A Power Domain UFMC System Design for Underwater Optical Communication with Reduced PAPR

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Abstract

The Power-Domain Universal Filtered Multi-Carrier (PD-UFMC) waveform is one of the most promising technologies for the upcoming modern Underwater Optical Communication (UOC) systems due to its significant benefits in terms of bandwidth performance, massive connectivity, multi-path fading robustness and short-packed burst support. However, it is unfortunate that the PD-UFMC based UOC (PD-UFMC-UOC) waveform suffers from the high Peak-to-Average Power Ratio (PAPR) problem as it is multi-carrier in nature. Therefore, this paper introduces a new PD-UFMC-UOC waveform method based on Discrete Sine Transform (DST) precoding that is designed to solve the aforementioned problem by reducing the high PAPR. In addition, DST precoding is also capable of taking advantage of the frequency variations in the multipath UOC channel that can help to reduce the Bit Error Rate (BER). MATLAB® computer simulations were performed to demonstrate the performance as well as to evaluate the proposed PD-UFMC-UOC waveform. It is concluded by observing the simulation results that the proposed waveform outperforms the UOC waveform based on Power Domain Orthogonal Frequency Division Multiplexing (PD-OFDM) in terms of reducing the high PAPR values.

Keywords: PD-UFMC, UOC, PD-UFMC-UOC, PAPR

1 Introduction

As Extensive developments and future applications in a wide variety of areas, including military and industrial fields, and research, among others, have given considerable importance to underwater wireless communication (UWC). There are three modes of possible communication for UWC: radio wave, acoustic and optical communication, which can be used with the pros and cons of each to transmit information in the underwater environment. The key issue for underwater radio frequency communication is attenuation, which is further compounded by an increase in frequency. Acoustic communication, on the other hand, suffers from high transmission losses which, as a result, restrict coverage as well as throughput. [1]. While we are focused on underwater optical communication (UOC) in this work, there are also some limitations in terms of lower spectra and power efficiency along with the limited range. Given the aforementioned problems of UWC, the attention of researchers is drawn toward the UWC-based Optical Orthogonal Frequency Division Multiplexing (O-OFDM) method, since that is quite promising in terms of providing higher bandwidth transmission, along with high data rates and low latency [2].

Based on the literature, it is claimed that O-OFDM is a type of multi-carrier modulation technique that has been used successfully for UWC systems for various applications because of its ability to handle long dispersion channels along with reducing the complexity of the channel equalization process. Using O-OFDM technology, a modern scalable optical network architecture can be set up in the form of spectrum allocation and data rate accommodation with great flexibility and scalability. For this architecture, the waveform needs to be designed to cover a wide variety of networks that can cope with the exponential rise of internet traffic due to the increase of smartphones and the arrival of a plethora of bandwidth hungry applications [3].

However, there is still a problem of inter-carrier interference (ICI) caused by the Doppler effect, which may result in the loss of orthogonality for the orthogonal subcarriers. Working on these lines, the authors in [4] have proposed a system that can cancel the natural as well the human made noise by using a single frequency network along with a new optical video broadcasting gap filler. Also the scheme proposed in [4] is quite promising in order to suppress the Doppler effect that can be used to avoid interference and echoes in the received signal.

When deploying O-OFDM, one-point consideration

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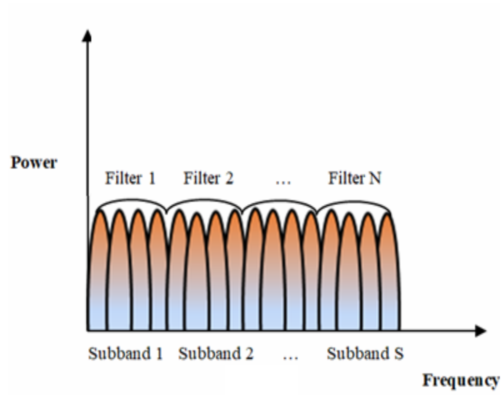
must be taken to ensure that the O-OFDM signal is both real and positive in order to introduce direct detection amplitude modulation. For this purpose, Hermitian transform symmetry is performed in conjunction with direct current. However, when the signal passes through the power amplifier or laser diode [5], it may induce significant signal distortion and loss of output due to the high peak-to-average power ratio (PAPR) which can result in non-linear distortion when the O-OFDM signals are in phase with each other. In order to address the above limitations of O-OFDM, an emerging waveform based on Universal Filtered Multi-Carries (UFMC) for UWC systems has been introduced.

For the sake of understanding, in Figure 1(a), the core concept of UFMC waveform is presented. In this Figure, the complete available bandwidth is divided into different ranges of frequencies which we dub as sub-bands. Furthermore, each sub-band can be further divided into a number of subcarriers. The important point about these subcarriers is that they are orthogonal to each other. First of all, these sub-bands are filtered out to eliminate the out of band emissions (OBE). The applied filtering process is also important for reducing the length of the filter as compared to the other related communication techniques hence; adding to the simplicity of the transceiver.

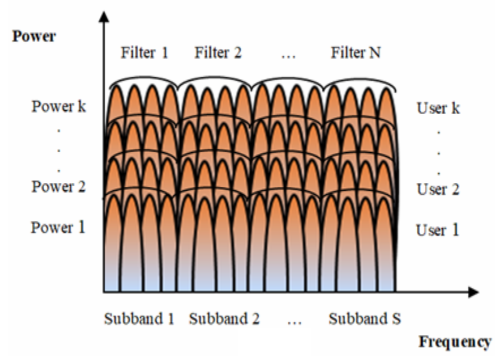
Moreover, each sub-band filtering offers a great deal of versatility in terms of architecture reducing the Inter Symbol Interference (ISI). Taking into account all these advantages, the UFMC waveform can be considered as one of the best available options for meeting the requirements of short-haul communications [6]. Additionally, the UFMC waveform can also help in improving the spectrum efficiency because it does not require any kind of Cyclic-Prefix (CP) [7], hence reducing the size of the signal to be transmitted that can contribute towards more throughput, less delay, and low power consumption. However, still the problem of high PAPR is really challenging in terms of the inefficient use of the spectrum. Consequently, these disadvantages make UFMC waveform impractical for the upcoming modern UWC networks.

Therefore, to compensate this, the conventional UFMC waveform requires a much more exhaustive study and new modification in the design that can significantly improve the utilization of the spectrum by reducing the high PAPR values [8]. Thus, a new waveform design for the UFMC Power Domain (PD-UFMC) is introduced in [9] to improve the capacity of the system. Figure 1(b), illustrates the basic concept of PD-UFMC waveform, where k users are multiplexed in the power domain in such a way that they all can communicate using the same time-frequency resources concurrently. Consequently, this leads to a major reduction in outage probability with enhanced capacity of serving large number of users.

This concept is illustrated in Figure 1(b), which shows that each kth user utilizes the same frequency band but has different power levels to assist in increasing the capacity of the network with much more users than before along with an increase in the overall throughput of the system. Besides these advantages, the PD-UFMC waveform also suffers from a high PAPR problem [10].



(a) UFMC vs



(b) PD-UFMC Waveform

Figure 1.

Hence, in this work, we design a new waveform based on Discrete Sine Transform (DST) precoding for UFMC which we name PD-UFMC waveform. This new designed waveform has much lower PAPR thus is a suitable candidate technique for the Underwater Optical Communication (UOC).

The rest of the topics discussed in this paper are as follows. The design and analysis of the proposed system is explained briefly in Section 2. Subsequently, the numerical results are discussed in Section 3 and finally, the paper is concluded in Section 4.

2 Proposed System

Figure 2 demonstrates the block diagram of proposed DST precoding based downlink PD-NOMA waveform design for UOC system. According to Figure 2, Base Station (BS) interact with all the k users at the same time by transmitting the information to them using same frequency but with different power assigned to the signal for each user.

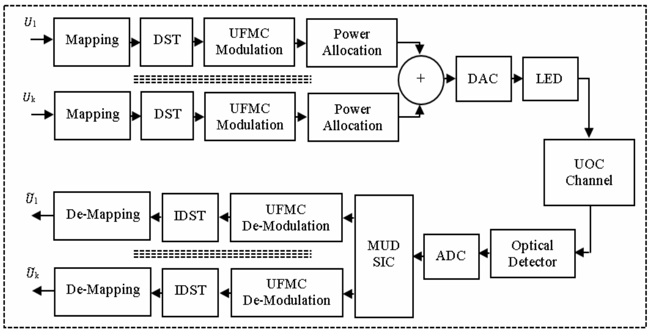


Figure 2. Proposed System Design

Now for the sake of analysis, let us take this assumption that the BS is communicating with k users. Each user is assigned a complete spectrum including N number of sub-carriers. First, these subcarriers are converted from Serial-to-Parallel (S/P). After we get conversion to parallel, the modulated QAM signal of any ith user represented by Xi mathematically can be expressed as follows:

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

Here *N* represents the total number of sub-carriers present in each sub-band. Then this signal is modulated using QAM modulation process. After the QAM modulation process, we applied DST precoding on this signal in order to distribute the modulated information over the entire spectrum and also to reduce the autocorrelation that can be found among the modulated data.

Once precoding is done, UFMC modulation is implemented in which the full-band *F* of the *N* sub-carrier for the ith user is divided into S sub-bands. Each sub-band in *S* comprises of *C* number of fixed number sub-carries. After UFMC, the obtained signal can be mathematically written as a *C* point IFFT which can be expressed as follows:

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

where X_i represents the constellation symbols found in the sub-bands of *S*. After the *C* point IFFT, the time domain signal is convoluted with the filter f of fixed length *L* and the resulting UFMC signal can be written as follows:

$$\breve{x}_{S_{i,l}} = x_{S_i} * f_L \tag{3}$$

After the filtering process, all of the filtered subbands are added to obtain the UFMC time area signal, which can be written as follows:

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

Where X_i is the UFMC signal for the mobile user. Eventually, in the power domain BS assigns different power levels to each UFMC signal in the downlink, and eventually, UFMC signal for each of the mobile user is multiplexed together. This multiplexing happens in the power domain, thus the resultant time domain signal for PD-UFMC can be written as follows:

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

p_i and x_i are used to denote the assigned power and signal for any mobile user respectively. After the power allocation process is completed, all PD-UFMC signals generated for each user by the BS are added together and converted to the analog form by the Digital-to-Analog Converter (DAC). Finally, the transmitter will transmit this signal over the medium using Light Emitting Diode (LED) for transmission on the UOC channel.

On the receiver side, the optical detector receives the signal and detects the signal from the UOC channel. The received signal obtained at the receiver can be mathematically written as follows:

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

Where h_i denotes a coefficient for a time domain channel for any user. Following the signal detection process, at the receiver's side Multi-User Diversity and Successive Interference Cancelation (MUD-SIC) is for cancelling the interference and reducing the ISI before the UFMC demodulation. Further to mitigate the channel and band filtering effects, equalization is performed for each of the subcarrier. Consequently, the data is unmapped to get the original data bits for each user.

3 Simulation Results & Discussion

This section includes a computer-based simulation study of the proposed waveform in the MATLAB® parameters as seen in Table 1 below. The PAPR output with different QAMs was investigated in conjunction with the proposed DST precoding based on PD-UFMC and the standard PD-OFDM waveform. Data is generated and modulated randomly by 4-QAM, 16-QAM, 64-QAM, and 256-QAM. The various simulation and analysis parameters are listed in Table 1. Table 1 reveals that the FFT size is 512, where sub-band numbers are 10 and sub-bands are equal to 20. DST precoding and DST precoding with Selective Mapping (SLM) PAPR reduction techniques are used to minimize the PAPR and the Dolph-Chebyshev filter is used with length L = 73 with Stop-Band Attenuation 40. Simulation parameters are based on the state-of-the-art literature [11-12] and mainly on the latest 3GPP LTE.

Table 1. Simulation parameters

Parameters	Specification
FFT Size	512
Sub-Band Size	20
No. of Sub-Bands	10
Subband Offset	156
Filter	Dolph-Chebyshev
Filter Length	73
Stop-Band Attenuation	40
Modulation	4-QAM, 16-QAM, 64-QAM and 256-QAM
Bits per Sub-Carriers	2, 4, 6
PAPR Reduction Scheme	DST and DST - SLM
LED Bandwidth	5 MHz

The PAPR of the signal in (5) can be written as:

$$PAPR = \frac{peak\_power\_of\_x}{average\_power\_of\_x} \quad \textbf{(7)}$$

Cumulative Distribution Function (CCDF) is widely used to approximate PAPR output in literature. It is a measure of the likelihood that the signal's instantaneous power is greater than the specified level above its average power. PD-UFMC CCDF signal can be written as:

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

Where $PAPR_0$ denotes the level of clipping. Figure 3, Figure 4, Figure 5, and Figure 6, respectively provide simulation evaluations of the PAPR for the proposed PD-UFMC waveform precoding DST and conventional PD-OFDM waveform for the UOC method. CP-OFDM waveform, DST preceded PD-UFMC waveform, DST precoded PD-UFMC waveform with SLM (*V* = *2*), and DST precoded PD-UFMC waveform with SLM (*V* = *4*) waveforms with 4-QAM, 16-QAM, 64-QAM and 256-QAM, respectively. It can be seen from Figure 3, Figure 4.

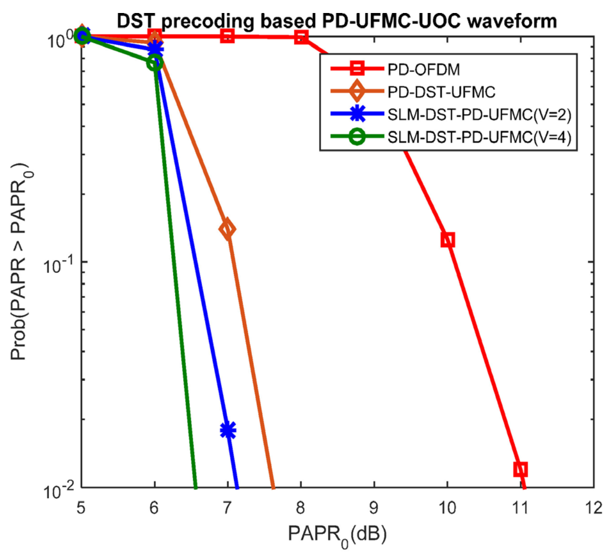


Figure 3. PAPR Analysis by using 4-QAM

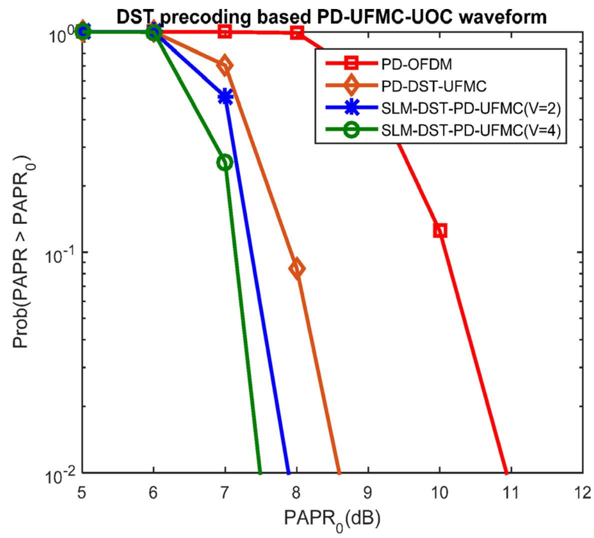


Figure 4. PAPR Analysis by using 16-QAM

Figure 5 and Figure 6 show the PAPR gain from the proposed DST precoding based PD-UFMC is higher than the traditional PD-OFDM. In addition, the PAPR gain from the proposed waveform can be further improved by combining some kind of PAPR reduction scheme appropriate for the UFMC. Due to linearity, simplicity, sophistication and UFMC suitability, we have selected SLM [13] to combine with DST. The simulation Figures also reveal that the precoding of DST or mixture of both DST and SLM increases the PAPR gain. By using higher values in SLM *V* the PAPR gain of the proposed wave can be further enhanced but the system complexity would be increased on the other side. The choice of *V* in SLM should also be carefully considered, this is yet another research area beyond the scope of this study.

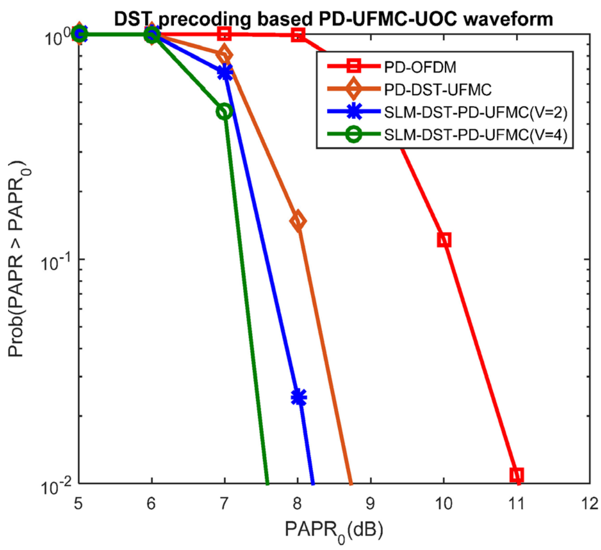


Figure 5. PAPR Analysis by using 64-QAM

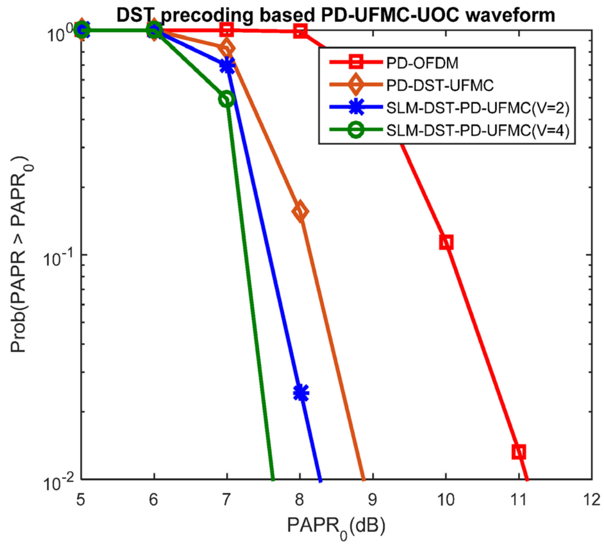


Figure 6. PAPR Analysis by using 256-QAM

Table 2, provides a description of the PAPR output of the various waveforms using various QAMs. The influence of different QAMs is more apparent on the proposed DST precoded PD-UFMC waveform, combined SLM and DST precoded PD-UFMC based systems using $V = 2$ and combined SLM and DST precoded PD-UFMC based systems using $V = 4$ compared to the traditional PD-OFDM waveform. According to Table 2, PD-UFMC precoded systems using $V = 2$ and SLM and DST precoded PD-UFMC systems using $V = 4$ are compared to the standard PD-UFMC wave format, which gives PAPR gain of 3.5dB, 3.8dB or 4.6dB respectively. With a higher modulation order the PAPR output of the proposed waveforms is degraded. The order of the modulation should also be picked carefully.

Table 2. PAPR comparisons in dBs

Waveform	4-QAM	16-QAM	64-QAM	256-QAM
PD-OFDM	11.1	11	11	11.1
DST-PD-UFMC	7.6	8.6	8.8	8.9
SLM-DST-PD-UFMC using $V = 2$	7.2	7.9	8.2	8.3
SLM-DST-PD-UFMC using $V = 4$	6.5	7.5	7.6	7.7

UFMC incorporates the simplicity of OFDM with the advantages of FBMC. However, these benefits are obtained with a cost of increasing transmitter's complexity due to the installation and deployment of filters for each FFT sub-band. The complexity of the various UFMC systems using FFT cutting methods is measured in [14] and the complexity is seen to be decreased by up to 50%.

Figure 1(a) and Figure 1(b) demonstrate that the proposed PD-UFMC waveform will use a multiplexing power domain for managing more nodes than the standard UFMC waveform. The major advantage of the proposed waveform relative to the other waveforms is the capacity improvement and the improvement in the output to handle a huge number of PAPR nodes.

4 Conclusion

This paper has established and proposed a new system design for the modern Underwater Optical Communication Systems. MATLAB® computer simulations have been carried out to investigate the properties of the PAPR. The DST precoding and SLM are used in conjunction with DST precoding in order to reduce the PAPR of the proposed system. According to the computer simulation results, the proposed system is superior to the standard PD-OFDM system. The complexity of implementing the proposed system indicated is slightly high, but by choosing smaller FFTs and limiting the number of subbands, it can be reduced. The key advantage of the proposed waveform suggested over other waveforms is the capacity gain due to power domain multiplexing at the transmitter. As a consequence, more users will be accommodated under such limitations.

The hardware implementation of the proposed system design will be considered in future work. In addition, the Multiple Input Multiple Output (MIMO) can be integrated with the proposed system to improve the potential specifications of the Underwater Optical Communication Systems.

References

[1] H. Kaushal, G. Kaddoum, Underwater Optical Wireless Communication, *IEEE Access*, Vol. 4, pp. 1518-1547, April, 2016.

[2] W. C. Cox, J. A. Simpson, J. F. Muth, Underwater optical communication using software defined radio over LED and laser based links, *Military Communications Conference*, Baltimore, MD, USA, 2011, pp. 2057-2062.

[3] G. Zhang, M. D. Leenheer, A. Morea, B. Mukherjee, A Survey on OFDM-Based Elastic Core Optical Networking, *IEEE Communications Surveys & Tutorials*, Vol. 15, No. 1, pp. 65-87, First Quarter, 2013.

[4] E. M. Ar-Reyouchi, Y. Lamrani, K. Ghoumid, S. Rattal, Very High-Performance Echo Canceller for Digital Terrestrial Television in Single Frequency Network, *International Journal of Advanced Computer Science and Applications*, Vol. 11, No. 2, pp. 368-376, 2020.

[5] J. Bai, C. Cao, Y. Yang, F. Zhao, X. Xin, A. H. Soliman, J. Gong, Peak-to-average power ratio reduction for DCO-OFDM underwater optical wireless communication system based on an interleaving technique, *Optical Engineering*, Vol. 57, No. 8, pp. 086110, August, 2018.

[6] F. Schaich, T. Wild, Y. Chen, Waveform Contenders for 5G - Suitability for Short Packet and Low Latency Transmissions, *79th Vehicular Technology Conference*, Seoul, South Korea, 2014, pp. 1-5.

[7] T. Wild, F. Schaich, Y. Chen, 5G air interface design based on Universal Filtered (UF-)OFDM, *19th International Conference on Digital Signal Processing*, Hong Kong, China, 2014, pp. 699-704.

[8] P. N. Rani, C. S. Rani, UFMC: The 5G modulation technique, *IEEE International Conference on Computational Intelligence and Computing Research*, Chennai, India, 2016, pp. 1-3.

[9] A. Singh, K. K. Naik, C. R. S. Kumar, Impact of SC-FDMA and Pilots on PAPR and Performance of Power Domain NOMA-UFMC System, *10th International Conference on Ubiquitous and Future Networks*, Prague, Czech Republic, 2018, pp. 507-511.

[10] M. Attar, Y. Chen, S. A. Cheema, T. Wild, M. Haardt, NOCA versus IDMA using UFMC for 5G Multiple Access, *22nd International ITG Workshop on Smart Antennas*, Bochum, Germany, 2018, pp. 1-5.

[11] X. Zhang, L. Chen, J. Qiu, J. Abdoli, On the Waveform for 5G, *IEEE Communications Magazine*, Vol. 54, No. 11, pp. 74-80, November, 2016.

[12] J. B. Doré, R. Gerzaguet, N. Cassiau, D. Ktenas, Waveform contenders for 5G: Description, analysis and comparison, *Physical Communication*, Vol. 14, pp. 46-61, September, 2017.

[13] Y. Zhang, K. Liu, Y. Liu, A Novel PAPR Reduction Algorithm Based on SLM Technique in UFMC Systems, *International Conference on Communications in China*, Beijing, China, 2018, pp. 178-183.

[14] M. V. Eeckhaute, A. Bourdoux, P. D. Doncker, F. Horlin, Performance of emerging multi-carrier waveforms for 5G asynchronous communications, *EURASIP Journal on Wireless Communications and Networking*, Article. No. 29, pp. 1-15, February, 2017.

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