Journal of Artificial Intelligence, Machine Learning and Neural Network
ISSN:2799-1172
Vol: 02, No. 06, Oct-Nov 2022
http://journal.hmjournals.com/index.php/JAIMLNN
DOI: https://doi.org/10.55529/jaimlnn.26.13.23

Study and Analysis of OTFS and OFDM

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Received: 08 August 2022 **Accepted:** 24 October 2022 **Published:** 28 November 2022

Abstract: High mobility wireless communication systems have been proposed to be robust to channel-induced Doppler shift using Orthogonal Time Frequency Space (OTFS) modulation. The OTFS modulation technique is described in this paper. In addition to being in the delay-Doppler (DD) domain, OTFS has a unique and important feature. The OTFS modulation offers maximum diversity over frequency and time when coupled with an equalizer. This technique converts fading, time-varying wireless channels into time-independent, non-fading interactions that reveal their underlying geometry. Even in challenging 5G deployment settings, OTFS achieves Massive MIMO throughput gains by scaling throughput linearly with MIMO order. An analysis of peak to average power ratio (PAPR) of OFTS modulation wave forms is presented in this paper. OTFS with rectangular pulses is characterized analytically using the complementary cumulative distribution function (CCDF). The simulated CCDF for the PAPR of OTFS is compared with that for orthogonal frequency division multiplexing (OFDM) for different pulse shapes. The results show that OTFS has a better PAPR than OFDM.

Keywords: 5G, Delay-Doppler (DD), Doppler Shift, Modulation, PAPR, OTFS, OFDM.

1. INTRODUCTION

The existing wireless communication infrastructures are saturated as a result of the growing demand for wireless applications and the exponential growth in the number of internet-enabled users. Researchers and network designers are urged to create answers for these fundamental problems by guaranteeing ultra-high data speeds, ultra-wide radio coverage, a large number of coupled devices that are incredibly efficient, and minimal latency [1]. The growth of 5G of wireless networks will be facilitated by wireless network solutions utilizing clever and effective technology. The 5G standard has to be ready to handle significant obstacles in order to create a secure, dependable, and effective 5G network. Several wireless networks use OFDM for downlink communication. They are perfect for usage with challenging channels since they are adaptable [2]. It's a wise decision to employ OFDM for 4G communications. However, the fundamental drawback of OFDM is its PAPR, the PAPR can be decreased using a variety of techniques. It is anticipated that next-generation wireless communication technologies would offer high-speed, reliable connectivity even at very high mobile speeds [3]. However, the OFDM-based modulation waveform utilized in 5G communication systems is known to impair communication reliability and data throughput in high mobility scenarios. OTFS modulation has recently been presented as being more resilient to channel-induced Doppler shift [4-6] compared to OFDM. Information is encoded in the DD domain in OTFS modulation. After that, a time domain (TD) transmit signal is created from the information-carrying DD signal. The received TD signal is changed at the receiver into a DD domain signal, which is then used to decode the information symbols [7].

In mathematics and science, the DD representation of signals has a long history. [8] Provides a fantastic basic introduction to the Zak transform. Bello's landmark work [9] provides a detailed description of the DD representation of time-varying channels; generalizations to directional time-varying channels, which are pertinent to multiple-antenna systems, were provided in[10-11]. A number of articles have recommended the use of time-frequency(TF) diversity transmission since the 1990s. The signal model presented in references[13-14] constructed a DD RAKE receiver that takes use of the dispersion in both dimensions and displays the received signal as a canonical decomposition into delay and Doppler shifted versions of a base signal. These concepts are expanded upon for the situation of many antennas in[12]. In [15], guard intervals are built for the frequency domain. These papers all take a different approach from OTFS in that they all construct their systems in the TF domain as opposed to the DD domain. Based on the initial description of OTFS in [16], several follow-up papers by various organizations have been produced. Various forms of streamlined receiver layouts are proposed in references [17] through [18], mostly based on iterative methods. In [19-20], there is some discussion of a discrete signal model, modulator design, and performance analysis. In [21] discusses the diversity order that may be achieved with various block coder architectures. The theoretical development is more thorough in the current study. We anticipate that it will inspire additional community investigation of different system aspects. In particular circumstances when the dispersion is at a high frequency, OTFS offers a number of benefits. These types of environments are common in mm-wave systems because of the increased phase noise and bigger Doppler spreads. Recently, it has also been suggested to use OTFS waveforms for RADAR[22].

A newly proposed two-dimensional(2-D) modulation method called OTFS modulation multiplexes information symbols using the DD domain[23]. When compared to traditional multicarrier approaches, bit error performance is enhanced by OTFS' use of operations for pre- and post-processing in traditional multicarrier modulation(MCM) methods. Additionally, a multipath channel with rapid temporal fluctuations will show sluggish variations in the DD domain. A multipath channel is time invariant for a longer amount of time when represented using DD as opposed to TF. This can lower the channel estimate cost in a rapid time-varying channel and enable OTFS evaluation of the channel less often. When OTFS modulation was inaugurated in [24], it was demonstrated that for vehicle speeds as high as 500km/h, it had much better error performances than OFDM systems. Several papers on other OTFS modulation-related topics have since been published [25-31]. Given that OTFS is a novel modulation method, it is important to comprehend its PAPR features. There has not yet been a formal PAPR evaluation of OTFS described. The CCDF of the PAPR of the OTFS for rectangular pulse shape is also analytically calculated. The CCDF simulation results for additional pulse forms are obtained. We examine the OFDM with OTFS. Our results demonstrate that OTFS has lower PAPR than OFDM.

OFDM

The fundamental block diagrams of OFDM shown in figure 1. R.W. Chang developed the fundamental ideas of OFDM. Interference inside the channels is prevented when the bands of orthogonal signals considerably overlap. In order to transport data over a variety of frequencies, we may employ OFDM to construct a number of subcarriers[32]. These subcarriers need the use of orthogonal functions. The mathematical definition of an orthogonal function is one where the integral over a given time interval is equal to 0. Because their transmission routes are frequency selective, broadband signals are often constrained. A technology called OFDM can be used to overcome a frequency selective channel. By splitting the complete bandwidth into N sub-bands with the same spacing in OFDM, a frequency selective channel is transformed into N frequency flat channels. Since orthogonal carriers are used for modulation, there is no interference between them[33]. This criterion is met at the transmitter using IFFT. The information is recovered by the receiver using FFT. The OFDM waveform's broad sideband means that a guard band will be left over to choose the following channel. Guard bands make OFDM spectrally inefficient. By selecting the best modulation schemes, it is possible to increase bandwidth efficiency and minimize multipath fading in wireless technology[34-36]. One of the greatest methods for attaining these goals is OFDM. In this instance, a high PAPR resulted in an inefficient radio frequency portion that in turn caused an inefficient transmitter section. OFDM is a well organized and effective 5G modeling methods, in addition to being more efficient and requiring less time. A significant problem with OFDM is that its PAPR is greater. The ability of OFDM receivers to perceive nonlinear devices, such as digital amplifiers and HPA[37]. When an OFDM signal is split into N subcarriers, the resulting complex baseband representation is as follows:

$$s(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} S_n e \frac{j2\Pi nt}{N}; 0 \le t \le N-1$$

In this case, $S=[S_0, S_1, S_2, \ldots .S_{N-2}, S_{N-1}]^T$ and t represent an input symbol sequence and a discrete time index, respectively.

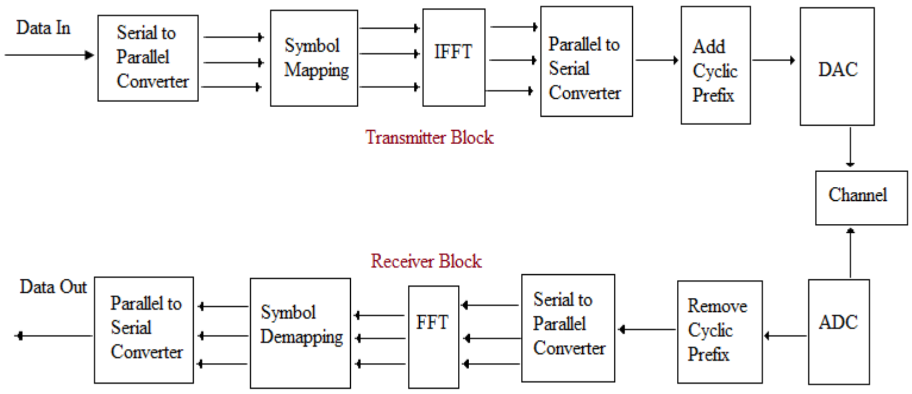

Figure 1. Block diagrams of OFDM

OTFS

OTFS utilizes a group of basic functions that are orthogonal to both time and frequency changes to operate in the DD coordinate system. In this coordinate system, both data and reference signals or pilots are conveyed. The wireless channel's geometry is mirrored in the DD domain, where changes occur much more gradually than in the quickly changing TF domain. Strong Doppler conditions cause OTFS symbols to experience the entire range of the channel across time and frequency, trading delay for efficiency. The modulation and demodulation processes, as well as the modulation's effects on the channel, are shown in Figure 2. A 2-D Symplectic Fourier Transform (SFT) is used to transform the transmit information symbols from the 2-D DD domain to the TF domain. In OTFS, on the other hand, each QAM symbol is dispersed throughout this TF plane using a separate basis function. As a result, every symbol with the same power experiences the exact same channel and has the same SNR. The consequence is that there is no frequency or time selective fading of QAM symbols when the proper frequency and time observation window is used. The signal is then routed through a multicarrier filter bank, providing the same benefits of filter shaping as other types of filtered OFDM[40]. The reverse processing is done at the receiving end.

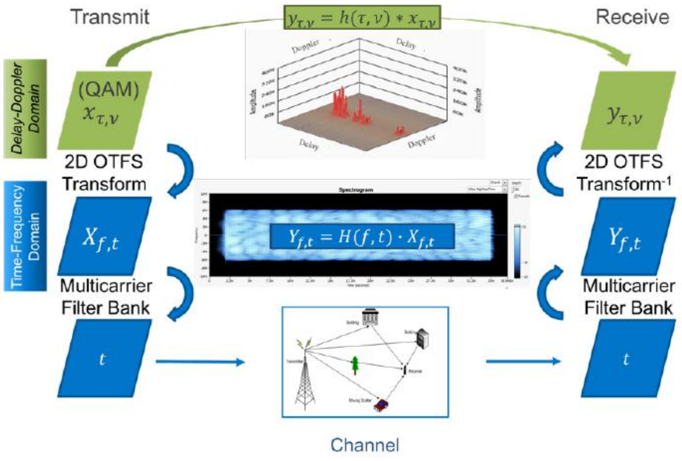

Figure 2. OTFS Processing

The relationship between the channel and the transmit signal is also depicted in Figure 2. The wireless channel's physical structure, which comprises of a transmitter, a receiver, and several reflectors, is seen in the lower graphic. The central figure displays a spectrogram2 of a high-speed, high-delay spread channel's time-varying frequency response. It is clear that this intricate channel has both high frequency and high time selectivity. The connection between the signals that are sent and received in this domain is multiplicative. The DD domain of the same channel is depicted in the top graphic[38]. The channel is monitored in this domain over a longer observation period, and it is modeled by a condensed DD impulse response. With the use of the OTFS Simplistic transform, the channel's multiplicative action is changed into a 2-D convolutive interaction with the transmitted QAM symbols.

The diagram of OTFS modulation designed over a generic MCM system is shown in Figure 3. The information symbols are represented as points in a 2-D DD grid at the OTFS transmitter, and they are then translated using the 2-D inverse symplectic finite FT to the TF plane (ISFFT). A MCM technique is then used to process the newly received TF signal. Heisenberg transform is used to convert the TF signal into a TD signal for transmission. The linear time variant channel is used to communicate the Heisenberg transform's output. At the receiver, the Wigner transform is employed to turn TD signals received into TF domain, which is then transferred back to DD domain symbols[39]. The TD signal produced by the Heisenberg transform at the transmitter must be amplified before it can be sent over the wireless channel. Because of this, it is important to describe the PAPR of this TD signal. In a specific packet burst, the sent signal using OTFS modulation has a length of NT and uses bandwidth BW=M/T= M.Δf. The information symbols are represented by s[p,q]; where p = 0 to N-1 and q=0 to M-1; No. of Doppler bins are N and no. of delay bins are M (multicarrier system with M subcarriers).

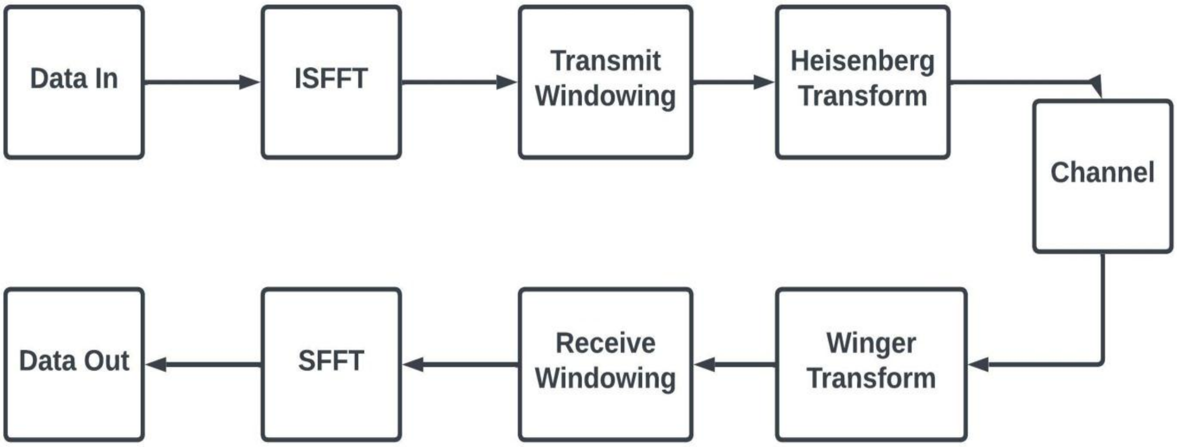

Figure 3. OTFS modulation scheme

The transmitter converts these symbols from the DD domain to the TF domain using the ISFFT, and it is provided by

$$S[k,l]=\sum_{p=0}^{N-1}\sum_{q=0}^{M-1}s[p,q]\,e^{-j2\Pi\left(\frac{lq}{M}-\frac{kp}{N}\right)} \tag{1}$$

The ISFFT output TF signal is then transformed using the Heisenberg transform into a TD signal for transmission and given by

$$x(t)=\sum_{k=0}^{N-1}\sum_{l=0}^{M-1}S\left[k,l\right]f\left(t-kT\right)e^{j2\Pi l(t-kT)\Delta f} \tag{2}$$

Here f(t) is the prototype pulse shape of length NT. Samples having a sampling rate of $F_s=1/T_s=B$ can be used to produce the discrete time representation of (2), given by

$$x\left(rT_s\right)=\sum_{k=0}^{N-1}\sum_{l=0}^{M-1}S\left[k,l\right]f\left(rT_s-kT\right)e^{j2l\Pi(rT_s-kT)\Delta f} \tag{3}$$

Here r = 0 to MN-1. The representation of the samples x(r) as an N×M matrix with entries represented by s(a, b) such that r = b+aM, where b=0 to M-1 and a=0 to N-1.
Substituting r = b + aM and (1) in (3),

$$x\left(b+aM\right)=\sum_{k=0}^{N-1}\sum_{l=0}^{M-1}\sum_{p=0}^{N-1}\sum_{q=0}^{M-1}s[p,q]e^{-j2\Pi\left(\frac{ql}{M}-\frac{pk}{N}\right)}f\left(\left[b+aM-kM\right]MN\right)e^{\frac{j2\Pi l(b+aM)}{M}} \tag{4}$$

A simpler version of (4) is

$$x\left(b+aM\right)=\sum_{p=0}^{N-1}\sum_{q=0}^{M-1}s[p,q]\sum_{l=0}^{M-1}e^{\frac{j2\Pi l(b-q)}{M}}\sum_{k=0}^{N-1}f\left(\left[b+aM-kM\right]MN\right)e^{\frac{j2\Pi kp}{N}} \tag{5}$$

$$x\left(b+aM\right)=M\sum_{k=0}^{N-1}\sum_{p=0}^{N-1}s[p,b]e^{\frac{j2\Pi kp}{N}}f\left(\left[b+aM-kM\right]MN\right) \tag{6}$$

The PAPR of a discrete time sample of an OTFS transmit signal is described as

$$P_{APR}=\frac{\underset{b,a}{Max}\left\{\left|x\left(b+aM\right)\right|^2\right\}}{\frac{1}{MN}\sum_{b=0}^{M-1}\sum_{a=0}^{N-1}E\left\{\left|x\left(b+aM\right)\right|^2\right\}} \tag{7}$$

The CCDF of PAPR is $P(PAPR>\gamma)\approx 1-\left[1-e^{-\gamma}\right]^{MN}$ (8)

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2. SIMULATION RESULTS

A simulation of an OTFS system is presented in this section to illustrate how it performs, OFTS and OFDM are compared. Figure 4 shows the PAPR of OTFS with pulse shaping. The system parameters are M=256, N=8 and 16-QAM. When CCDF=10^{-3}, the PAPR with Gaussian pulse is 12.2dB and Rectangular pulse is 11.3dB. We observe that the PAPR of the OTFS with rectangular pulse is lower to that of the Gaussian pulse.

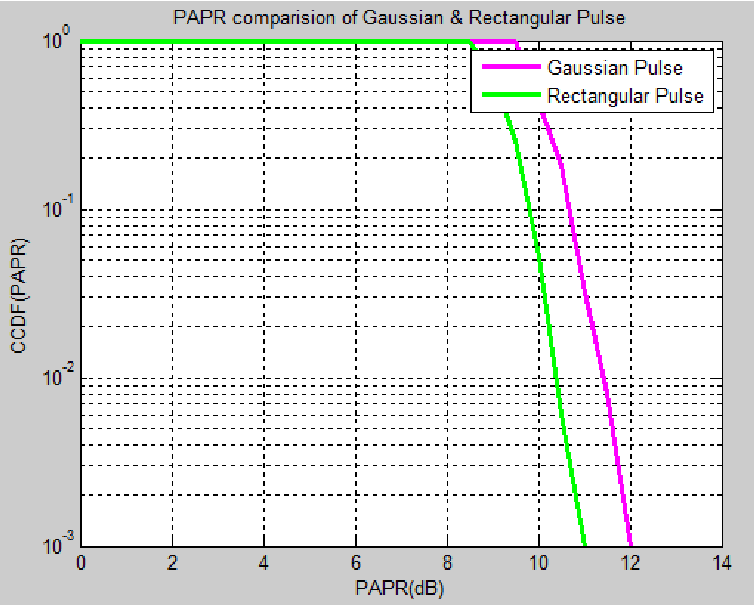

Fig. 4: PAPR of Gaussian & Rectangular pulse shapes

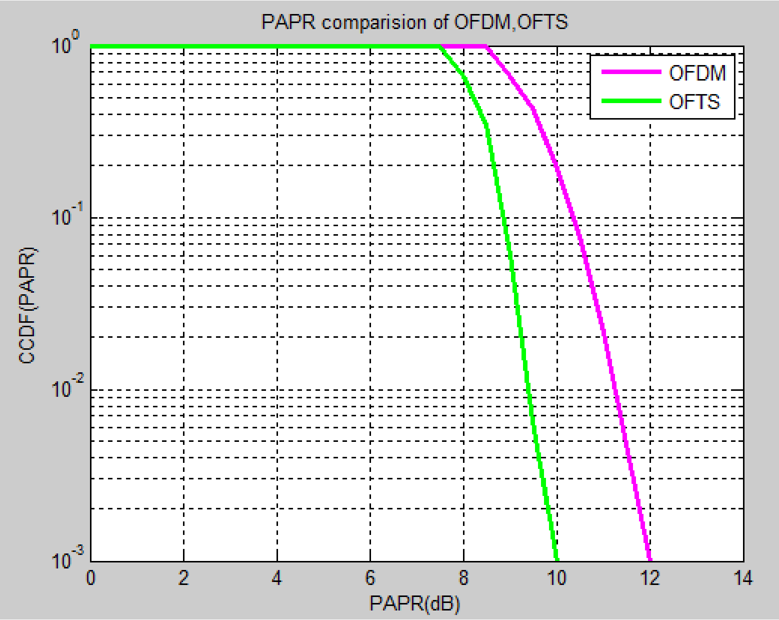

Figure 5. PAPR : OTFS vs OFDM

We examine the PAPR of OTFS with OFDM in Figure 5. The system parameters are M=256, N=4, an oversampling ratio=4 and 16-QAM. At a probability of 10^{-3}(CCDF=10^{-3}), the PAPR of OFDM is 12.13dB and OFTS is 10.1dB. We observe that the PAPR of the OTFS is lower than OFDM.

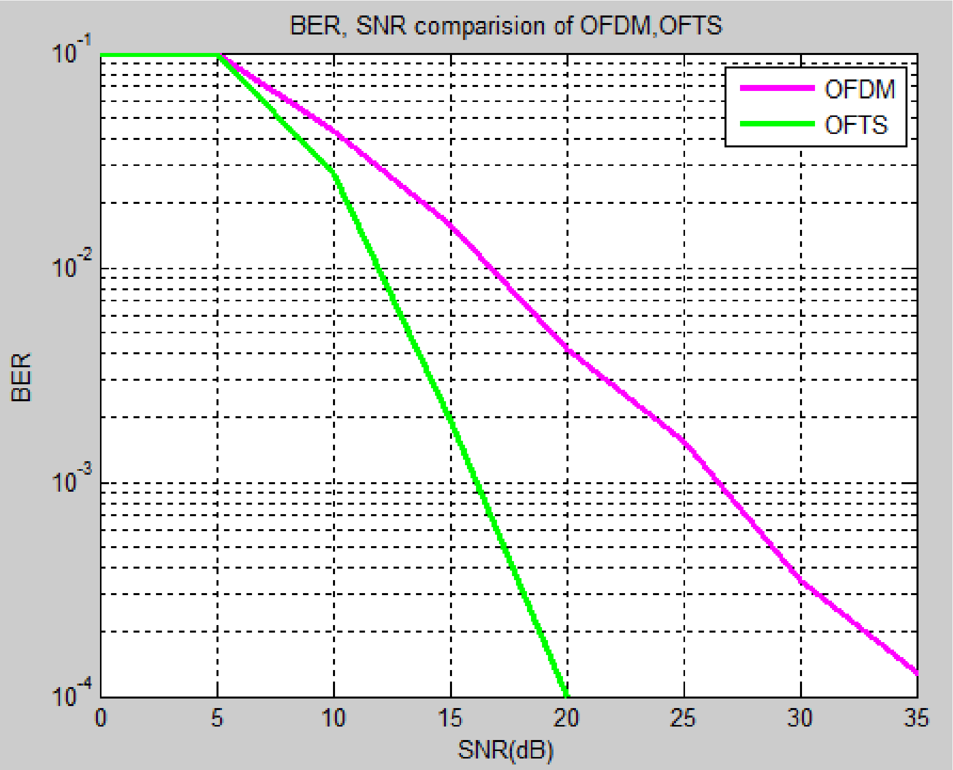

Figure 6. SNR vs BER of OFDM, OFTS

3. CONCLUSION

Doppler effects in wireless communications have been addressed using OTFS modulation. In this study, we created OTFS, a brand-new 2-D modulation scheme with considerable performance improvements for wireless communications. The DD coordinate system is used by OTFS. With significant spectrum efficiency benefits in high order MIMO and high Doppler settings, OTFS is a novel air interface paradigm. Efficiency in pilot packing of reference signals for channel estimation and prediction is another benefit of OTFS. Depending upon the fundamental multicarrier components, OTFS has a natural design compatibility with OFDM. The higher delay of DD domain modulation comes at the expense of Doppler shift stability. In order to maximize diversity gains for radar processing, OTFS spreads the transmitted signal across the entire TF range. OTFS has a shorter transmission time than OFDM because it uses a less number of cyclic prefix. The characteristics of OFDM can be demonstrated with OTFS. It has been demonstrated that OTFS has much lower BER and PAPR than OFDM. Performance of OFTS is better than OFDM.

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