Design and Evaluation of OTSM(Orthogonal Time Sequency Multiplexing) Communication System in Rayleigh Fading Channel

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Abstract — **As a next generation waveform candidate of the OFDM (orthogonal frequency division multiplexing) system used in 4G LTE (long tern evolution) and 5G NR (new radio), the orthogonal time sequency multiplexing (OTSM) communication system has been studied and investigated for the possibility. OTSM system is a single carrier modulation scheme, which operates in delay–sequency domain. Walsh-Hadamard transform (WHT) is used to convert data from time domain to sequency domain and backwards. Modulation includes interleaving of data symbols. The paper describes OTSM system and shows its performance in Rayleigh fading channel, compared to equivalent OFDM system. OTSM system can be described as an alternative to OFDM, which shows great potential in Rayleigh fading channel in presence of Doppler shift. Performance improvement is achieved due to zero padding, or, in other words, due to guard delay between blocks, resulting in loss of data-rate, comparing to equivalent OFDM system.**

Keywords—OTSM, OFDM, Rayleigh fading

I. INTRODUCTION

As a next generation waveform candidate of the OFDM (orthogonal frequency division multiplexing) system used in 4G LTE (long tern evolution) and 5G NR (new radio), the orthogonal time sequency multiplexing (OTSM) communication system has been studied and investigated for the possibility. OTSM system is a single carrier modulation scheme, which operates in delay–sequency domain. Orthogonal time sequency multiplexing (OTSM) is a single carrier modulation scheme, which is based on Walsh-Hadamard transform (WHT). Initially data is formed into a grid in delay–sequency domain. Then, by applying WHT along sequency dime, data is formed into grid in delay–time domain, interleaved, and, finally, is sent through the wireless channel.

The Walsh-Hadamard transform is a non-sinusoidal, orthogonal transformation technique that decomposes a signal into a set of bases functions [1]. These basis functions are Walsh functions, which are given by rectangular waves taking values +1 or -1. Sequency is defined as one half of the average number of zero-crossings per unit time interval. Walsh-Hadamard transform matrix H_n can be defined as a $2^n \times 2^n$ matrix, which transforms vector x of size 2^n into vector X. Elements of this matrix can be achieved recursively, by the following way:

$$H_n = \frac{1}{\sqrt{2}}\begin{pmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & -H_{n-1} \end{pmatrix}, \tag{1}$$

where H_1 is equal to 1, and $1/\sqrt{2}$ is a normalization factor, which can be omitted. WHT matrix elements are real numbers, that simplifies computation of WHT compared to Fourier transform.

II. SYSTEM DESCRIPTION

The general scheme of OTSM system [2] is shown in the Fig. 1. Initial data bits are modulated into complex symbols, using QAM method, for example. These symbols of total length of MN are formed into a grid, which has M rows and N columns. N must be equal to 2^n, and it determines sequency dimension, while M is a delay dimension. Last L rows are filled with zeros.rpose of this will be described later.

After data is formed into a grid, Walsh-Hadamard transform is applied to each row of that grid, so that data is converted into delay-time domain. So, in other words, initial data is given by matrix of size $M \times N$:

$$\mathrm{X} = [\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_\mathrm{M}]^T, \tag{2}$$

where x_m are vectors of length N, $m = 1..M$. WHT operation in matrix form can be calculated as follows:

$$\mathrm{Y} = \mathrm{X} \cdot \mathrm{H}_\mathrm{n}. \tag{3}$$

After that matrix Y is vectorized, $\bar{Y} = [y_1^T, y_2^T, \ldots, y_n^T]^T$, so we obtain a stream of time-domain samples. Samples are pulse shaped, converted to digital signal, and transmitted through wireless channel. So, data is transmited as consistent N blocks, each of length M. Each of these blocks is ending with L zeros, or, in other words, blocks are separated with guard delay. Value of L is chosen depending on maximum path delay, expected to appear in channel.

The signal passes through Rayleigh fading channel. Receiver processes the signal by converting it from analog to digital signal and detecting blocks. These blocks are formed into delay-time domain grid of size M×N by serial to parallel

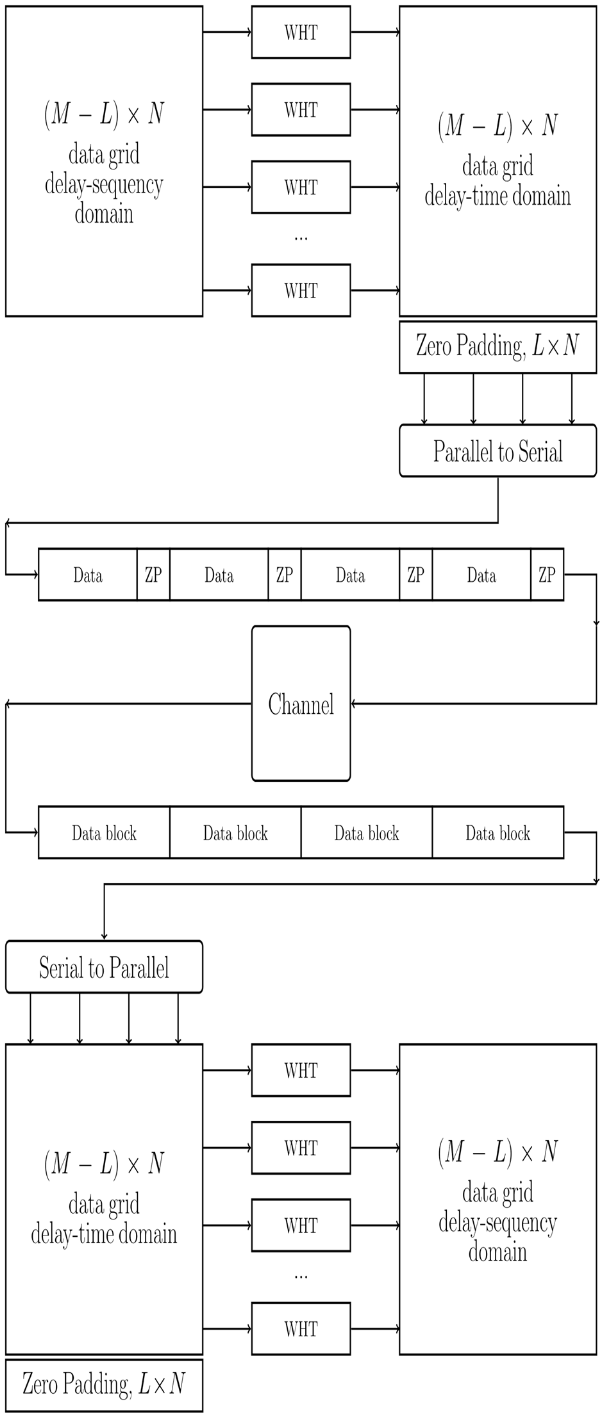


Fig. 1. OTSM system block diagram.

converter. Zero padding is removed and WHT is applied to each row of the grid, resulting into data grid of size $(M-L)\times N$ in delay-sequency domain. Then, after applying an equalizer and demodulating decision function, we get stream of bits, which is transmitted.

III. SYSTEM AND CHANNEL

A. *System parameters*

Investigation of OTSM system performance was made by simulation it in MATLAB. Achieved performance was compared to performance of equivalent OFDM system. For both systems, carrier frequency was set to 4 GHz. Length of FFT for OFDM system N_ofdm was set to 1024, while for OTSM system N and M were set both to 32. Parameter L is set to 2, according to channel model parameters, this aspect will be discussed further. Duration of OFDM symbol is equal to the duration of OTSM symbol, which is set to 2.1 ms.

So, the sample rate is equal to 480 kHz. System parameters comparison is given in Table I.

TABLE I. SYSTEM PARAMETERS COMPARISON

	System Name	
	OFDM	***OTSM***
Total number of symbols per frame	$N_{ofdm}=1024$	$M\times N=32\times 32$
Length of zero padding	(CP length)	$L\times N, L=2$
Frame duration	T_f +25% CP	$T_f=NT$ +25% CP
Bandwidth	$\Delta F\approx\frac{N_{ofdm}}{T_f}$	$\Delta F=\frac{M}{T}=\frac{MN}{T_f}$

B. *Channel model*

Rayleigh channel model, used for system performance investigation, is standard EVA model. Maximum delay for this model is equal to 2 samples for described system parameters, that’s why parameter L for OTSM is 2. This results to sacrifice of 6.5% of data-rate for OTSM compared to OFDM. Performance is compared for channel without Doppler frequency shift, and with shift, equal to 74 Hz, which is moving with 20 km/h for this carrier frequency. Transmitted s and received r symbol vectors in descrete time domain are related the following way

$$r=G\cdot s. \tag{4}$$

$G(k)$ is the channel matrix, where columns are in time domain and rows are in delay domain. The matrix elements look the following way:

$$G=\begin{pmatrix} g_{11} & 0 & 0 & 0 & \cdots & 0 \\ g_{22} & g_{12} & 0 & 0 & \cdots & 0 \\ g_{33} & g_{23} & g_{13} & 0 & \cdots & 0 \\ \cdots & \cdots & \ddots & \ddots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \ddots & \ddots & \cdots \\ 0 & 0 & g_{l_{max}D} & \cdots & g_{2D} & g_{1D} \end{pmatrix}. \tag{5}$$

This matrix of size $D\times D$, where D is a number of signal samples, is formed from matrix of channel path gains g of size $D\times l_{max}$, where l_{max} is maximum discrete path delay. So, in matrix G, elements on the main diagonal are complex gains of the direct path, while other elements are complex gains of the delayed paths.

IV. SIMULATIONA AND DISCUSSIONS

A. *PAPR and Spectrum*

Firstly, systems are compared in terms of PAPR. CCDF function is shown in the Fig. 2. Three curves are built: one for OFDM and two for OTSM with zero padding and without it. OTSM system without zero padding shows slightly better CCDF curve, while curve for OFDM is equal to the curve of OTSM with zero padding length L equal to 2.

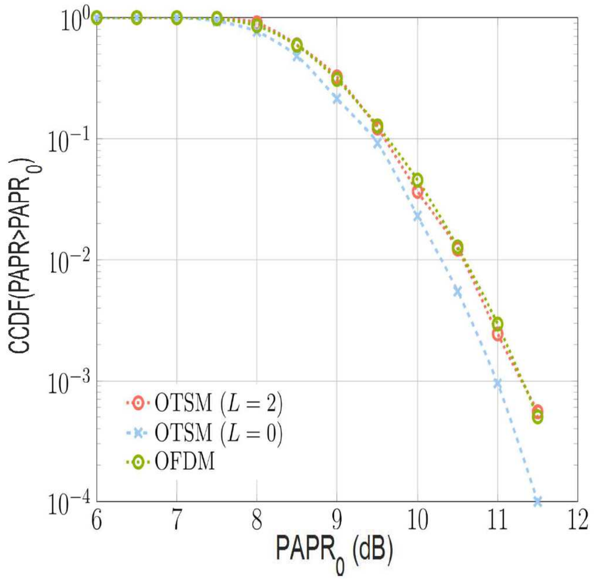


Fig. 2. PAPR comparison of OFDM and OTSM with zero padding and without zero padding

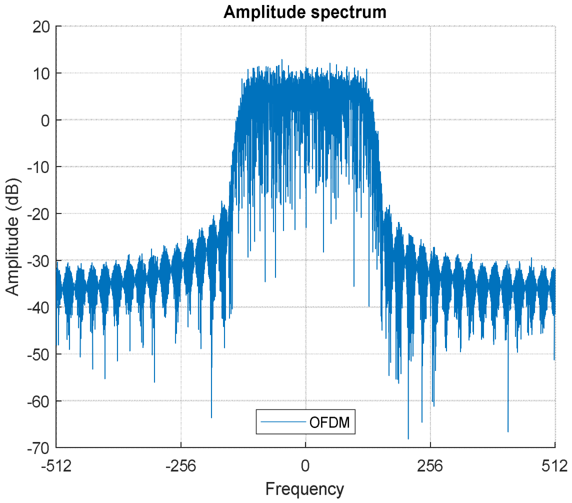
Spectrum comparison of OFDM and OTSM systems is shown in Fig. 3. Oversampling factor in both cases is 4. OTSM symbols are pulse shaped by raised cosine FIR filter. System parameters, such as frame duration, and number of symbols per 1 frame, were set the same. As it can be seen, OTSM spectrum is slightly wider, but the level of side lobes for both of these systems is equal.

B. *BER performance*

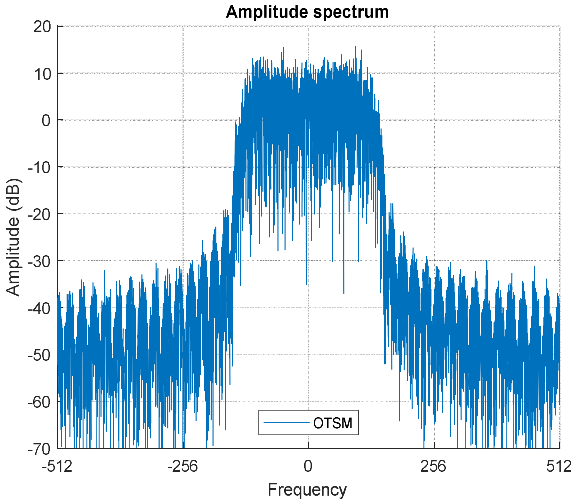
In AWGN channel both OTSM and OFDM showed same performance, which is shown in the Fig. 4. These results match the theoretical BER curves of OFDM in AWGN channel.

The key difference of the systems is in their BER curves in Rayleigh fading channel. Signal, passed through fading channel, requires equalization in processing algorithm. A simple one tap MMSE equalizer was used to process signal from both systems. We also assume, that we obtain perfect channel function estimation

In the OTSM system we can perform equalization parallel on N block, each of length M [2]. This can be done due to absence of interference between these blocks because of zero padding, and also in assumption, that small duration of each block compared to whole frame results in time-invariance of the channel response during one block and variance from block to block. Received demodulated symbols are placed into delay-sequency domain, so for equalization we have to transform them into frequency time domain. Firstly, WHT along sequency domain transforms data into delay-time domain. FFT operation along delay domain results into transformation into frequency-time domain. After applying single tap MMSE equalizer, we have to transform symbols back to delay-sequency domain. Firstly, we implement IFFT along frequency domain, obtaining symbols in delay-time domain, and then we calculate WHT along time domain.



(a) OFDM



(b) OTSM

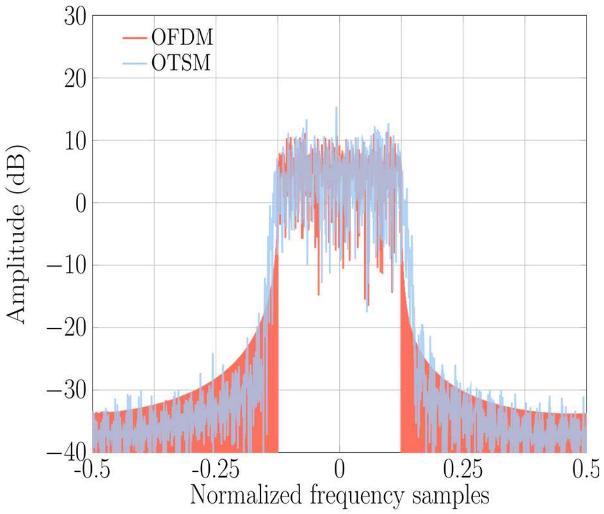


Fig.3. Spectrum comparison of OFDM and OTSM

As it was said before, performance is compared for channel model with Doppler frequency, and without it. Fig. 5 shows comparison in case, when there is no Doppler frequency shift at the channel. Model, used to describe Rayleigh fading channel, is a standard EVA model. As it can be seen, in this case OFDM shows better performance, compared to OTSM system. OTSM without zero padding has highest BER.

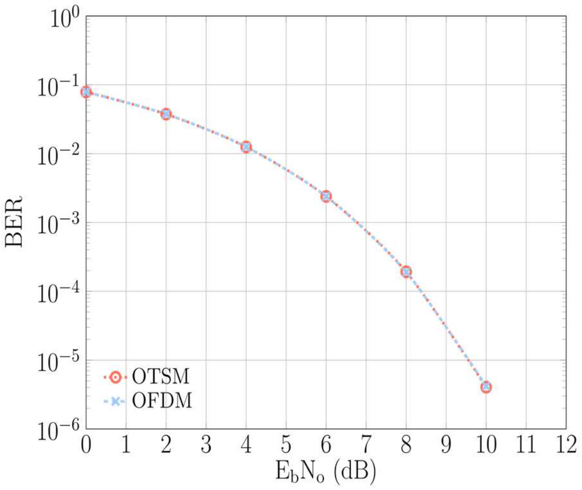


Fig.4. BER performance in AWGN channel

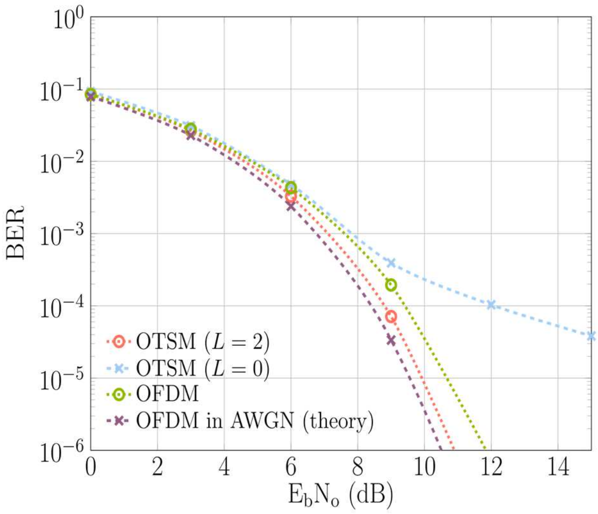


Fig.5. BER performance comparison for EVA channel model without Doppler frequency shift

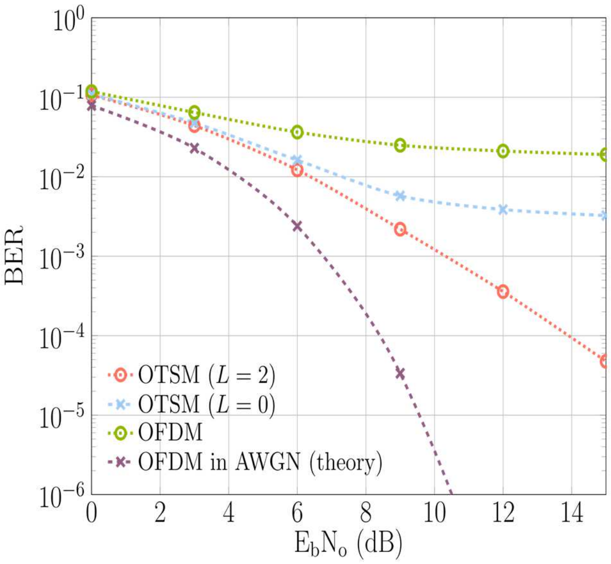


Fig.6: BER performance comparison for EVA channel model with maximum Doppler frequency shift of 74 Hz

Fig. 6 shows BER performances comparison in channel model with maximum Doppler frequency shift equal to 74 Hz, which can be conditioned by moving with 20 km/h speed. OTSM curves are equal to the curves in case of no Doppler shift, while OFDM performance decreases significantly. OTSM performance can be greatly improved by adding zero padding, resulting in 6.5% percent of data-rate sacrifice for described system parameters.

V. CONCLUSION

Overall, OTSM system can be described as an alternative to OFDM, which shows great potential in Rayleigh fading channel in presence of Doppler shift. Performance improvement is achieved due to zero padding, or, in other words, due to guard delay between blocks, resulting in loss of data-rate, comparing to equivalent OFDM system. OTSM performance can be improved more by designing more complex equalizer, that can be a topic for future studies.

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