Flexible Communication System for 6G Based on Orthogonal Chirp Division Multiplexing

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HAL Id: hal-03886249
https://hal.science/hal-03886249v1

Submitted on 6 Dec 2022

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Abstract—This paper deals with the orthogonal chirp division multiplexing (OCDM) modulation, and its capability to generate inherited waveforms, such as the orthogonal frequency division multiplexing (OFDM) or precoded OFDM, covering a large number of use cases. To this end, we first prove that the OCDM signal can be generated by a transmission chain composed of a discrete Fourier transform (DFT) matrix, followed by a multiplication by a chirp, and then an inverse DFT (IDFT). Then, we show that the OCDM transmission chain can be split into 6 sub-blocks from which we can generate numerous inherited waveforms. Thus, the OCDM waveform is an interesting candidate for flexible communication systems such as multiple radio access technology (multi-RAT).

Index Terms—OCDM, 6G, multi-USER, multi-RAT.

I. INTRODUCTION

The orthogonal chirp division multiplexing (OCDM) waveform [1] is a good alternative to the orthogonal frequency division multiplexing (OFDM), precoded OFDM [2], or filterbank-based modulations [3], especially for future generations of wireless communication post 5G or 6G. In fact, the data symbols are carried by chirps in OCDM instead of sinusoids in OFDM, such as illustrated in Fig. 1. This chirp multiplexing allows the receiver to optimally decode the signal in presence of selective channels in both time and frequency domains [4], whereas the OFDM and precoded OFDM modulations are only sub-optimal against channels that are selective in frequency and time, respectively [5]. This optimal reception is due to the fact that the chirps inherently spread the possible errors induced by the propagation channel over the whole time and frequency grid. This feature is also achieved by the orthogonal time frequency space (OTFS) modulation [6], but it requires a precoding over a block of OFDM symbols, whereas the time-frequency spreading in OCDM is carried out symbol per symbol, therefore limiting the latency. In addition, the
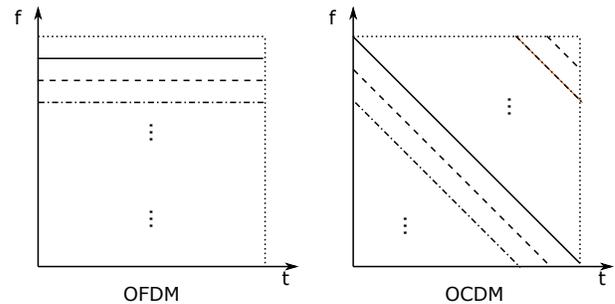

Fig. 1. Variation in frequency (Y axis) of the data symbols subcarriers in function of the time (X axis) in OFDM (sinusoids) and OCDM (chirps).

OCDM modulation scheme may be especially relevant for sensing and communication in 6G [7], since chirps can be used in radar applications.

The OCDM modulation is based on Fresnel transform instead of Fourier transform in OFDM. It is nevertheless shown in [1] that the OCDM modulation can be processed by means of a usual inverse discrete Fourier Transform (IDFT), preceded and followed by a multiplication by chirps in both frequency and time domains, therefore reducing the complexity of the transceiver compared with Fresnel transform. The authors in [8] suggest an alternative modulation process by describing the OCDM as the usual OFDM modulation precoded by a DFT matrix (similar to DFT-s-OFDM) and a multiplication by a chirp. The scheme in [8] offers the advantage that the sampling rate at the output of the IDFT can be set as expected whereas the solution in [1] is limited as it generates OCDM signal sampled at Nyquist rate. Furthermore, the authors in [8] show that filtered-OCDM can be also designed (similarly to OFDM) in order to reduce the amplitude of the side lobes.

In this paper, on the one hand we mathematically formalize the principle of the OCDM modulation pro-

posed in [8], whereas the authors in [8] introduce their scheme and *a posteriori* prove that the assumption of orthogonality among chirps holds. On the other hand, we propose a split of the steps of the OCDM modulation into 6 sub-blocks such that enabling or disabling these sub-blocks leads to a large number of waveforms inherited from OCDM. Among those modulations, we can find the OFDM, the single carrier-frequency division multiplexing (SC-FDM), or the chirp spread spectrum (CSS), which are used in numerous communication technologies and standards. Thus, besides its inherent robustness against time-frequency selective channels [4] and its capability for sensing and communication applications [7], the OCDM modulation scheme enables the design of multi-radio access technology (multi-RAT), which could be implemented in 6G systems while being compatible with other existing technologies.

The remaining of this paper is organized as follows: Section II introduces the OCDM modulation and mathematically formalizes the DFT-based scheme with precoding and multiplication by a chirp. The split of the OCDM modulation into sub-blocks, and how inherited waveforms are obtained from OCDM is described in Section III. Finally, Section IV concludes this paper.

II. OCDM SYSTEM MODEL

We consider the OCDM signal x_n sampled at Nyquist rate, where $n = 0, 1, .., N-1$ and N is the number of subcarriers (in OCDM the subcarriers refers to chirps instead of sinusoids as in OFDM), as the inverse discrete Fresnel transform of the symbols of constellation $\{C_0, C_1, .., C_{N-1}\}$ [1]:

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} C_k \underbrace{e^{-j\frac{\pi}{N}(n-k)^2 + j\frac{\pi}{4}}}_{g_{k,n}}, \tag{1}$$

where we note $g_{k,n} = e^{-j\frac{\pi}{N}(n-k)^2 + j\frac{\pi}{4}}$ the chirp carrying the constellation symbol C_k. In order to design the modulation scheme based on IDFT such as described in [8], it must be noticed that the DFT of the chirp $g_{k,n}$, that we denote by $G_{k,m}$, can be straightforwardly expressed by using the quadratic Gauss sum [9], which leads to:

$$
\begin{aligned}
G_{k,m} &= \sum_{n=0}^{N-1} g_{k,n} e^{-2j\pi\frac{mn}{N}} \\
&= e^{j\frac{\pi}{4}} \sum_{n=0}^{N-1} e^{-j\frac{\pi}{N}(n-k)^2} e^{-2j\pi\frac{mn}{N}} \\
&= \sqrt{N} e^{j\frac{\pi}{N}(m^2-2km)} \sum_{n=0}^{0} e^{j\pi(Nn^2-(2m-2k)n)} \\
&= \sqrt{N} e^{j\frac{\pi}{N}(m^2-2km)}, \tag{2}
\end{aligned}
$$

where m is the index of the frequency samples. Then, by substituting $g_{k,n}$ by the IDFT of $G_{k,m}$ in (1), we obtain:

$$
\begin{aligned}
x_n &= \frac{1}{N} \sum_{k=0}^{N-1} C_k \left[\frac{1}{N} \sum_{m=0}^{N-1} G_{k,m} e^{2j\pi\frac{mn}{N}}\right] \\
&= \frac{\sqrt{N}}{N^2} \sum_{m=0}^{N-1} \left[\sum_{k=0}^{N-1} C_k e^{j\frac{\pi}{N}(m^2-2km)}\right] e^{2j\pi\frac{mn}{N}} \\
&= \frac{\sqrt{N}}{N^2} \sum_{m=0}^{N-1} e^{j\pi\frac{m^2}{N}} \left[\sum_{k=0}^{N-1} C_k e^{-2j\pi\frac{km}{N}}\right] e^{2j\pi\frac{mn}{N}}, \tag{3}
\end{aligned}
$$

where we highlight the DFT of the constellation symbols $\{C_0, C_1, .., C_{N-1}\}$ within bracket, the multiplication by the chirp $e^{j\pi\frac{m^2}{N}}$ and the IDFT, such as described in [8]. We can generalize (3) to consider a DFT of size $K \leq N$ corresponding to K symbols of data $\{C_0, C1, .., C_{K-1}\}$ and a IDFT of size N, such that $Q = \frac{N-K}{2}$ null subcarriers are located at the edge of the band. Then x_n is expressed as

$$x_n = \frac{\sqrt{K}}{KN} \sum_{m=0}^{N-1} \alpha_m e^{j\pi\frac{(m-Q)^2}{K}} \left[\sum_{k=0}^{K-1} C_k e^{-2j\pi\frac{k(m-Q)}{K}}\right] e^{2j\pi\frac{mn}{N}}, \tag{4}$$

with $\alpha_m = 0$ if the m-th subcarrier is null, and $\alpha_m = 1$ otherwise. The corresponding OCDM transmission chain is illustrated in Fig. 2, where the cyclic prefix has been introduced to avoid intersymbol interference, similarly to OFDM. It is worth emphasized that the oversampling rate at the output of the IDFT is given by the ratio $\frac{N}{K}$. The corresponding OCDM receiver is composed of the inverse sub-blocks to the transmitter, such as illustrated in Fig. 3. It includes the CP removal, the DFT of size N leading to the received samples Y_m, the multiplication by the inverse chirp $e^{-j\pi\frac{m^2}{N}}$, and the IDFT of size K. Moreover, the channel estimation and equalization is performed after the DFT of size N. The way the channel
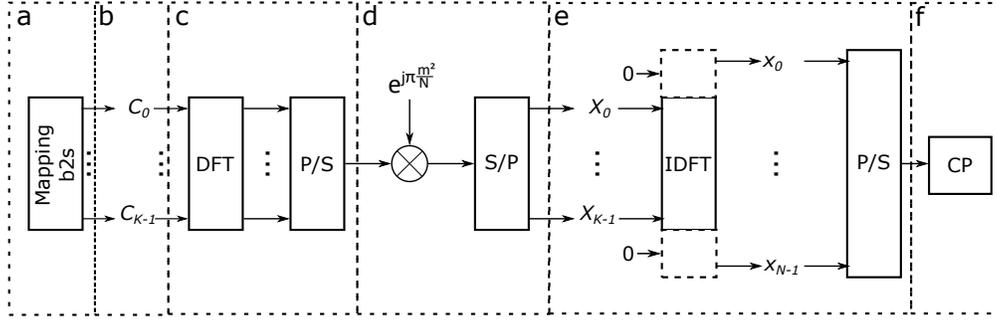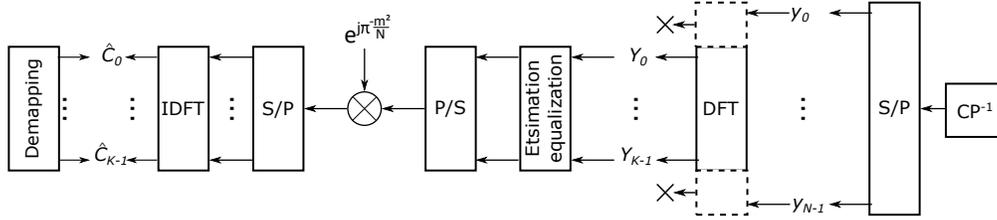
Fig. 2. OCDM transmission chain.

Fig. 3. OCDM reception chain.

is estimated and equalized is out of the scope of this paper, but details can be found in [1], [5], [8].

Fig. 4 shows the bit error rate (BER) performance of OCDM compared with OFDM versus the signal to noise power ratio (SNR) in dB. Two channel models are considered: the additive white Gaussian noise (AWGN) channel (a), and Rayleigh channel (b). The latter has been modeled using a uniform power profile, and the maximum delay spread is equal to 1/4 the length of the CP. On the other hand, the OCDM signal is composed of $K = N = 256$ subcarriers and data symbols are randomly chosen from a 16-QAM constellation. Furthermore, an equalizer based on the minimum mean square error (MMSE) has been used [8]. We can observe that the performance of the OCDM and OFDM match in presence of the AWGN channel, but the OCDM modulation scheme outperforms the OFDM over Rayleigh channel for SNR values larger than 20 dB. Such as aforementioned, this result is due to the inherent spreading of the errors induced by multipath channels by the chirps in OCDM, which cannot be achieved with sinusoids in OFDM.

In the following, we suggest a split of the OCDM transmission chain into sub-blocks in order to highlight other modulation schemes by simply enable and disable these sub-blocks. Beyond this suggested split, obtaining numerous inherited modulations from the OCDM waveform makes this modulation a relevant solution for flexible multi-technology systems, besides its inherent robustness against time and frequency selective channels.

III. GENERATING OTHER WAVEFORMS FROM OCDM

Such as illustrated in Fig. 2, we suggest a split of the OCDM transmission chain into 6 sub-blocks noted 'a', 'b', .., 'f'. After a brief description of each of the blocks, we list (non exhaustively) the different modulation schemes that can be obtained by enabling and disabling these sub-blocks, covering a large number of communications technologies, therefore proving the capability of the OCDM waveform to design flexible communication systems such as multi-RAT transceivers.

The aforementioned sub-blocks are summarized as follows:

- a : the binary to symbol conversion (or mapping b2c).
- b : the mapping of these symbols to subcarriers.
- c : the DFT of size K and the parallel to series conversion.
- d : the multiplication by the chirp $e^{j\pi\frac{m^2}{N}}$.
- e : the IDFT of size N.
- f : the CP addition.

From these 6 sub-blocks, we can define a large number of inherited modulation schemes. Among others, we describe the three waveforms that are usually used in numerous communication standards and technologies, such as:
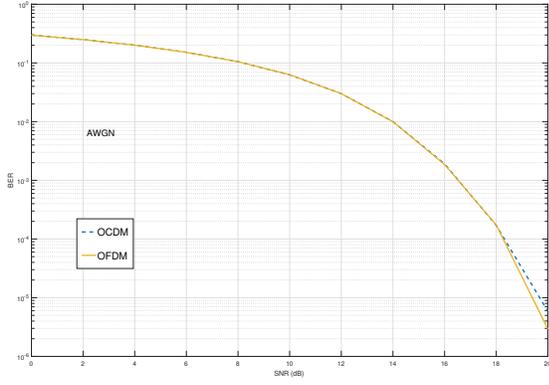
(a) AWGN channel.
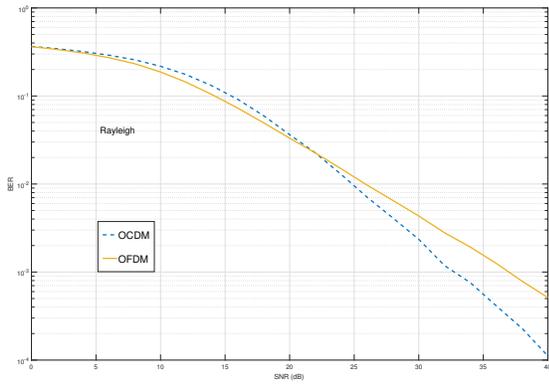
(b) Rayleigh channel.

Fig. 4. BER performance of OCDM and OFDM versus SNR (dB) for AWGN channel (a) and Rayleigh channel (b).

1) **a + b + c + e + f**: the OFDM precoded with a DFT matrix, such as the SC-FDM or the DFT-s-ODFM. They are used in particular in uplink in LTE, LTE-M, NB-IoT [10], or in 5Gnr [11]. In that case, the sub-block 'a' corresponds to a conversion of binary packets to symbols of constellation of types X-PSK or M-QAM. Such as indicated in introduction, it is possible to design an optimal receiver for the precoded OFDM, but only for frequency selective channel [5].

2) **a + b + e + f**: the OFDM, used in plenty of cellular technologies (LTE, 5Gnr, NB-IoT, etc.), in WiFi, as well as in digital video and audio broadcasting (DVB, DAB, DRM). Once again, 'a' corresponds to a binary conversion of binary packets to symbols of constellation of types X-PSK or M-QAM. Moreover, such as indicated in introduction, a suboptimal received only is achievable in OFDM for

frequency selective channels [5].

3) **a + b + c + d + e**: the CSS waveform, such as used in LoRa [12]. In that case, the sub-block 'a' is a conversion of binary packets to an integer symbol corresponding to the index of the unique non-null subcarrier in sub-block 'b'. It is worth mentioning that we here omit the CP addition to match the usual LoRa technology, but it is possible to consider a CSS modulation with CP addition. Moreover, note that the scheme **'a + b + c + d + e'** enables the modulation of chirps symbols at any desired sampling frequency, which could be used in sensing and communication applications for 6G.

These three examples cover a large number of applications from low data rate solutions (NB-IoT, LoRa) up to (ultra-)high data rate systems (4 & 5G). Furthermore, it can be noticed that the OCDM transmission chain is generic enough to cover use cases dedicated to specific technologies as well. For instance, we can highlight the chain **'b+e+f'** where 'b' is a pseudo-random choice of the subcarrier index. In that case, **'b+e+f'** corresponds to the transmission of sinusoids with pseudo-random frequency hopping, used to generate NB-IoT preambles during the random access procedure. Otherwise, the chain **'d+e+f'** with an adaptation of step 'd' (m^2 is substituted by $u.m(m+1)$ where u is an integer number) leads to a Zadoff-Chu (ZC) sequence, which is used for synchronization signals and pilots in 4&5G, NB-IoT, and LTE-M. The authors of [13] suggested the OFDM waveform with index modulation (OFDM-IM), where the binary data stream is converted in complex symbols from a constellation, but also defines the active subcarriers. The OFDM-IM can then be designed using the chain **'a + b + e + f'** where the sub-blocks 'a' and 'b' are adapted to the index modulation. Recently in [14], a new waveform generalizing the OCDM has been proposed, where the chirp $e^{j\pi \frac{m^2}{N}}$ in the sub-block 'd' can be substituted by $e^{j\pi f(m)}$ with $f(m)$ a generic quadratic function of m. This modulation is called affine frequency division multiplexing (AFDM). Thus, we have shown that the OCDM modulation, through its general transmission chain, enables the generation of numerous inherited waveforms, and can actually used to design multi-RAT systems.

IV. CONCLUSION

In this paper, we have presented the OCDM system model and mathematically formalized the signal to highlight the transmission chain based on a precoding composed of a DFT matrix and the multiplication by

a chirp, followed by an IDFT. Then, we have split the OCDM transmission chain into 6 sub-blocks from which we can generate numerous inherited waveforms, by enabling or disabling these sub-blocks, such as the OFDM, precoded OFDM, or CSS. It results that the OCDM modulation, besides being a good candidate for 6G communications, enables the design of flexible multi-RAT transceivers compatible with numerous existing standards and technologies. The future works will consist in dealing with the pending technical challenge related to the OCDM.

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