOMA) (Ding, Z., et al., 2017), and conventional UFMC (Schaich, F., & Wild, T., 2014, May) are some of the waveforms connected to the proposed study.

The FBMC waveform allows for proper frequency domain localization. This method employs correctly modeled pulse shaping filters and raises the pulse timespan in the time domain to obtain acceptable frequency domain localization. The filters are designed to be used on subcarriers. This increases the filters' adaptability, allowing them to be used in a wide range of channel conditions and scenarios. The FBMC may be used in various ways, including filtered multitoned FBMC and cosine modulated multitoned FBMC. Staggered Modulated Multitoned is the most prevalent implementation of FBMC (SMT). SMT is also known as Offset Quadrature Amplitude Modulation FBMC (OQAM-FBMC) (Zhang, X., Chen, L., Qiu, J., & Abdoli, J., 2016). Because of its capacity to deal with interference while managing dense symbol placement in a frequency-time lattice, SMT is a feasible option for 5G networks. OQAM ensures orthogonality between different subcarriers in OQAM-FBMC, resulting in improved spectral efficiency than CP-OFDM. This technology is particularly well-suited for mobile carriers because of its well-localized sub-carriers since it is very resistant to Doppler effects. However, this method, like others, has several disadvantages. Two of these challenges are poor integration with MIMOs and high inherent interference from OQAM signals (Lin, H., 2015).

The Multi-Carrier based Non-Orthogonal Multiple Access (MC-NOMA) waveform is one of the most satisfactory waveforms presented in the literature for supporting a greater number of users and applications in 5G cellular networks. Thanks to the MC-NOMA, signals from many users can overlap in time and frequency domains. The transmit strength of signals is set variable (different), and a Successive Interference Cancellation (SIC) is performed on the receiving device to reduce unwanted interference (Al-Imari, M., Xiao, P., Imran, M. A., & Tafazolli, R., 2014, August). Compared to the traditional CP-OFDM waveform, the MC-NOMA waveform offers substantial advantages and is believed to be more potent due to lower spectral side-lobe levels. However, there are significant implementation concerns with the MC-NOMA, such as error propagation, channel estimate errors, complexity, and the lack of support for short messages packet burst (Dai, L., et al., 2015). Due to its brief packet burst transmission support, the UFMC is the most promising waveform proposed for 5G cellular networks. The UFMC waveform combines the benefits of FBMC and OFDM while avoiding their disadvantages (Schaich, F., Wild, T., & Chen, Y., 2014, May). The UFMC is a sub-band filtering method with a fixed frequency domain granularity that combines sub-band filtering. The anticipated ISI determines the usage of CP at UFMC. The ISI decreases when CP is used, and vice versa. CP is not required in most UFMC systems since the transition zones offer ISI protection. The signals are supplied in the time domain to produce orthogonality in the frequency domain. In contrast to the CP-OFDM waveform, the lack of CP in the UFMC waveform suggests more complex receiver designs (Zhang, L., Xiao, P., & Quddus, A., 2016).

Time localization is also improved by including sub-bands within the UFMC waveform. A coordinated multi-point receiving approach has also been published in the literature to provide interference-free one-tap equalization in varied Carrier-Frequency Offsets (CFOs) (Vakilian, V., et al., 2013, December). All of the techniques discussed above outperform the 4G LTE-A CP-OFDM waveform in terms of OBE. However, the traditional UFMC waveform has spectral efficiency limitations and faults, rendering it unsuitable for future 6G networks. Table II shows a comparison of the 5G proposed waveforms.

3. Proposed Waveform

The suggested waveform's block diagram is shown in Figure 1. According to Figure 1, all k mobile users are connecting with the Base Station (BS) simultaneously and using the same frequency resources, albeit at different power levels. Assume there are k users, each of whom (or device) uses a whole band of N sub-carriers. After Serial-to-Parallel (S/P) conversions, the QAM modulated signal Xl of the ith device may be expressed as follows:

$$X_l = [X_0, X_1, X_2, \dots, X_{N-1}]^T \tag{1}$$

There are N sub-carriers in total. Following S/P conversions, an entire band F of N sub-carriers for each user is divided into S sub-bands, each with C fixed sub-carriers. With the S sub-band in the time domain, i.e., The signal for the ith user in a C point IFFT may be described mathematically as follows:

$$x_{S_i}[n] = \frac{1}{\sqrt{C}}\sum_{l=0}^{C-1} X_l \cdot e^{j2\pi\frac{n}{C}l}, 0 \le n \le C-1 \tag{2}$$

where Xl represents WHT precoded constellation symbols based on SLM, stored in S sub-bands. The C point IFFT time-domain signal is then convolved with a fixed length L filter f, and the resulting signal may be represented as:

$$\breve{x}_{s_{i,l}} = x_{s_i} \cdot f_L \tag{3}$$

After the filtering procedure is completed, all of the filtered sub-bands are put together to produce the filtered UFMC signal, which may be stated as follows in the time domain: -

$$x_i = \sum_{l=0}^{S-1} \breve{x}_{s_{i,l}} \tag{4}$$

where xi expresses the UFMC signal for the ith device, and finally, the BS executes power domain multiplexing with minimal PAPR on the selected time domain UFMC signal. After the total power allocation Pt, the signal in the time domain can be expressed as below:

$$x = \sum_{i=1}^{k} \sqrt{p_i x_i} \tag{5}$$

where pi and xi represent allocated power and signal for any ith mobile user, respectively.

The signal y on the receiving device thus can be expressed as:

$$y = \sum_{i=1}^{k} h_i \otimes x_i + w \tag{6}$$

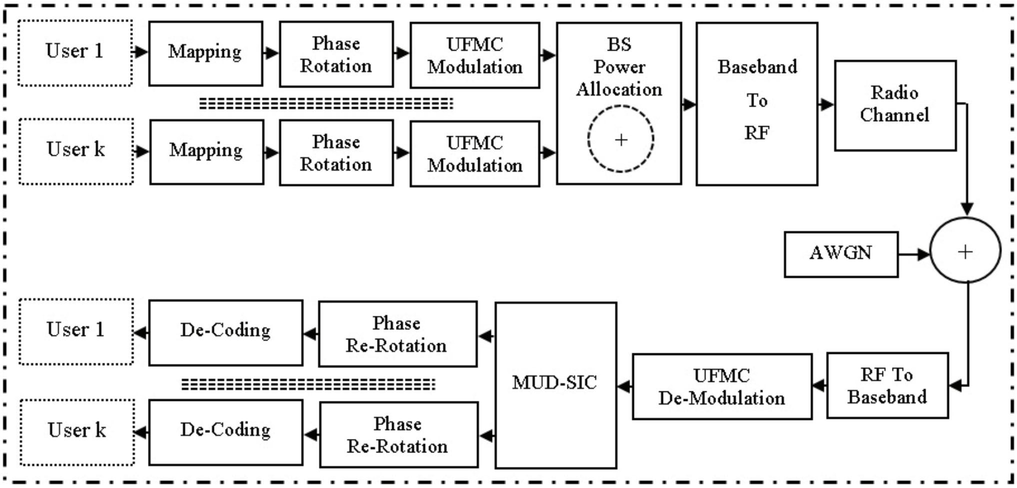

Fig. 1. Proposed Phase-Rotation Based NOMA-UFMC Downlink System.

where hi denotes the channel parameters and coefficients in the time-domain for any ith device. The Multi-User Diversity SIC (MUD-SIC) operation is used on the received UFMC demodulated signal to segregate the different users before the phase re-rotations. Finally, the data is unmapped and decoded to retrieve the original signals and data bits.

4. Numerical Results

This section shows the computer-based simulation investigation of the recommended waveform in MATLAB® is shown in this section. To investigate PAPR performance, data is created at random and then modulated using 4-QAM, 16-QAM, 64-QAM, and 256-QAM, respectively. Table I lists the many parameters that are used in simulations and studies. Table I specifies 512 as the FFT size, with a total of 10 sub-bands and 20 sub-carriers. SLM-based WHT precoding and a Dolph-Chebyshev filter with length L = 73 and Stop-Band Attenuation 40 are employed to decrease PAPR.

Table 1: Simulation parameters

Parameters	Specification
FFT Size	512
Sub-Band Size	20
No. of Sub-Bands	10
Sub-Band Offset	156
Filter	Dolph Chebyshev
Filter Length	73

Stop-Band Attenuation	40
Modulation	4-QA.M 16-QAM. 64-QAM and 256-QAM
Subcarrier Mapping	Localized
Bits per Sub-Carriers	2, 4, 6
Sampling Frequency	15.36MHz
PAPR Reduction Scheme	SLM, WHT Precoding
Channel Bandwidth	30 MHz

The PAPR of the specified time-domain signal in eq. (4) with minimum PAPR can be expressed as: -

$$PAPR = \frac{peak\_power\_of\_x_i}{average\_power\_of\_x_i} \tag{7}$$

The Complementary CDF (CCDF) is applied to measure the PAPR. Thus, we can then write CCDF of the signal as: -

$$P(PAPR > PAPR_0 = 1 - (1 - e^{-PAPR_0})^N \tag{8}$$

where PAPR0 denotes the extent of clipping.

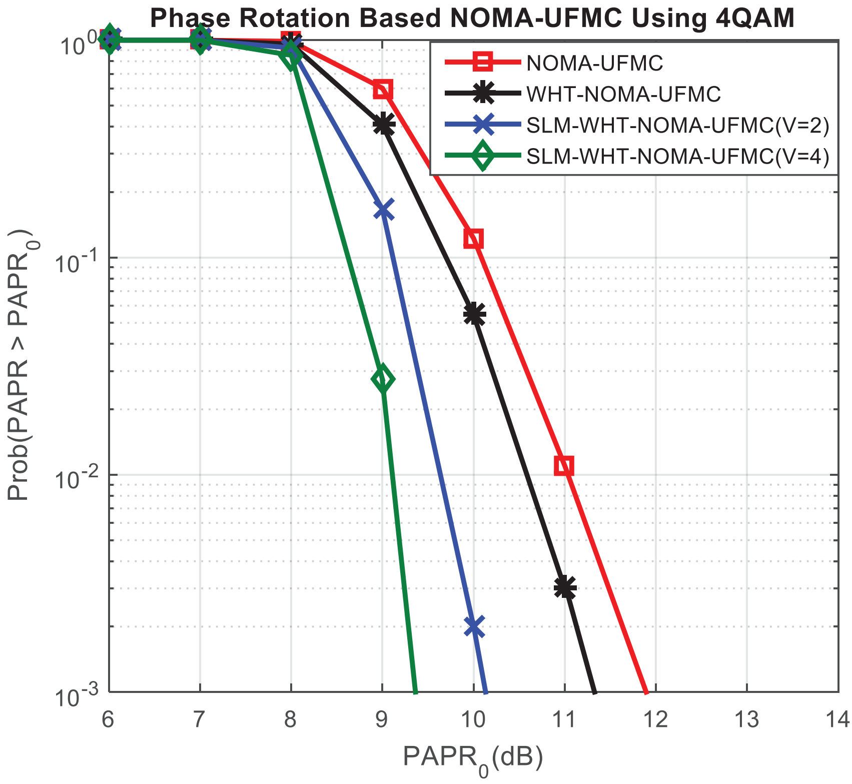

Fig. 2. PAPR Analysis by using 4-QAM.

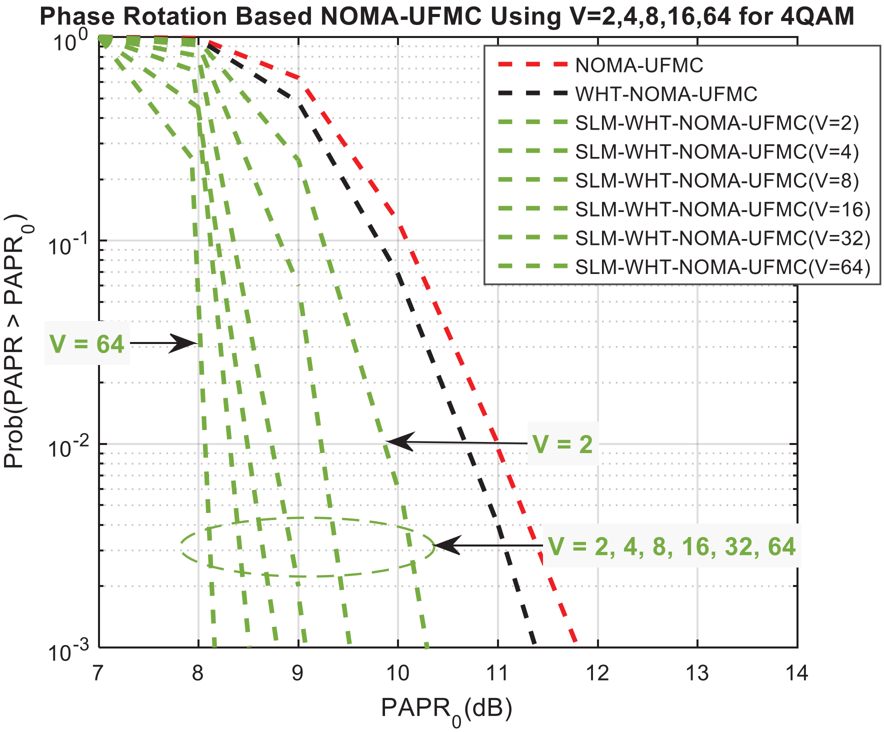

Fig. 3. PAPR Analysis with different Phase Rotation Values

Figures 2 show CCDF comparisons of PAPR for NOMA-UFMC waveform, WHT precoded NOMA-UFMC waveform, WHT precoded NOMA-UFMC waveform with SLM (V = 2), and WHT precoded NOMA-UFMC waveform with SLM (V = 4) for NOMA-UFMC waveform, WHT precoded NOMA-UFMC waveform with SLM (V = 2), and WHT precoded. The PAPR of the WHT precoded NOMA-UFMC waveform with SLM is lower than that of other typical NOMA-UFMC waveforms, as shown in Figure 2.

Based on WHT Precoding, Figure 3 displays a PAPR examination of the NOMA-UFMC with different SLM phase potation factors (V = 2, 4, 8, 16, 32, 64). The PAPR of the NOMA-UFMC signal is reduced by increasing the magnitude of V, which is a phase rotation factor while increasing system complexity. In addition, the magnitude of the modulation has an impact on PAPR decrease. Compared to the NOMA-UFMC waveform, employing various QAMs on the WHT precoded NOMA-UFMC waveform and SLM-based WHT precoded NOMA-UFMC waveform using (V = 2, 4) is more visible. As order modulation sizes get larger, PAPR performance suffers. As a result, the modulation size must be set carefully.

5. Conclusion

For the following 6G communication networks, this paper proposes and constructs a revolutionary Phase Rotation Based NOMA-UFMC downlink system. A combined SLM and WHT precoding is employed to reduce the high PAPR of the waveform design reported in this research. Numerical simulations in MATLAB® were used to assess the PAPR's performance. Based on simulation findings and comparative performance evaluations, the recommended waveform design has the potential to outperform NOMA-UFMC-based waveforms. The recommended waveform has high complexity and intricacy; however, this may be lowered by using smaller FFTs and reducing the number of sub-bands. Increased capacity is one of the primary performance advantages of the proposed waveform design with decreased PAPR over existing 5G options due to power domain multiplexing on the transmitting device. Consequently, total system capacity may be increased, and more users may be accommodated in specific scenarios. Consequently, the proposed waveform might be one of the most viable options for future 6G communication networks in the 2030s.

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