A Review on Orthogonal Time Frequency Space Modulation

Suresh Kumar[a] and Seema Deshwal[a]

[a] University Institute of Engineering & Technology, Maharshi Dayanand University, Rohtak, Haryana, India

Abstract

Orthogonal Time Frequency Space (OTFS) modulation scheme is an advanced modulation scheme having two-dimension widely used in futuristic wireless networks due to its high data rate, more flexibility and higher reliability. In high mobility cases OTFS provide better performance of connectivity. OTFS modulation operates in delay –Doppler domain while OFDM operates in time frequency domain. This paper provides an overview of OTFS operating in delay Doppler domain with its advantage and disadvantage. This modulation scheme has numerous applications in next generation network such as drone communication, communication in hilly area, high speed mobility such as railway communication and vehicle to vehicle communication. This paper presents the latest developments in OTFS modulation in a simpler and easy way. Performance comparison of OTFS with other modulations schemes has also been presented in the terms of evaluation parameters like: BER, PAPR and SNR.

Keywords 1

OTFS modulation, delay-Doppler domain, OFDM, Future wireless network, BER, PAPR, SNR.

1. Introduction

In future we are expecting wireless networks to meet the requirement of higher mobility to support user equipment. It is expected to have the speed up to 300Km/hr for automobile connections and up to 550Km/hr in railways network connection applications. New emerging high-speed vehicle scenarios such as high-speed railway communication, drone communication, communication in hilly regions, vehicle to vehicle communication will be engineered based on OTFS [1]. In wireless communications, due to the hostile channel variation at high carrier frequencies in high mobility scenarios is extremely challenging. Relying scheme will offer certain degree of robustness against variations in channels, which may be coherently adaptive or non- coherent in nature for detection [2]. For high mobility communication of future wireless network research attention has been increased and resulted in design of modified modulation waveform and schemes.

High-mobility communications mainly suffer from severe Doppler spreads operating at high carrier frequencies, which is mainly due to higher relative motion existence between the Receiver, Transmitter, and scatterers. Although, Orthogonal Frequency Division Multiplexing (OFDM) modulation suffers in high –mobility scenarios, which found wide application in 4G and 5G cellular system.

In a digital multicarrier modulation technique that consists on sending multiple subcarriers orthogonal to each other with overlapping spectra in the frequency domain. They carry data in parallel and are closely spaced. OFDM is resilient to selective fading, interference, and multipath effects due to low bit rate in each of its carrier. OFDM also have several challenges such as high Peak to Average Power Ratio (PAPR), sensitive to drift with carrier offset, and hence not found suitable for selective

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EMAIL: skvashist_16@yahoo.com (Suresh Kumar)
ORCID: 0000-0002-3679-1049 (Suresh Kumar)

fading channels. Currently a modified modulation scheme executed in two dimension and named as OTFS has been introduced in order to support the increased mobility communications [3].

OTFS modulation uses modulation in Delay-Doppler (DD) domain rather in Time – Frequency (TF) domain as done in OFDM. To support reliable communication OTFS provides strong DD resilience. In the DD domain OTFS modulation transforms a time-variant channel into a 2Dquasi-time-invariant channel. OTFS seems to have full potential for challenging fundamental research to overcome the problems in channel estimation together for detection, application of multi-antenna system and multi-user designs.

2. OTFS

OTFS is a modulation technique in two-dimension, which operates in DD domain. OTFS gives an output as non-fading, time independent channel on getting an input of fading time variant channel. Basic diagram of wireless network consists of transmitter and receiver, with multipath fading is shown in given figure1.

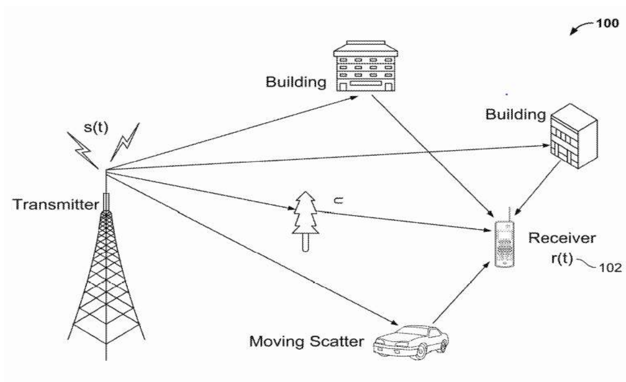

Figure 1: Wireless network with multipath fading between Tx and Rx

Let the signal transmitted is s(t) than signal received is r(t) be given by

$$r(t) = \iint h(\tau, v) e^{j2\pi v(t-\tau)} s(t-\tau) dv d\tau \quad (1)$$

Here $h(\tau, v)$= represents function for the channel spreading [it represents Fourier-transform of time-variant impulse response$h(\tau, \mathrm{t})$][4]. Where τ is for delay and v is for Doppler shift .

2.1. OTFS Transmitter and Receiver

Heisenberg transform which can be parameterized by function $h(\tau, v)$, is used for mapping the transmitted signal into received signal. OTFS modulation consists of a cascade of two 2- dimensional transforms for the Transmitter and Receiver. Basic block diagram for OTFS is shown in figure 2.

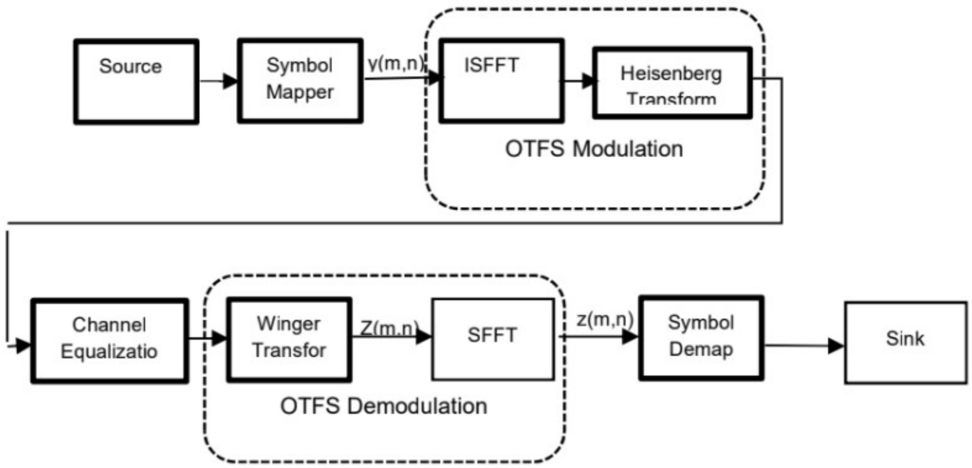

Figure 2: Block diagram of OTFS modulation: Transmitter and Receiver

In the first step, at the transmitter side the information symbol $y[n,m]$ reside in DD domain, which are designed to convert, time frequency domain using 2D Inverse Simplistic Fourier Transform(ISFT). This designing includes windowing and periodization with period (N,M): $Y[n,m]$=SFFT̄ $^{-1}(y[k,l])$ for

$$Y[n,m]=\frac{1}{\sqrt{NM}}\sum_{l,k}y[k,l]e^{j2\pi(\frac{nk}{N}-\frac{ml}{M})} \tag{2}$$

In equation (2) l=0, 1…. M-1and k=0, 1…. N-1.

While in the receiver side, SFFT of Y $[n, m]$ is used in inverse process, to obtain y $[k, l]$ = SFFT ($Y[n,m]$) for

$$y[k,l]=\sum_{n=0}^{N-1}\sum_{m=-\frac{M}{2}}^{\frac{M}{2}-1}Y[n,m]\,e^{-j2\pi(\frac{nk}{N}-\frac{ml}{M})} \tag{3}$$

The OTFS transform, combination of windowing and inverse SFFT is described further as under:

Subsequently, it is shown in the figure 2 that Heisenberg transform carry out the function to generate time domain signal s(t) from a time frequency signal as shown:

$$s(t)=\sum_{m=M/2}^{M/2-1}\sum_{n=0}^{N-1}Y(n,m)g_{\mathrm{t}}(t-nT)e^{j2\pi m\Delta f(t-nT)} \tag{4}$$

Where $Y=W_t * SFFT^{-1}(y)$,Whereas at transmitter W(t) represents the time -frequency windowing function. It can be described as Heisenberg operator having the parameter $X[n,m]$ applied to basic pulse of transmission $g_{\mathrm{t}}(t)$. It is also noticed that transmitted and received pulse follow the bi-orthogonality condition and is given by:

$$\int g_{\mathrm{t}}(t)g_{\mathrm{r}}(t-nT)e^{j2\pi m\Delta f(t-nT)}dt=\delta(m)\delta(n) \tag{5}$$

Thus, it is seen that received signal is the result of cascading of two Heisenberg operators operating on basic pulse. One of them is OTFS transform without modulation and the second is expressed due to interaction with channel. The parameter h_1 and h_2 are the cascading of two Heisenberg operators and used here to represent the two original operators in the form of twisted convolution.

$$h_1(\tau, \upsilon) * \sigma h_2(\tau, \upsilon) \;=\; \iint h_2(\tau', \upsilon')\, h_1(\tau - \tau', \upsilon - \upsilon') e^{j2\pi\upsilon'(t-\tau)} d\tau' d\upsilon' \tag{6}$$

Therefore, the received signal is given as

$$r(t) = \iint f\,(\tau, \upsilon) e^{j2\pi\upsilon(t-\tau)} g_{\mathrm{t}}(t - \tau) d\tau' d\upsilon' \tag{7}$$

In equation (7), $f(\tau, \upsilon)$ is called the Impulse response resulted from the combined transform.

$$f(\tau, \upsilon) \;=\; h(\tau, \upsilon) * \sigma Y[n.m] = \sum_{m=0.5M}^{0.5M-1} \sum_{n=0}^{N-1} Y[n, m] h(\tau - nT, \upsilon - m\Delta f) e^{j2\pi(\upsilon - m\Delta f)nT} \tag{8}$$

A cascaded combination of OTFS transform with the Wigner transform is performed at the receiver side. It means firstly the received basic pulse is used to filter the signal. Representation of this filtered signal in DD domain is given as

$$A_{g_{\mathrm{r}}}(\tau, \upsilon) \triangleq \int e^{-j2\pi\upsilon(t-\tau)} g_{\mathrm{r}}\,(t - \tau) r(t) dt \tag{9}$$

Above signal is sampled at $\tau = nT$ and at $\upsilon = m\Delta f$, therefore it becomes

$$A_{g_{\mathrm{r}}, \Pi_f(g_t)}(\tau, \upsilon) = f(\tau, \upsilon) * \sigma A_{g_r, g_t}(\tau, \upsilon) \tag{10}$$

Therefore, E2E channel may be denoted as

$$(\tau, \upsilon) = h(\tau, \upsilon) * \sigma X[n, m] * \sigma A_{g_r, g_t}(\tau, \upsilon) \tag{11}$$

At the receiver SFFT is performed (on the sample, windowed and then periodized of the signal Z) in order to get the signal. After demodulation, information sequence is received. This sequence is periodic convolution of two-dimensional input signals which are (i) QAM signal and (ii) sampled version of windowed impulse response.

$$\hat{y}[k, l] = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} y[n, m] h_w\left(\frac{k - n}{NT}, \frac{l - m}{M\Delta f}\right) \tag{12}$$

$$h_w\left(\frac{k - n}{NT}, \frac{l - m}{M\Delta f}\right) = \; h_w(\upsilon', \tau')\big|_{\upsilon' = \frac{k-n}{NT}, \tau' = \frac{l-m}{M\Delta f}} \tag{13}$$

Above equation the channel response is represented by circular convolution having a windowing function.

From all above equations it is noticed that each of the received symbol obtained has similar channel gain for each transmitted symbol, also for both DD domain it obtains the full diversity [5].

3. Latest Update in OTFS Field

- OTFS based matched filter algorithm which is used in radar system for determination of velocity and object range. It shows that radar processing depending on OTFS exhibits the basic inherent advantages because of multi carrier modulations but also provides better radar capability i.e., faster tracking rate, longer range and estimation of large Doppler frequency as compared to OFDM based radar [6].
- OTFS do offers improved PAPR comparing to OFDM and GFDM. This paper considers modulation symbols of an order of $M \times N$ DD grid (where M are representing number of delay bins and N denotes number of Doppler bins). The simulated CCDF gets represented for the PAPR of OTFS due to varying pulse shape in comparison to OFDM and GFDM [7].
- To reduce the PAPR, a modified version of ICF was formally suggested in pilot embedded OTFS. This idea is used to denote free degree offered due to guard region. The signal present in guard region varied with a small magnitude by providing afunctional design with proper filtering. The results show that PAPR can be reduced effectively with low BER performance loss.[8]
- OTFS modulation is beneficial for channels having high Doppler fading and large delay spread channels. It also gives vectorized image of OTFS system in existence of PA and IQI non-linearity. Twostep process is used to improve the BER performance at the Transmitter. However, at the Receiver impairments must be addressed and compensated to be high resilient to PA and IQI non-linearity in the mm-meter Wave band.[9]
- In [10], performance of OTFS is tested using common waveforms. It computes the error probability using discrete model of modulation/demodulation. It also discusses the level of diversity that can be attained on fading channels.
- In [11], OTFS assuming a delay-Doppler channel from two paths and rectangular waveform is studied. It also introduces the concept of Effective Diversity (ED) which is notably effective in comparison to standard diversity in order to transmit higher quantum of symbols. It also examines the condition for which OTFS attains full ED in case of all QAM symbols.
- In [12], it is shown that OTFS modulation uses a low complexity iterative rake detector. In it OTFS input-output relation is formulated and based on maximum ratio combining strategy. A linear complex iterative rake detector algorithm is proposed for OTFS. Here the BER performance achieved by MRC detector is like MPA detector but with small storage and complexity requirements.
- In [13], an E2E OFDM based OTFS model is presented in the form of vectorised shape, in which an oscillator having phase noise incorporated at the Transmitter and Receiver. It is also shown that in mm Wave band OTFS is having greater resilient in comparison to phase noise and Doppler shifts.
- In [14], an efficient message passing MP algorithm was proposed to cancel the ICI and ISI by using appropriate phase shifting. This algorithm is widely used for Doppler spreads. It also shows that error performance of OTFS is better than OFDM under different communication scenarios including low latency communication, ideal and non-ideal form of channel estimation etc.
- In [15], to minimize the receiver complexity of OTFS modulation a new type of detector is proposed, which is named as Variational Bayes Detector using the optimal MAP detection. It is observed that its complexity is lower than both MP and MAP receiver. It also confirms the superior detection and fast convergence as compared to MP algorithm.
- Zhiqiang Wei, who introduced a window design after analysing the effect of transmitter and receiver [16]. He found that after applying a window at both Tx and Rx an identical performance is achieved. Figure 3 shows that a DC window is applied to increase the channel sparsity by which channel estimation performance is improved.

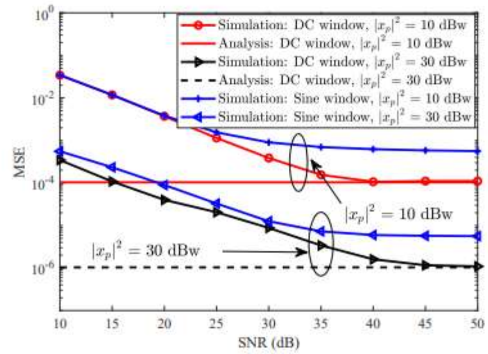

Figure 3: Comparison of performance of Channel estimation after applying DC window

- One of the major issues in OTFS is selection of receiver antenna for better performance. SIMO-OTFS and MIMO-OTFS are the basic parameter for selection of receiver antenna. The comparison shows that MIMO-OTFS have better performance as compare to SIMO-OTFS as given in figure 4(a) and figure 4(b)[17].

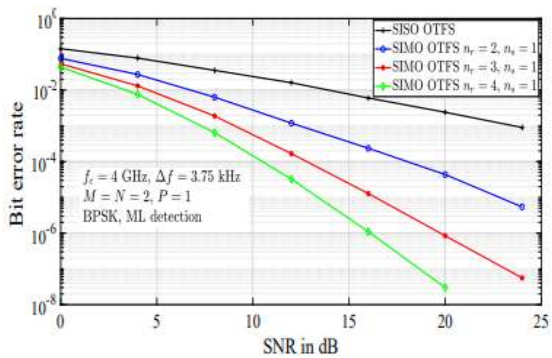

Figure 4 (a): BER performance of SIMO-OTFS

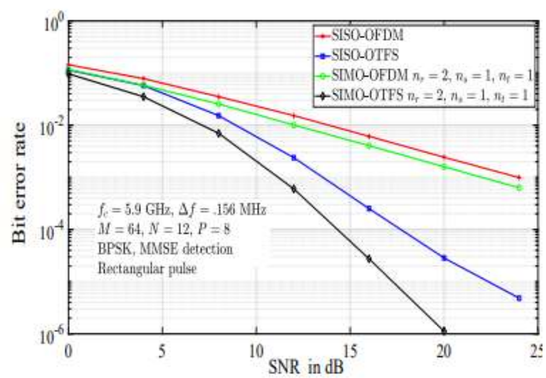

Figure 4 (b): BER Performance of MIMO-OTFS

- To improve faster coverage and error performance a new type of successive over relaxation parameter is introduced which is based on Gauss- Seidel method. Using turbo iterations, the performance of MRC detector gets improved. Comparison for complexity of various linear detector for OTFS and OFDM is shown in figure5[18].

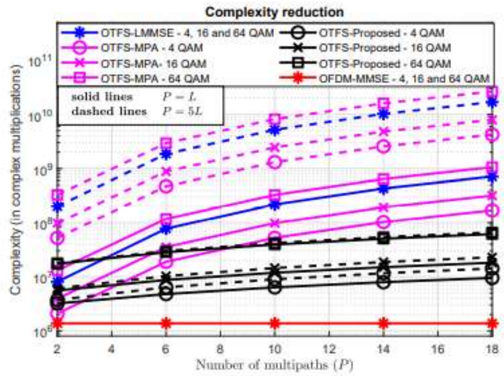

Figure 5: Complexity comparison of various linear detectors for OTFS and OFDM

- One of the latest approaches used to design OTFS is Fractionally Spaced Sampling (FSS) approach. FSS receiver have better performance as compared to SSS (traditional) receiver as shown in figure 6. FSS approach includes following two algorithms: Turbo message passing and Iterative combining message passing [19].

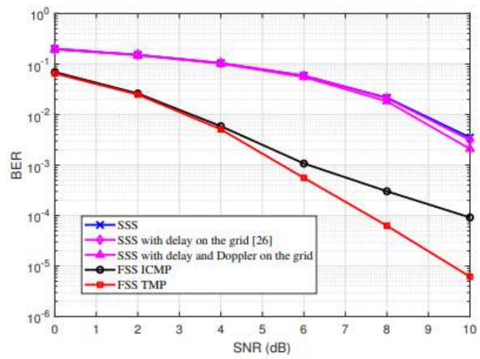

Figure 6: BER performance comparison of OTFS with dissimilar traditional Rx design

- To enhance the performance of OTFS modulation a cross domain iterative detection algorithm is introduced. It is different from conventional OTFS detection method. This algorithm is applied to both time domain and DD domain. BER performance for OTFS modulation with fractional Doppler shifts for P=10 is shown in figure 7[20].

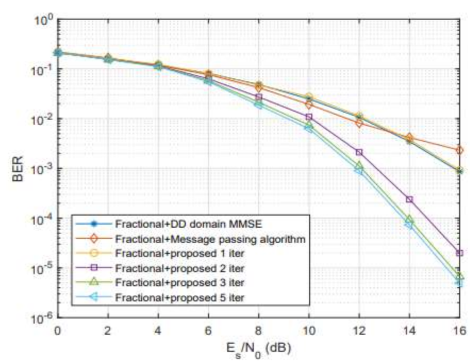

Figure 7: BER performance for OTFS with fractional Doppler shift.

- A new type of iterative SIC turbo receiver has been investigated, which is having the better performance over existing receivers. Yao Ge in [21] used a NOMA technique to overcome co-channel interference.

- OTFS operating in delay Doppler domain have performance as compared to OFDM. But due to the presence of residual synchronization error representation of time domain channel is easier as compared to delay Doppler domain representation [22]. To overcome this inherent nature of DD domain channel a estimation technique based on compressed sensing is introduced [23]. In which an algorithm based on modified subspace pursuit and orthogonal matching pursuit is introduced. BER performance for these two algorithms is shown in Figure 8.

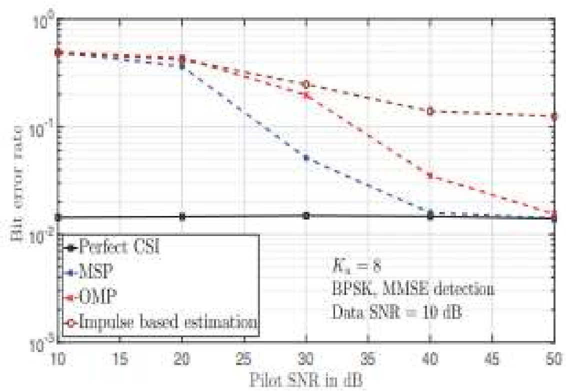

Figure 8: BER and SNR performance for MSP and OSP algorithm

- In high-speed vehicle communication OTFS has drawback of power emission outside the frequency band. To overcome this, a novel PHY layer is developed by introducing Windowing and Restructuring (WR) OTFS system. In figure 9(a), 9(b), 9(c) it is shown that WR-OTFS have better power rejection outside frequency band as compared to OFDM and OTFS scheme. [24]

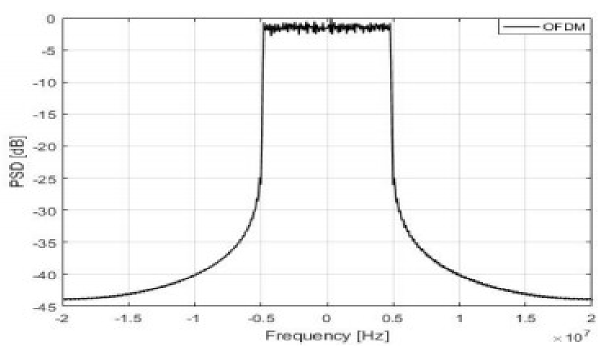

Figure9 (a): Power rejection outside frequency band in OFDM scheme

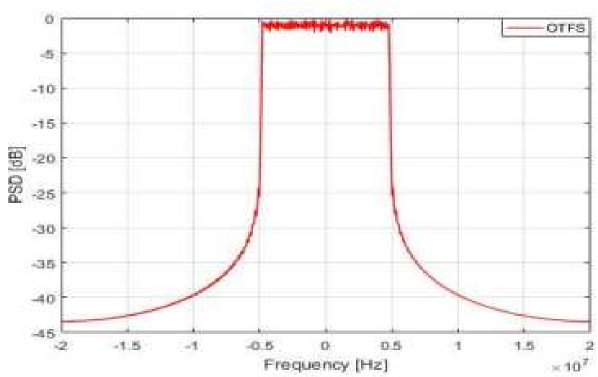

Figure 9 (b): Power rejection outside frequency band in OTFS scheme

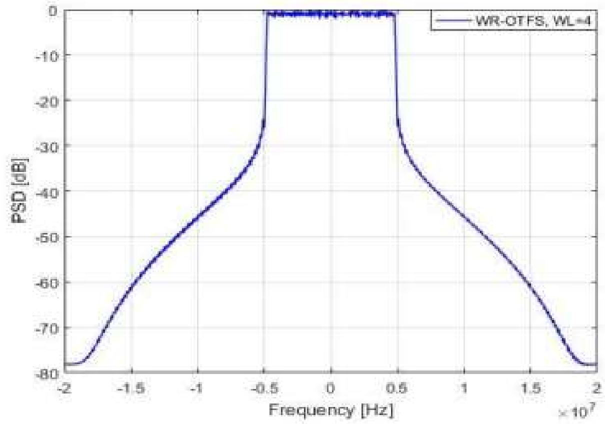

Figure 9(c): Power rejection outside frequency band in WR-OTFS scheme

BER performance for different user equipment speed at AWGN and DD channel is shown in figure 9(d)

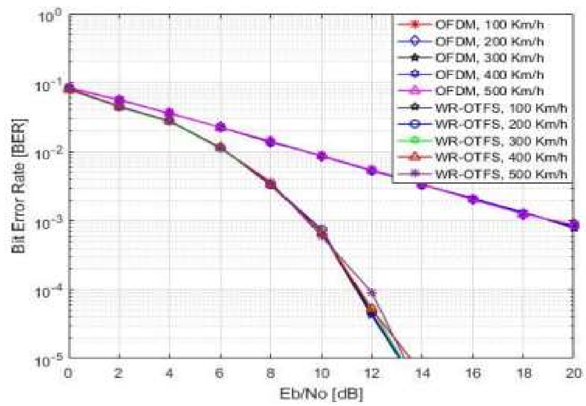

Figure 9(d): Comparison of BER performance for OFDM and WR-OTFS scheme.

- Performance of OTFS is improved by adding large number of pilot and guard symbol but it degrades the channel capacity, which can be further improved by optimizing the overhead for channel estimation.[25]
- Channel spreading due to fractional delay and Doppler shift in OTFS can be removed by Off-grid channel estimation with sparse Bayesian learning. Here data –aided channel estimation is used to achieve the performance gain, as shown below in figure 10 [26].

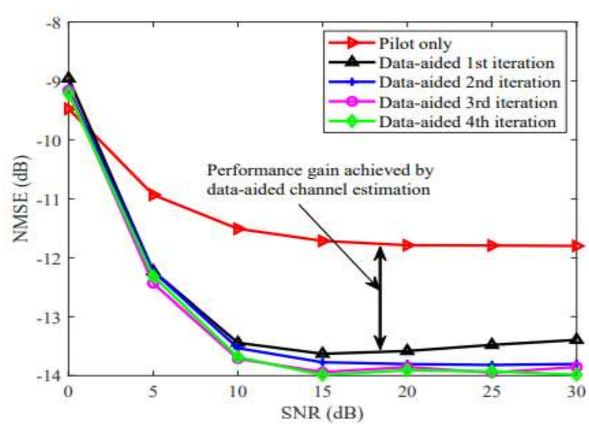

Figure 10: Performance improvement of OTFS by optimizing pilot and data overhead

4. Advantages and Disadvantages

In section 3, after taking an overview of latest updates in OTFS field it is noticed that however OTFS has various new opportunities in wireless network of future but still it has several drawbacks. A list of several advantages and disadvantages has been drawn and explained below.

4.1. Advantages

- OTFS provide high date rate, better flexibility and reliability as compared to OFDM.
- OTFS provides high frequency dispersion. This is because of large Doppler spreads and increased phase noise in millimetre wave communications.
- As SNR is increased than BER will get decreased as shown in figure 11[27].

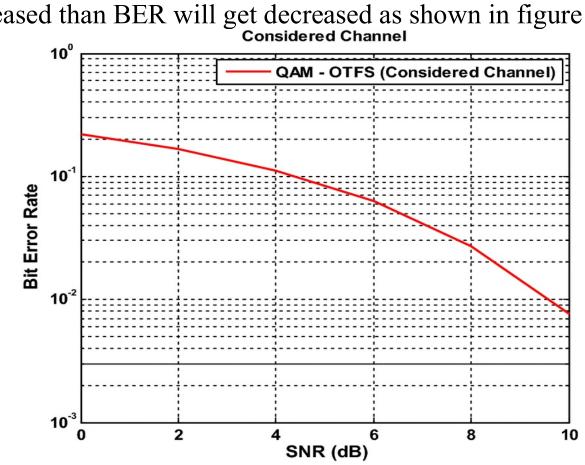

Figure 11: Relationship between BER and SNR

- It has lower BER as compared to OFDM as shown in figure 12[28].

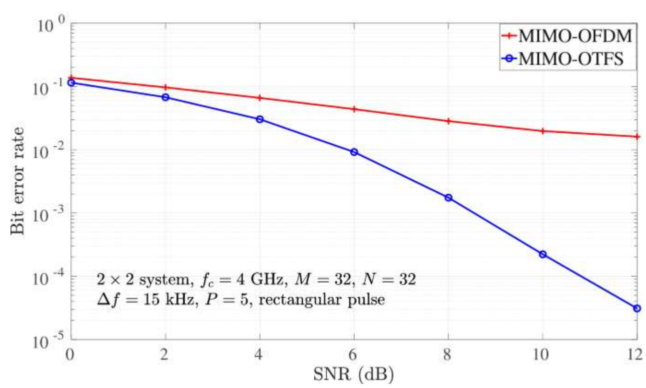

Figure 12: BER comparison of MIMO-OFDM and MIMO-OTFS

- It also allows longer ranges for Radar applications and faster target tracking rate.
- OTFS provides a lower PAPR for better communication coverage as compared to OFDM and GFDM as shown in below figure13[29].

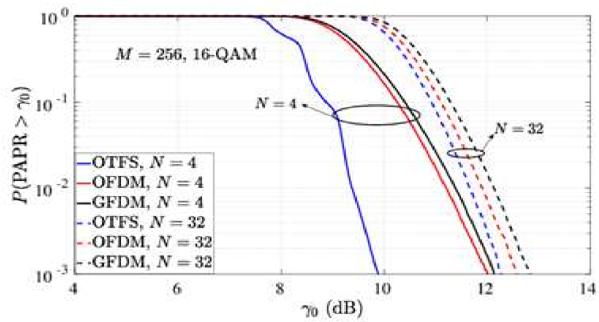

Figure 13: Comparison of PAPR for OTFS, OFDM and GFDM

- OTFS have better performance as compared to OFDM over high mobility channel. As shown in figure 14[30]

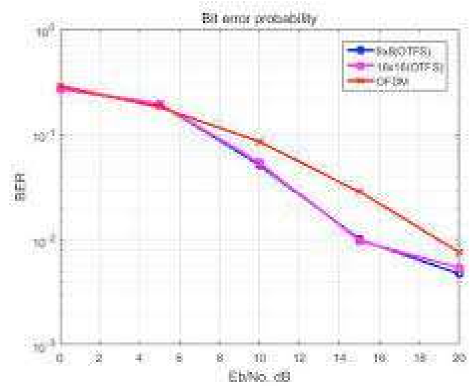

Figure 14: Comparison of performance of OTFS and OFDM over high mobility channel

4.2. Disadvantages

- OTFS has major disadvantage especially for receiver complexity.
- Performance of OTFS modulation gets degraded in DD domain according to MIMO's dimension in the presence of frequency shift.[31]

5. Application and Future Scope of OTFS Modulation

OTFS modulation has large number of application and future scope in next generation wireless networks, as described in the following section

Vehicle to Vehicle Communications: Due to increase of vast traffic, Vehicle to Vehicle communications permits various motor vehicles to communicate wirelessly to another motor vehicles or to a Roadside system. It provides various benefits such as management of cooperative traffic, improvements of road – safety and help in autonomous driving. OTFS can play an important role in vehicle-to-vehicle communication over high mobility channel. The current standards used for vehicle-to-vehicle communication are IEEE802.11bd and 5G NR V2X.

Millimetre-wave communications: The millimetre wave for 5g networks provides Giga-bit-per-second communication services by utilizing large amount of under –utilized spectrum at low and medium velocity. By increasing the carrier frequency, Doppler effect becomes more critical. OTFS analyse the impact of Doppler spread, phase noise, and delay spread, which have different value as compared to conventional Radio bands.[5][32]

Non-Terrestrial communications: Non-Terrestrial communications contains airborne and space-borne vehicles such as UAVs or High-Altitude Platforms (HAPs) and satellites. It supports 5G networks by providing global coverage and mobility, enhanced network reliability and connectivity. High speed of space-borne and airborne vehicles provides large Doppler spread, which can be easily handled by OTFS modulation. In order to overcome the limited computing capability and on-board power supply of space-borne and airborne platform, OTFS offers an important feature having low complexity and low PAPR.

Underwater Acoustic (UWA) communications: Due to limited bandwidth, high delay spread and rapid time variations, Under Acoustic (UA) channels are one of the most challenging wireless channels. For UWA communication some of the most popular single carrier modulation schemes are OFDM, Orthogonal Signal Division Multiplexing (OSDM) and Decision Feedback Equalizers (DFE).However all of them transmit information in time frequency domain in which ICI and ISI equalization is one of the tedious task. UWA channels operate in DD domain which has easier equalization than that of TF domain [33].

6. Conclusion

This paper gives a detailed description of OTFS as one of the emerging two-dimensional modulation for future wireless network with an overview of basic concept of OTFS modulation and demodulation in DD domain with its basic diagram. Most popular advantage of OTFS having high frequency dispersion, lower BER, lower PAPR with its critical challenge of receiver complexity are highlighted with waveform description. The potential applications have been discussed with example and latest research in the field thereby highlighting the latest updates in OTFS modulation in a genuine manner. This review paper will meet the expectation of readers and will lead future research in this area for designing next generation networks.

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