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OTFS Waveform Effectiveness in 6G Communication Networks

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Abstract*- Recently, the Orthogonal Time Frequency Space (OTFS) waveform has been suggested for use in the Fifth Generation (5G) and continues to be used in the Sixth Generation (6G) communication networks. The main feature of OTFS is the utilization of the Delay-Doppler (D-D) domain for symbol representation based on channel geometry. Through the use of the D-D domain, a multipath time-varying fading channel is transformed to a non-fading time-invariant channel (similar to the Additive White Gaussian Noise (AWGN) channel in terms of effects on the signal). The investigation of OTFS waveform is presented in this paper. The main novelty in this study is the utilization of the 6G specifications that have not been used previously. The performance results in terms of Bit Error Rate (BER) successfully accomplished acceptable characteristics for various OTFS design parameters specified for 6G networks. The OTFS BER obtained outperforms OFDM by about 3 dB, and the OTFS Peak to Average Power Ratio (PAPR) is about 1.3 dB lower than OFDM.

***Index Terms*- OTFS, 6G, 5G, Delay-Doppler, OFDM, BER**.

I. INTRODUCTION

There has recently been a lot of interest in systems beyond Fifth Generation (5G), also known as sixth-Generation (6G) communication systems. 6G will boost such applications with higher system bandwidths to that seen in 5G with new physical layer techniques and higher layer capabilities not currently available. More spectrum, and especially frequencies utilization between 100 GHz and 1 THz, has become important for 6G to support higher data rates. Certain sub-bands within this band have extremely high absorption and are thus unsuitable for communication over distances greater than a few meters. Nonetheless, there are a number of spectrum blocks with existing services [1]. Due to the larger channel response variations within these frequencies and standardization of the frame shape for the 6G, the physical layer waveform is the more important issue. Lattice domain will be used in 6G rather than Time-Frequency (T-F) representation to increase the numerology options [2]. Orthogonal Time Frequency Space (OTFS) waveform candidates to use in the 6G to suppress the time-varying dynamics of the multi-path channel [3], which was first proposed in [4]. The channel response is required to detect the OTFS signal on the receiving side. The Delay-Doppler (D-D) domain is a contrasting representation of the geometry of a time-varying channel caused by moving objects [5]. In comparison to multicarrier modulations, which represent the information in the T-F domains, the multiplexing of constellation symbols in the D-D coordinate offers delay resilience and improved robustness against high Doppler shifts [6]. Using the D-D domain enables the OTFS to extract full diversity, where full diversity means the multipath components distinct in the dimension of delay or Doppler. OTFS waveform can be considered as a set of pre and post processing blocks for multicarrier modulation, thus allow to compatible with previous generation waveform [7]. The OTFS will combine the characteristics of three main waveforms Orthogonal Frequency Division Multiplexing (OFDM), Carrier Sense Multiple Access (CSMA), and Time Division Multiple Access (TDMA) [8]. The authors in [4] first proposed the new two-dimensional modulation technique known as OTFS. According to simulation results, OTFS outperforms OFDM by a few decibels or more in terms of block error rate. Furthermore, these results demonstrate that, also at higher Dopplers (500 kilometer per hour), OTFS scheme channel capacity with linear scaling of gain information with Multiple Input Multiple Output (MIMO) order while the OFDM performance under the representation design specifications fails totally. In [9], the authors assess the performance of OTFS in millimeter wave. In a variety of scenarios, the results show that OTFS has a lower BER than OFDM. Using pilot symbols, the OTFS modulation-based channel estimation was investigated in [5]. The results show that even with non-ideal channel estimation, the proposed OTFS scheme outperforms OFDM with ideal channel estimation. In [10], the impact of phase noise on the behavior of OTFS scheme in millimeter wave transmission was studied. The results of the signal detection algorithm demonstrate that, at higher Doppler channels, OTFS is less sensitive to phase noise than OFDM. The authors in [7] present the diversity formulation analysis attained by OTFS scheme as well as supporting simulations. Higher diversity achievement has been observed in the limited Signal to Noise Ratio (SNR) system prior to the diversity one system taking over, and the diversity one regime begins with lower BER measurements for larger frame sizes. To capture full diversity, a phase rotation approach based on transcendental numbers was suggested. The diversity analysis and results for MIMO-OTFS also included. In [11], the OTFS diversity using rectangular waveforms and a two paths D-D channel was investigated. The results show that with relatively larger signal constellations, the OTFS can achieve full effective diversity. The authors in [12] proposed a low-complexity linear equalizer for OTFS that utilizes the structure of the appropriate channel matrix. The suggested model gives accurate minimum mean square error (MMSE) and zero-forcing (ZF) solutions. The suggested method can offer low complexity for local search strategies to achieve an improvement in the performance of bit error. In [13], the authors was presented the most recent developments in OTFS modulation in a more straightforward manner. The OTFS performance also been compared to other modulation schemes in terms of evaluation parameters such as BER, Peak to Average Power ratio (PAPR), and SNR. The authors in [6] performed a comprehensive evaluation of OTFS scheme in the airborne network of high Doppler. The results show that OTFS can accommodate the higher Doppler frequencies of larger relative speeds between airborne frameworks, operation frequencies, and bandwidths while maintaining a bit error profile. The OTFS scheme with a reflection channel of two-ray and MIMO-OTFS offers a reliable airborne network with limited BER.

In this work, the transmitter and receiver sides of the OTFS scheme are constructed. This work employs new design specifications that have not been used in previous studies. The 6G specifications are used for performance investigations, such as the use of very high carrier frequencies, the highest vehicle speed for the 6G (1000 km/h), and the use of the highest Quadrature Amplitude Modulation (QAM levels).

II. OTFS WAVEFORM MODEL

OTFS is a 2-Dimentional waveform that arranged the modulated symbols into D-D coordinate. The main feature of the OTFS is to convert the time-varying fading channel to an invariant non-fading channel resulting better performance in bit error compared to the conventional multicarrier systems [10]. OTFS can handle the extreme Doppler channels that is useful for point-to-point communication, high speed train and other applications [8].

A. Delay-Doppler Representation

In wireless communication, the signal at the receiver is a copies of the transmitted signal, and each copy has a time delay (τ) and Doppler shift (υ) due to the reflectors. The D-D plane at the transmitter represents the geometry of the mobile channel, where each of the transmitted constellation symbols arranged in the D-D grid. The D-D used to cancel the effect of the channel in terms of delay and Doppler shift. Fig. 1 represents the relationship between the T-F domain and D-D domain, where D-D domain signal transform to T-F signal through the 2-Dimensional Symplectic Finite Fourier Transform.

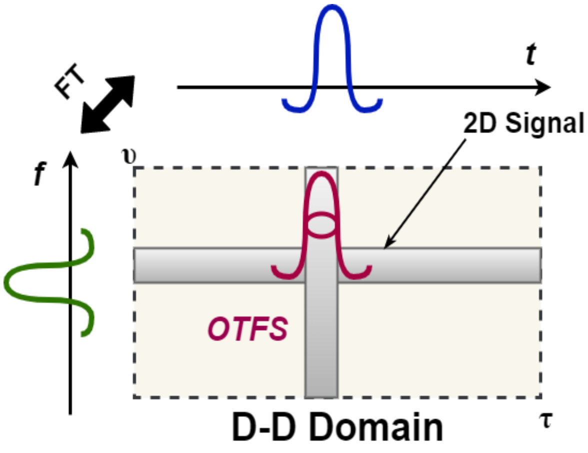

Fig. 1. Delay-Doppler plane relation to time-frequency plane

B. *OTFS Block Diagram*

Fig. 2 illustrates the OTFS modulation block diagram. At the transmitter side, the QAM symbols are placed over the D-D grid $x[k,l]$, where l is the index of delay domain and k is the index of Doppler domain index. The 2-dimensional Inverse Symplectic Finite Fourier Transform (ISFFT) is performed to the D-D symbols to generate the T-F signal representation $X[n,m]$ [6]:

$$X[n,m] = \frac{1}{\sqrt{NM}}\sum_{k=0}^{N-1}\sum_{l=0}^{M-1} x[k,l]\, e^{j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \quad (1)$$

where n and m are the indices of the time and frequency domain, respectively.

Finally the signal is converted to the time domain representation $s(t)$ through the Heisenberg Transform with suitable transmit pulse $g_{tx}(t)$ to be transmitted over the wireless channel.

$$\boldsymbol{s}(t) = \sum_{n=0}^{N}\sum_{m=0}^{M} X[n,m]\, g_{tx}(t-nT)e^{j2\pi\Delta f(t-nT)} \quad (2)$$

where, T and Δf is the time and frequency sampling intervals, respectively. On the receiving side, the received signal $r(t)$ can be obtained as:

$$r(t) = \int H(t,f)S(f)e^{j2\pi ft}df \quad (3)$$

where, $H(t,f)$ is the time varying channel transfer function and $S(f)$ is the frequency domain of the transmitted signal $s(t)$.

After that the signal is transformed back to the T-F representation $Y[n,m]$ through Wigner filter $g_{rx}^{*}(t)$ that is respect to $g_{tx}(t)$.

$$Y[t,f] = \int g_{rx}^{*}(t'-t)\; r(t')e^{-j2\pi f(t'-t)}dt' \quad (4)$$

The T-F signal $Y[n,m]$ is obtained by sampling the $Y[t,f]$ signal in time $t = nT$ and frequency $f = m\Delta f$.

To demodulate the received QAM symbols, the T-F signal is converted to the D-D representation $Y[k,l]$ using the Symplectic Finite Fourier Transform (SFFT).

$$Y[k,l] = \frac{1}{\sqrt{NM}}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} Y[n,m]\, e^{-j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \quad (5)$$

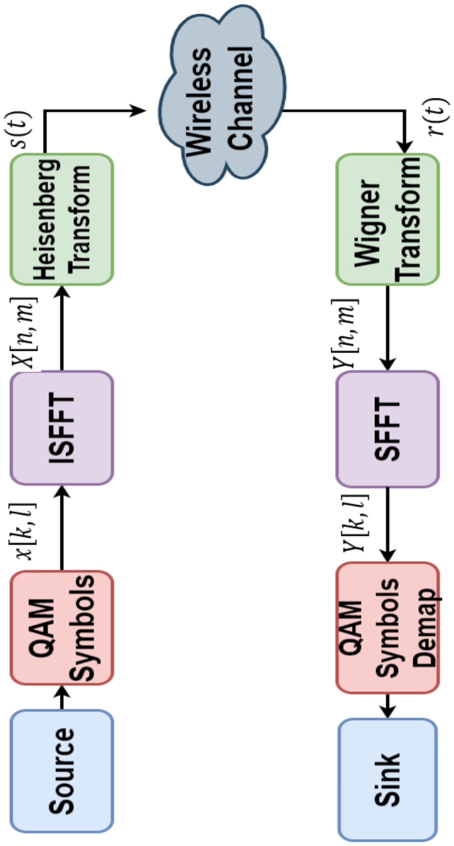

Fig. 2. OTFS block diagram

III. SIMULATION RESULTS, ANALYSIS AND COMPARISONS

The OTFS waveform is designed to evaluate its performance for 6G communication networks with various simulation parameters. The waveform is designed based on the block diagram shown in Fig. 2 and Table 1 listed the parameters of simulation.

Table 1: OTFS simulation parameters

Parameter	Setting
M and N	8, 16, 32, 64
QAM level	16, 32, 64, 128
Channel Tap	4, 6, 8
Frequency (f GHz)	90, 95, 140
Max Speed (km/hr)	500, 1000
Subcarrier space (Δf)	15 KHz

The first simulation part compare the Bit Error Rate (BER) performance between the OTFS and OFDM as shown in Fig. 3. It can be noticed that the OTFS outperform OFDM at higher SNR values of about 3 dB.

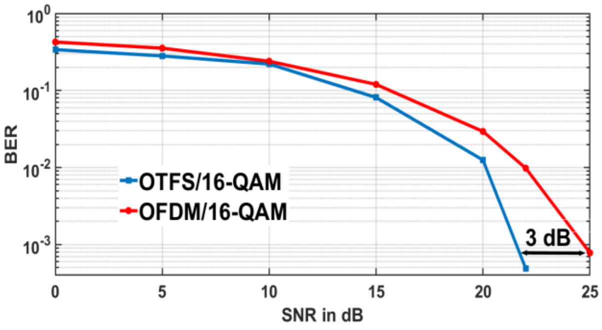

Fig. 3. BER comparison between OTFS and OFDM

The second part of simulation involved changing the QAM levels to evaluate the performance of the OTFS modulation. Fig. 4 illustrates the BER performance for various QAM orders. It can be seen that the OTFS BER at higher QAM levels is clearly worse than lower levels.

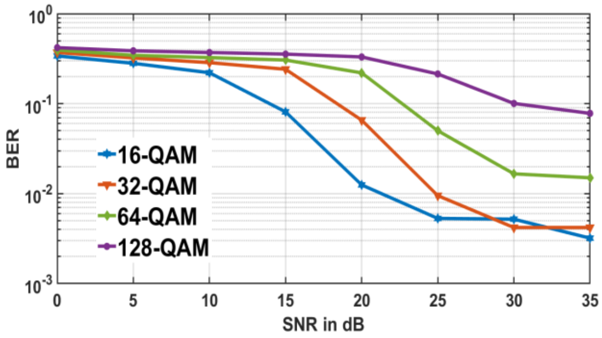

Fig. 4. BER of OTFS for various QAM levels

The third simulation part assesses the performance of the OTFS modulation for various numbers of symbols (N) and subcarriers (M). Fig. 5 illustrates the BER curves of the OTFS for various N and M states. It can be noticed that at lower SNR the OTFS BER curves have the same performance, while at higher values the BER curves at higher N and M values are better. Higher M values enhance the performance and the effects of M higher than N values.

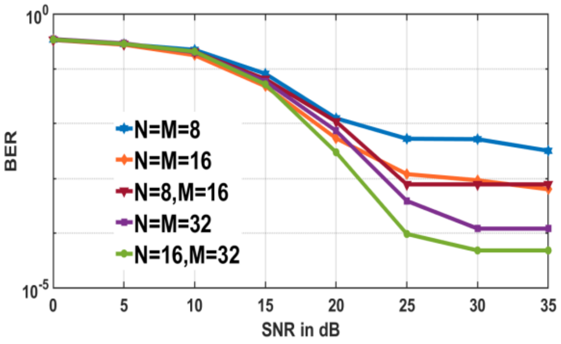

Fig.5. BER of OTFS for various numbers of symbols and subcarriers

The fourth simulation part depends on changing the number of channel taps for the OTFS system. The BER curves shown in Fig. 6 for various channel taps indicate that at lower SNR values, the OTFS has the same performance. At higher SNR values, the performance is different, where the higher taps provide better performance.

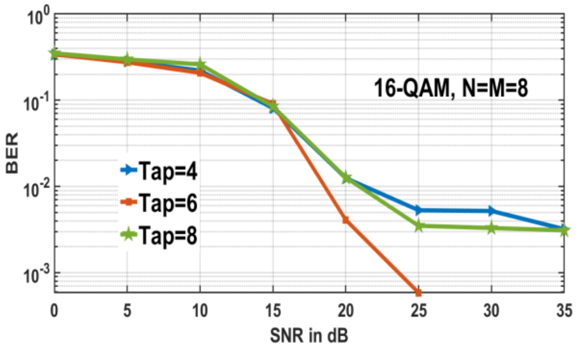

Fig. 6. BER of OTFS for various channel taps

The spectrum of 6G networks includes some sub-Terahertz spectrum windows. Fig. 7 depicts the OTFS BER curves for various candidate frequencies. It can be observed that the BER is worse at higher frequencies than at lower frequencies.

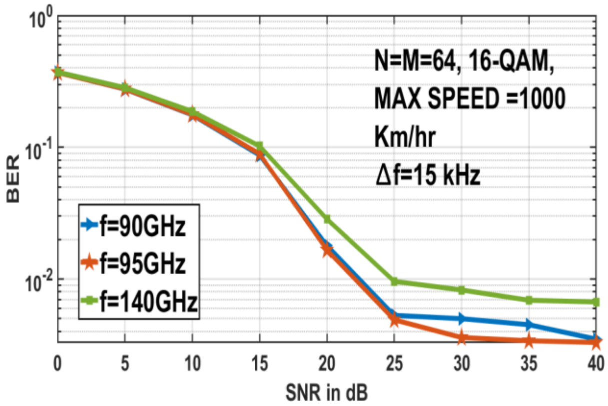

Fig. 7. BER of OTFS for various operation frequencies

The BER performance of the OTFS is evaluated at the maximum user speed that has been identified for the 6G system. Fig. 8 compares the OTFS BER at 1000 km/hr and 500 km/hr maximum speeds for 6G and 5G, respectively. It can be noticed that the BER at lower SNR values, the two performances are the same, while at higher SNRs, the performance is worsened at 6G speed.

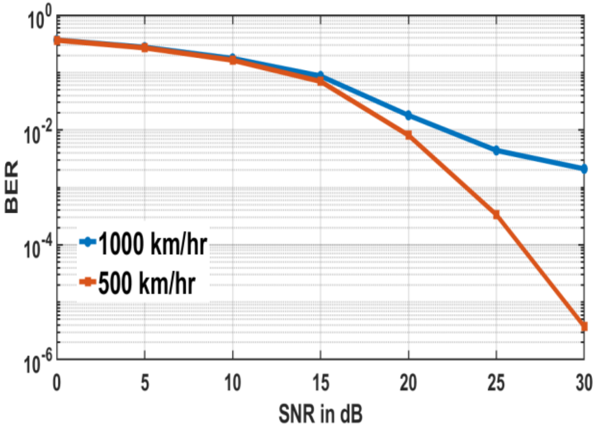

Fig. 8. OTFS BER comparable between 6G and 5G maximum speeds

Table 2 compares the performance of the designed OTFS and some relevant works to that of the OFDM in terms of BER. As can be seen, all previous studies and the obtained results show that the OTFS BER is superior to that of conventional OFDM. The third column exhibits the maximum BER achieved in this work and in previous literature. It can be noticed that there are differences between the BER values. This is due to the utilization of various QAM levels, carrier frequencies, and also different speeds. Table 3 compares some OTFS simulation specification to that in relevant literature in terms of carrier frequencies, modulator type, level, and maximum vehicle speed. Fig. 9 compares the difference BER values between OTFS and OFDM for this work and previous literature. It can be seen that the designed OTFS accomplished 3 dB less BER than that of OFDM.

Table 2: OTFS BER comparisons with some relevant works

Reference	OTFS BER compare to OFDM (dB)	OTFS Maximum BER
[4]	2.5 lower	10^{-2}
[5]	8 lower	9×10^{-4}
[7]	10 lower	10^{-6}
[9]	8.5 lower	10^{-5}
[10]	4 lower	2×10^{-6}
[12]	7.5 lower	4×10^{-4}
This work	3 lower	9×10^{-3}

Table 3: OTFS specifications comparisons with some relevant works

Reference	Carrier frequency (GHz)	Modulator type and Level used	Maximum speed (km/h)
[4]	Not specified	(4,16, 64)-QAM	30, 120, 500
[5]	4	4-QAM	120
[7]	4	BPSK,8-QAM	220, 500, 506.25
[9]	28	16-QAM	Not specified
[10]	4, 28, 60	Not specified	47
[12]	4	BPSK	Not specified
This work	90, 95, 140	(16, 32, 64, 128)-QAM	500,1000

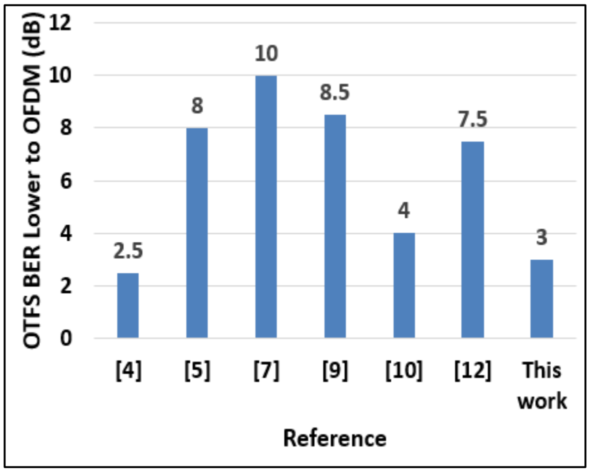

Fig. 9. OTFS BER compare to OFDM

Finally, the PAPR of the OTFS is compared to that of conventional OFDM at 16-QAM, N = 8, and M

= 8, as shown in Fig. 10. It is evident that OTFS has a lower PAPR than OFDM of about 1.3 dB.

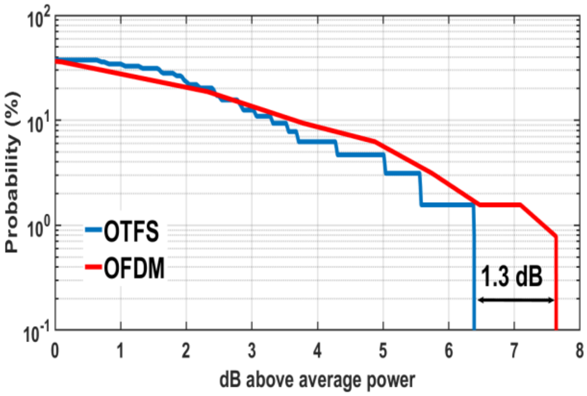

Fig. 10. OTFS PAPR comparison to OFDM

IV. CONCLUSION

This paper investigates the performance of the OTFS waveforms for 6G communication networks. The OTFS was designed and evaluated with several simulation variables such as in terms of modulation order, numbers of symbols and subcarriers, channel taps, operation frequencies, and maximum user speed. For the various design parameters, the OTFS BER curves achieved an acceptable simulation results with additional complexity at the receiver. Furthermore, the OTFS outperforms OFDM in terms of BER of about 3 dB and PAPR of about 1.3 dB. The OTFS is among the effective approaches for use in next-generation applications.

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