jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 71, NO. 2, PP. 505-512
Manuscript received March 7, 2025; revised May, 2025. doi: 10.24425/ijet.2025.153598

Performance and evaluation of OTFS modulation systems using different high mobility channels

Sura H. Khadum, ThamerM.Jamel, and Hassan F.Kkhazaal

Abstract—**This research examines how Nextgen wireless systems can benefit from Orthogonal Time Frequency Space (OTFS) modulation in different high-mobility channel situations. We test the BER performance of OTFS and OFDM with varying lengths of symbol under varied transmit power (TX power) conditions utilizing simulations employing Doubly-Selective, Extended Vehicular A (EVA), Unmanned Aerial Vehicle (UAV), and Extended Typical Urban (ETU) channel models. Compared to OFDM, OTFS reliably reduces the impact of multipath propagation and Doppler spread more effectively. Importantly, to maximize BER performance in UAV channel simulations, the OTFS symbol length had to be carefully selected; increasing the symbol length without thinking about it led to decreasing results. It was shown that OTFS is connected to a few resources in the ETU channel due to its minimal demand on TX Power. Based on these results, OTFS seems to be a good modulation technique for demanding mobile communication applications, particularly for UAV communications where picking the right parameters is key. Methods for adaptive OTFS that can change symbol length and other parameters in reaction to channel circumstances in real-time should be the focus of future studies.**

Keywords—**OTFS; High Mobility Channels; Doubly Selective; EVA; UAV; ETU**

I. INTRODUCTION

THE ever-increasing demands have greatly tested conventional wireless communication systems for fast data transfer rates and dependable connection in ever-changing contexts like fast-moving vehicles and aircraft. Because of its intrinsic susceptibility to Doppler spread and inter-carrier interference (ICI), the dominant modulation technology for 4G and 5G systems, Orthogonal Frequency Division Multiplexing (OFDM), has difficulty functioning in such environments [1]. Orthogonal Time Frequency Space (OTFS) modulation has emerged as a compelling alternative [2]. This paradigm shift promises improved performance, particularly in scenarios characterized by fast-varying channels. Various high-mobility channel models are examined and evaluated in this research about the performance of OTFS modulation systems. Unmanned Aerial Vehicle (UAV) communications are one example of a scenario where we will take LOS fluctuation and dynamic connectivity into account [3]. Additionally, we will analyze OTFS's performance under doubly selective channel models, which cause significant delay and frequency dispersion [4], to learn more about the effects of frequency and time variations. In addition to more theoretical depictions of these channels, our research will use simulations based on the classical Jake's model [5].

We investigate the advantages and disadvantages of OTFS while dealing with delays and Doppler shifts of different intensities, which are common in communications between vehicles and aircraft. We will compare OTFS's bit error rate (BER) performance to OFDM. Also examine how channel parameters like multi-path delay, Doppler spread, and coherence time affect OTFS systems' spectral efficiency and reliability. In addition, we assess various receiver algorithms that address the deficiencies caused by the doubly dispersive channel. We want to shed light on the capabilities and applicability of OTFS modulation for demanding mobile applications through simulations and extensive performance analysis. This paper aims to identify important trade-offs that can help make the best design decisions for OTFS modulation in dynamic communication settings.

Below is the way the rest of the paper is structured: Section II provides a literature survey of OTFS modulation, covering its history, current uses, and potential alternatives for channels experiencing rapid temporal fluctuations. Section III provides an overview of the OTFS idea, outlining its foundation, system model, and methods for application. To assess OTFS's efficacy in high-mobility channel circumstances, the methodology, simulation parameters, and channel models are detailed in Section IV. Section IIV shows and discusses the BER performance outcomes for OTFS, OFDM, and the Doubly Selective Channel in those kinds of situations, the BER performance outcomes for the Extended Vehicular A Channel, the Unmanned Aerial Vehicle (UAV) Channel, and the Extended Typical Urban (ETU) Channel. The conclusion, is the final part, summarizes the important findings, describes the benefits of OTFS, talks about real-world applications, and recommends areas for future study.

II. RELATED WORK

Numerous works have evolved since the potential of signal processing in the Delay-Doubler (DD) domain was revealed with the introduction of OTFS modulation in [6]. These pieces of literature deal with theoretical and practical problems with OTFS modulation, such as a discrete-time vectorized

First Author and Second Author are with Department of Communications Engineering, University of Technology, Baghdad, Iraq (e-mail: coe.23.02@grad.utechnology.edu.iq, thamer.m.jamel@uotechnology.edu.iq).

Third Author is with Department of Electrical Engineering, Wasit University, Wasit, Iraq (e-mail: hfahad@uowasit.edu.iq).

representation of input-output relationships and OTFS analysis discussed in [2], the authors introduced channel estimation and detection for MIMO-OTFS systems in [7-9], and new path division multiple access for massive MIMO-OTFS systems is presented in [10], among other things. 5G new radio (5G NR) OTFS modulation performance review millimeter wave communication systems are discussed in [11].

Despite its widespread popularity, Orthogonal Frequency Division Multiplexing (OFDM) has significant drawbacks in channels with fast temporal variations, such as inter-carrier interference (ICI) and Doppler spreading which degrade receiver performance with increasing velocity as presented in [12]. Researchers proposed that High-Speed Rail (HSR) services might offer users with high data rates with mmWave Fifth Generation Mobile Radio (5G) in [13]. In the [14], At velocities of up to 500 km/h, the mmWave system's performance is evaluated. With a speed of less than 500 km/h and up to 100 Mbps capacity, the Shanghai maglev system utilizes 38 GHz mmWave wireless communication technology introduced in [15]. The authors provide an extensive overview of channel modeling approaches for UAV communications in [30], discussing both theoretical and empirical models while drawing attention to important obstacles in this field. The LTE downlink performance by simulation and analysis, evaluating the EPA and ETU channel models presented in [31]. In their evaluation of Orthogonal Time Frequency Space (OTFS) modulation for high Doppler aerial communication networks, the researchers show that it can be useful in situations involving severe mobility [32]. Describe in detail the state of the art in vehicular channel characterization by going over measurement campaigns, channel models, and the consequences for wireless system design in regards to [33]. In [34], the authors provide a classification and overview of vehicular propagation and channel models, with an emphasis on how well they may be utilized to evaluate protocols and ITS applications. Researchers look at the advantages and disadvantages of OTFS in reducing Doppler and delay problems in dynamic mobile situations in a study comparing OTFS and OFDM modulation.

III. OTFS CONCEPT

Traditional orthogonal frequency division multiplexing (OFDM) systems could have trouble maintaining efficient and dependable communication in highly mobile situations with huge Doppler spreads, leading to significant frequency dispersion. 5 G NR utilizes a multi-numerology OFDM system to solve many 5G problems, such as those involving scenarios requiring high speeds. In 5G NR, boosting sub-carrier bandwidth can reduce Doppler spread, but when delay spread is also considerable, decreasing Cyclic Prefix (CP) length can induce Inter symbol Interference (ISI). In response to these difficulties, a novel modulation system known as OTFS was suggested in [2]. Demonstrating considerable enhancements in performance compared to OFDM. When compared to other models, we found that the delay-Doppler channel one best captures the shape of wireless channel models. By converting the multipath channel into a slowly time-varying channel, OTFS provides a solution to the limitations of multicarrier approaches over double dispersive channels. For better channel modeling in the delay-Doppler domain, OTFS modulates data in this domain rather than the time-frequency domain, as is the case with OFDM.

A. System Model

OTFS system is designed to function over a high-mobility channel that includes P distinct paths. It operates with a bandwidth B and is designed to handle a maximum delay spread τ_{max}, and maximum Doppler shift ν_{max}.
An OTFS frame that contains M sub-carriers, each with a bandwidth of Δf, and N symbols, each with a duration of T. The overall bandwidth of an OTFS system is B = MΔf and the total time of Ts = NT. NM information is contained in the OTFS frame. The symbols that are put into the delay-Doppler domain matrix X_{DD} [m, n] from a modulation alphabet (such as QAM). The investigation focused on clarifying the fundamental model [20] as shown in Figure 1.

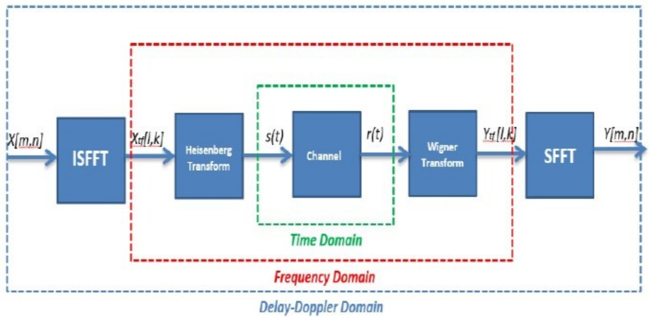

Fig. 1. OTFS system model [20]

Two approaches can be taken to apply OTFS modulation. Direct implementation of OTFS in the delay-Doppler domain using the Zak Transform (ZT) and Inverse Zak Transform (IDZT) is one approach; Figure 2 shows this in practice [16]. Using the IDZT to immediately transform the information symbols X_{DD} [m, n] to the time domain, resulting in a continuous signal x(t). The signal is sent to the two choosing the right channel to receive the y(t) signal at the base station. Afterward, in the delay-Doppler domain, we obtain Y_{DD} [m, n].

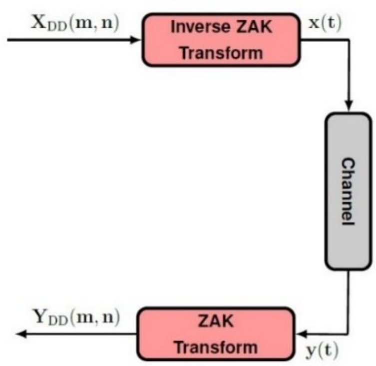

Fig. 2. OTFS modulation implementation, direct approach [16]

Figure 3 shows the second method, which is a two-step process using the time-frequency domain [2]. Using the X_{DD} [m, n] information symbols from the delay-Doppler domain to the X_{TF} [k, l] symbols from the time-frequency domain using the ISFFT (Inverse Symplectic Finite Fourier Transform). Once X_{TF} [k, l] is prepared, the time domain signal x(t) is obtained by applying the Heisenberg transform. At the receiver, the signal y(t) in the time domain is transformed to the time-frequency domain using the Wigner transform after it has traversed the channel. Subsequently, it is transformed to the delay-Doppler domain by the use of SFFT (Symplectic Finite Fourier Transform) for symbol demodulation.

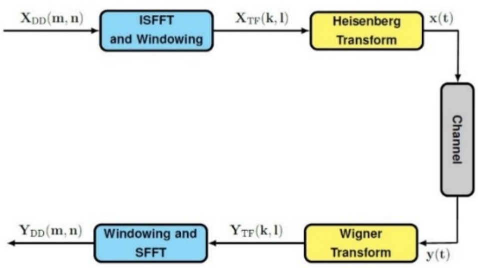

Fig. 3. OTFS modulation implementation, two-step approach [2]

B. OTFS Transmitter

The delay-Doppler domain matrix X_{DD} is filled out at the transmitter with the MN data symbols from a traditional modulation alphabet, such as Quadrature amplitude modulation (QAM) with entries $X_{DD}[m, n]$, for m = 0 to M − 1,
n = 0 to N − 1. The packets are sent out with a bandwidth of MΔf and a duration of NT. When the time-frequency domain samples XTF $[k, l]$ are transferred to the delay-Doppler samples $X_{DD}[m, n]$, utilizing ISFFT in the following way:

$$\boldsymbol{X}\mathrm{TF}\,[l, k\,] = \frac{1}{\sqrt{NM}} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X_{DD}[m, n]\; e^{(\mathrm{j}2\pi(\frac{nl}{N} - \frac{mk}{M})} \tag{1}$$

The time domain OTFS signal x(t) is broadcast over the wireless channel after XTF $[k, l]$ is transformed using the Heisenberg transform.

$$\mathrm{x}(t) = \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} X\mathrm{TF}[l, k]\; \mathrm{gtx}\,(t\text{-}lT)\; e^{j2\pi k\Delta f(t-lT)} \tag{2}$$

where the pulse-shaping waveform at the transmitter has a duration of T and is represented by $g_{tx}(t)$.

C. Wireless Channel

The signal x(t) is sent through a channel. The received signal y(t) in the time domain is given if we ignore the noise component:

$$\begin{aligned} y(t) &= \iint h_{DD}\,(\tau, v\,) x(t-\tau)\; e^{j2\pi v(t-\tau)}\; d\tau\; dv \\ &= \int h\mathrm{TD}\,(t, \tau) S(t-\tau)\; d\tau \end{aligned} \tag{3}$$

The delay-Doppler channel response h_{DD} (τ, v) is displayed when considering a small number of reflectors in the channel, which are represented by P paths. Each path is linked to delays τi, Doppler shifts vi, and gains hi.

$$h_{DD}\,(\tau, v\,) = \sum_{i=1}^{p} hi\; \delta(\tau\text{-}\tau i)\; \delta(v\text{-}vi) \tag{4}$$

Taking the Fourier transform of h_{DD} (τ, v) concerning v yields the delay-time channel response:

$$h\mathrm{TD}(t, \tau) = \sum_{i=1}^{p} hi\;\; e^{j2\pi vi(t-\tau i)}\; \delta(\tau\text{-}\tau i) \tag{5}$$

At t = qT/ M, we can sample y(t), where q = 0 to NM − 1, and $\tau = l$ /MΔf. The signal y(t) is changed into:

$$y[q] = \sum_{i=1}^{p} hi\;\; e^{j2\pi \frac{ki}{NT}(\frac{qT}{M} - \frac{li}{M})}\; \mathrm{x}(q\text{-}li) \tag{6}$$

Where hi is the channel coefficient.

D. OTFS Receiver

The signal received at the receiver, denoted as y(t), is in the time domain. To begin, to convert the received signal y(t) from the time domain to the time-frequency domain, Y_{TF} $[l, k]$, the receiver must first utilize the Wigner transform in conjunction with the pulse shaping receiver [19]. $g_{yx}(t)$ waveform, that is:

$$\mathrm{Y}_{tf}\,[l, k] = \mathrm{Y}\,(t, f)\,\big|\, t{=}lT\,,\;\; f{=}\,k\Delta f \tag{7}$$

IV. HIGH MOBILITY CHANNELS

The environment stays constant as both the transmitter and receiver move within a fixed wireless channel. As it travels from the antenna to the receiver, the signal takes multiple paths due to reflections from numerous nearby objects. Different path lengths cause fades and additions that don't make sense, which makes it challenging for receivers to figure out what information was sent first from the composite signals. These scenarios requiring a great deal of mobility are increasing in frequency due to the expanding uses of wireless networks. Take the growth of high-speed trains, automated vehicles, and airplanes as examples; these modes of transportation require massive amounts of data transfer. With so many moving parts transmitters, receivers, and reflected objects in a high-mobility wireless channel, data rates must be extremely high to keep up with the constant stream of information [17]. Existing system designs have problems in this area. When dealing with data in environments where both time and frequency can change, it's necessary to use doubly selective channel models. Different multipath sites necessitate different speeds, and any model for mobile communication must consider these factors [18]. Most of the time, though, these situations happen in places where many physical objects block transmissions at variable multipath. This adds both Doppler shift due to speed and position shift due to multi-path movement. These conditions can be tested in more detail by making them using better settings, such as the Extended Vehicular A or B channel models with very variable changes [21]. Also, a way for a ground station to communicate with an aerial drone is through what is known as a "Drone Channel" or "Unmanned Aerial Vehicle (UAV) Channel" [22]. ETU channels play a crucial role in enabling the transfer of signals and power. They provide effective communication while minimizing interruptions. Methods for reducing noise, ensuring signal integrity, and matching impedances are all part of the design process. Higher frequencies and data transfer rates are now possible thanks to advancements in materials and procedures that boost their capabilities [27]. These multipath configurations with "Doppler & reflective interference settings" and other parts show what happens when different systems or data are exposed during transmission in tests done on mobile devices using atmospheric signal transfers. They do this to show what the real effects are when different systems or data are exposed during transmission.

Thus, setting test parameters is necessary before both issues become relevant. The new tech technique would immediately fight these issues to achieve data with integrity and stability, thereby solving the design obstacle [23].

A. Doubly selective channel models

Doubly selective wireless channels are those where frequency and time selectivity are both present. Doubly dispersive or LTV channels are another name for these. For these types of channels, the incoming signal is a composite of many time-delayed replicas of the signal that was transmitted at a different frequency. A rapidly changing channel condition is the end consequence of this. It is common for the transmitter and receiver to move at quite high speeds in doubly dispersive channels, and the delay spread is also considerable. So, from a communication point of view, estimating and equalizing channels in doubly selective channels [24] presents big problems that need to be solved. In doubly selective channels, variations in both time and frequency degrade signal transmission and decrease performance. If you look at a doubly selective or time-variant multipath channel through different domains, like time delay, time-frequency, or delay-Doppler [17], you can figure out how it acts. The Impulse Response for the Doubly-Selective Channel is:

$$h(t, \tau) = \sum_{i=1}^{p} h_i \, e^{j2\pi vit} \, \delta(\tau - \tau i) \quad (8)$$

Where**:**

- h_i: Channel gain of the *i*-th path.
- ν_i: Doppler shift of the *i*-th path.
- τ_i: Delay of the *i*-th path.
- *P*: Total number of multipath components.

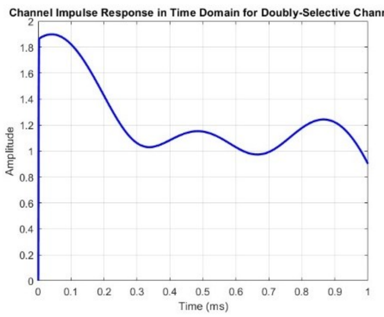

Fig. 4. Impulse Response for Doubly-Selective Channel

In the time domain, the graph is the impulse response of a channel that is both time- and frequency-selective. Multipath propagation generates both time-variability and frequency-selectivity, with the transmitter, and receiver. Variations in amplitude over time indicate channel gains affected by multipath interference or Doppler effects. When there is dynamic communication, like in doubly-selective channel systems, where changes in the environment and movement cause big channel fluctuations, this happens a lot.

B. Extended Vehicular A channel (EVA)

In 2006, there was a surge in interest in reliable vehicle connectivity due to initiatives like Wireless Access for Vehicle Environments (WAVE) and other related projects, which led to a surge in research into vehicular channels. The success of Intelligent Transportation Systems (ITSs) depends on their reliable connectivity. Communication between vehicles and infrastructure (V2I) and between vehicles and each other (V2V) is essential for ITSs. All drivers are expected to gather data about traffic and road conditions using sensors, to gather details about the state, and to share this information with the road network. Thus, all vehicles may combine and exchange data for better safety [25]. The impulse response of the EVA channel, when represented as a tapped delay line (TDL), is commonly given by:

$$h(t, \tau) = \sum_{i=1}^{N} h_i(t) \, \delta(\tau - \tau i) \quad (9)$$

where:

- $h_i(t)$ represents the time-varying fading coefficient of the i-th path.
- τ_i is the delay of the i-th path,
- $\delta(\cdot)$ is the Dirac delta function.

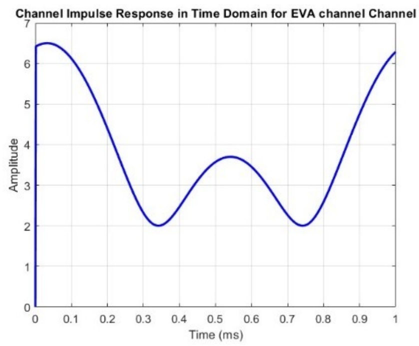

Fig. 5. Impulse Response for Extended Vehicular A channel

The time domain simulation of the EVA channel's impulse response takes into account nine multipath components, all of which have predetermined delays and power levels. Using a sum-of-sinusoids approximation, the fading process is modeled, accounting for real mobility effects by including random Doppler shifts for each path. The amplitude of the resultant impulse response varies with time, an effect known as time-varying Rayleigh fading. To better understand how the EVA channel affects signal propagation in vehicular communication environments, the produced map graphically displays its time-dependent behavior.

C. Drone Channel (UAV)

Unmanned aerial vehicles (UAVs) are increasingly used in communication, border surveillance, intelligence gathering, rescue operations, humanitarian missions, and scientific data collection. These low-altitude platforms can be remotely managed or autonomously operated. Definement of UAV channels is crucial for safety and reliability, with collaboration between research organizations and standardization authorities. Some of the most notable differences between UAV communication systems and more traditional forms of wireless communication, as well as between UAV communication channels, are that air-ground (AG) and air-air (AA) channels are two separate types of communication. Non-stationary channels can vary in both space and time. These characteristics are more difficult to manage in a varied propagation environment where the UAV flies. It is common for well-established analytical and empirical models to support the propagation properties of ground cellular systems. The mobile land systems' satellite connectivity [25-26]. Following is an expression for the UAV channel impulse response:

$$h(t, \tau) = h_{LoS}(t)\,\delta(\tau - \tau_{LoS}) + \sum_{i=1}^{N} h_{NLoS,\,i}(t)\,\delta(\tau - \tau i) \tag{10}$$

where:
- h_{LoS} (t) is the Line-of-Sight (LoS) component.
- τ_{LoS} is the LoS path delay.
- $h_{NLoS,\ i}$ (t) represents Non-Line-of-Sight (NLoS) multipath fading.
- τ_i is the delay of the i-th multipath component.

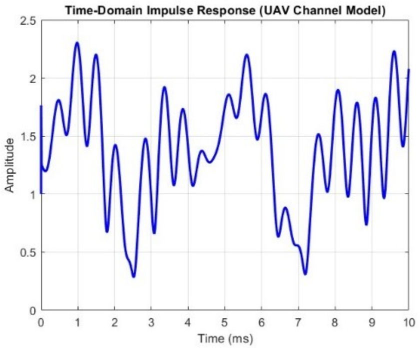

Fig. 6. Impulse Response for UAV channel

The channel impulse response of a UAV changes over time as a result of the UAV's motion and the ever-changing surroundings. This causes fading effects that are specific to either frequency or time, depending on how the transmitter and receiver are moving relative to one another. All of these effects, including path loss, Doppler shifts, and multipath propagation, are captured by the channel impulse response. When it comes to simulating and building systems like OFDM and OTFS, this response is essential since accurate channel models are required for optimizing and analyzing performance.

D. Extended Typical Urban (ETU) channel

Particular capabilities of train channels, also known as ETU channels, inefficiently encoding and conveying information have garnered substantial attention in the realm of signal processing. Research, standardization, and cellular network design often use channel models for urban organizations. Time scattering is often the decisive factor when measuring performance metrics like bit error rate and possible throughput. This makes time scattering an essential channel standard [28]. The relative speed of the user and the network edge, where a constant user experience must be guaranteed, is a measure of mobility needs. For instance, fast trains and airplanes need mobility assistance up to 500 km/h and 1000 km/h, respectively, for in-vehicle mobile broadband service [29]. The usual way to describe the channel impulse response h (t, τ) in the ETU model is:

$$h(t, \tau) = \sum_{k=0}^{N-1} \alpha k\ \delta(\tau - \tau k)\ e^{j2\pi f dt} \tag{11}$$

where:
- α_k is the complex gain (amplitude and phase) of the k-th path.
- τ_k is the delay of the k-th path, typically defined for a set of discrete delay bins.
- $\delta(\tau - \tau_k)$ is a Dirac delta function that represents the impulse response at the specific delay τ_k.
- f_d is the Doppler shift, related to the relative velocity between the transmitter and receiver.
- t is the time variable (can also account for time-varying behavior due to mobility).

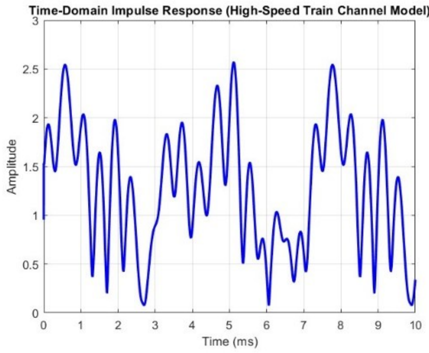

Fig. 7. Impulse Response for ETU channel

The UAV's mobility causes the channel's properties to rapidly change over time and introduce fading effects, resulting in a time-varying channel. Creating a multipath environment with many reflecting surfaces, like buildings and cars, is easy using the ETU model, making it ideal for urban settings simulations. For system analysis and design in real-world, dynamic communication scenarios like UAV communications, this model offers a complete foundation. The ETU channel's impulse response defines how a signal travels from its source to its destination over time. It shows the channel's reaction to a short input signal (a delta function) and specifies the multipath components (phase, amplitude, and latency) and Doppler shifts (transmitter and receiver relative motion).

V. SIMULATION AND EVALUATION OF RESULTS

This section presents the technique and results of the simulations run to evaluate the performance of OTFS modulation under high-mobility channels. The simulations were conducted using MATLAB (2024 version)**.** Table I shows the parameters that were used.

The system's performance under the stated propagation conditions can be derived from the simulation results for the first channel Doubly Selective channel with channel delay [0.2, 0.8, 1.5, 2.5] µs and Power Delay Profile [0.9, 0.5, 0.3, 0.2] dB. Important measures like bit error rate (BER), and the impact of multipath fading on signal quality are the primary focus of the investigation. We evaluate the effects of delay spread, Doppler shift, and fading on the received signal by looking at the channel's statistical properties and impulse response. The results are evaluated in detail in the following discussion, which emphasizes the system's resilience and performance trends under different channel conditions.

TABLE I
SIMULATION PARAMETERS

Parameter	symbol	Value
number of subcarriers	M	64
number of time slots	N	8, 16, 32, 64
Subcarrier Spacing	df	20 kHz
Carrier Frequency	fc	2 GHz
Padding Length	padLen	16
Type of padding	CP	-
Modulation scheme	-	QPSK
Transmission power	PwrTX	5 - 40 dB
Channel model	-	Doubly Selective channel Extended Vehicular A channel Drone Channel (UAV) Extended Typical Urban (ETU) channel

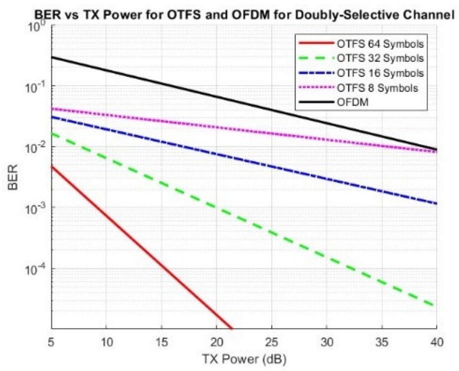

Fig. 8. The BER for both OFDM and OTFS systems for doubly selective channel

In a simulated doubly-selective channel, Figure 8 shows the Bit Error Rate (BER) performance of (OFDM) modulation and (OTFS) modulation with different symbol lengths as a function of transmit power. In mobile wireless communication environments with high multipath and Doppler dispersion, a doubly selective channel is characterized by impairments that change with both time and frequency. The Figure shows that for all simulated TX power values, OTFS modulation always achieves a lower BER than OFDM. Based on these results, it seems that OTFS can withstand the doubly-selective channel impairments better than OFDM. The performance gain is because OTFS takes advantage of the time-frequency domain's inherent diversity, which reduces the impact of multipath fading and Doppler shifts. However, as OFDM depends on the channel being nearly constant across each OFDM symbol, it is more likely to experience performance loss in doubly selective channels. Additionally, the symbol length affects the BER performance of OTFS. The BER is typically improved by increasing the OTFS symbol length, particularly at higher TX power levels. The declining bit error rate (BER) of OTFS while using 8,16,32, and 64 symbols is evidence of this. With longer OTFS symbols, the signal can cover more ground on the time-frequency plane, making better use of the channel's time and spectral variety.

Accurate channel conditions govern the operation of mobile communication systems in the real world. This section showcases the results of the simulation for the performance of OTFS and OFDM within the Extended Vehicular A (EVA) channel with channel delay [0 30 150 310 370 710 1090 1730 2510] ns and Power Delay Profile [0 -1.5 -1.4 -3.6 -0.6 -9.1 -7.0 -12.0 -16.9] dB, to offer a more realistic evaluation.

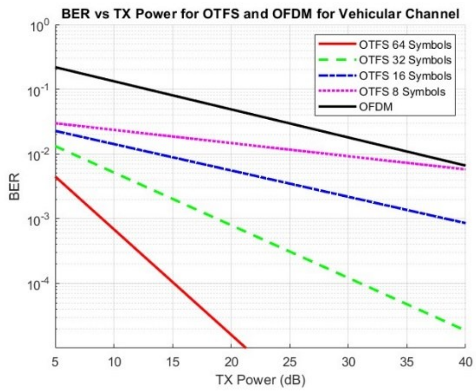

Fig. 9. The BER for both OFDM and OTFS systems for EVA channel

Figure 9 illustrates the relationship between transmit power (TX) and bit error rate (BER) in an Extended Vehicular A (EVA) channel simulation for (OFDM) and (OTFS) modulation at various symbol lengths. Over the entire range of the simulated TX power, OTFS outperforms OFDM in terms of BER in the EVA channel. This demonstrates that OTFS is capable of handling channel impairments, which is a good indicator that it can reduce the impact of mobile-specific problems like multipath fading and Doppler effects. When compared to OFDM in the same channel conditions, OTFS's lower BER indicates that it may improve system dependability. When utilizing OTFS modulation, the findings indicate that low symbols result in an extreme error and have an important effect on BER performance. However, using at least 32 symbols can be a smart technique for better BER value.

We'll continue to a drone communication scenario in this part with channel delay [0.0,0.2,0.4,1.0,1.5,2.0] μs and Power Delay Profile [0.0,1.0,3.0,5.0,7.0,9.0] dB. Because of their height, mobility, and often operating environment, Unmanned Aerial Vehicles (UAVs) offer unique channel characteristics during deployment. Here we show the outcomes of the simulations run in a UAV channel model, looking at how OTFS and OFDM fared in terms of BER in this specific communication setting.

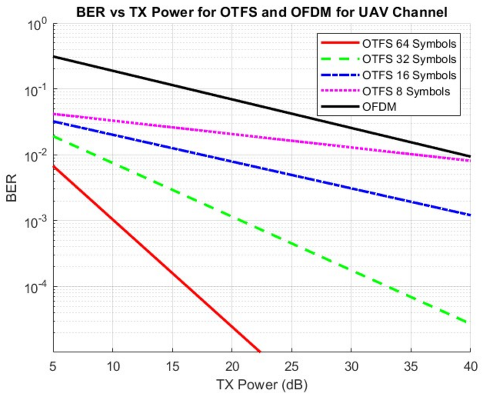

Fig. 10. The BER for both OFDM and OTFS systems for the UAV channel

For OFDM and OTFS modulation with different symbol lengths, Figure 9 shows the BER as a function of transmit power in a simulated UAV channel. Aspects of aerial communication are included in the UAV channel model, such as a component for expected line-of-sight (LOS) and Doppler changes caused by UAV motion. Consistent with earlier findings, OTFS shows a lower BER than OFDM in the UAV channel across the studied TX power range. This provides more evidence that the time-frequency variety built into OTFS helps to reduce the impact of channel impairments that are unique to UAV operations. The symbol length has a significant impact on the BER performance of OTFS. While there is a general trend toward better BER with longer symbols. With OTFS configurations of at least 16, and preferably 32, symbols, the relative performance advantages compared to OFDM are maximum. With increasing TX power, BER drops. It appears that greater power is needed to overcome path loss and other channel impairments, particularly in aerial situations, as indicated by the poorer relative TX power efficiency in the UAV channel simulations. In situations where UAV movement and environmental conditions can cause strong LOS components to still experience significant path loss and fading, the results highlight the potential of OTFS for UAV communications. To achieve the best possible BER, it is essential to choose the OTFS symbol length.

OTFS and OFDM are examined in this section for their performance in the Extended Typical Urban (ETU) channel with channel delay [0 50 120 200 230 500 1600 2300 5000] ns and Power Delay Profile [-1 -1 -1 0 0 0 -3 -5 -7] dB. Typical of mobile communications in urban environments, the ETU channel model has a distinct delay profile and substantial multipath propagation.

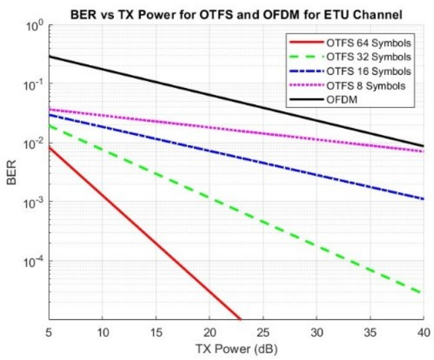

Fig. 11. The BER for both OFDM and OTFS systems for the ETU channel

Figure 11 shows the relationship between transmit power and bit error rate (BER) in a simulated Extended Typical Urban (ETU) channel (OFDM) and (OTFS) modulation with different symbol sequences. Urban radio propagation environments are characterized by time dispersion and multipath abundance, which the ETU model attempts to replicate. Demonstrating the channel's resource efficiency and revealing its multipath and time dispersion nature, OTFS keeps the BER below OFDM at all levels of the ETU channel. To operate effectively, the ETU channel requires additional symbol processing, as seen in the ETU results, which show the amount of data that can be sent at each stage. The ETU channel's low dependency on TX power suggests it can be a limitation or benefit. In urban areas, stable connections with limited resources are better than expensive, high-performance connections.

VI. SUMMARY

The table II summarizes the simulation results for all channels used in different symbol lengths:

TABLE II
SIMULATION RESULTS SUMMARY

Channel type	TX power	OTFS symbols N	OTFS BER	OFDM BER
Doubly Selective channel	20 dB	N=8 N=16 N=32 N=64	0.02 0.007 0.9×10^{-3} 1.7×10^{-5}	0.06 For all values
Extended Vehicular A (EVA) channel	20 dB	N=8 N=16 N=32 N=64	0.01 0.005 0.7×10^{-3} 1.5×10^{-5}	0.04 For all values
Drone Channel (UAV)	20 dB	N=8 N=16 N=32 N=64	0.02 0.007 0.001 2.4×10^{-5}	0.06 For all values
Extended Typical Urban (ETU) channel	20 dB	N=8 N=16 N=32 N=64	0.01 0.007 0.001 3×10^{-5}	0.06 For all values

VII. CONCLUSION AND FUTURE RESEARCH DIRECTION

From the simplified doubly selective models to the more complex EVA, UAV, and ETU channels, this study identified a consistent trend in high-mobility channel environments: OTFS modulation provides clear benefits over OFDM in reducing the negative impacts of multipath propagation, Doppler spread, and time-varying fading. Bit Error Rate (BER) reductions achieved by OTFS consistently demonstrate its robustness and adaptability, even when the exact performance increases and optimal OTFS setups differ across various channels. Based on these results, OTFS seems to be a good fit for topics like "nextgeneration wireless systems requiring robust and reliable communication links in challenging mobile scenarios". In addition, the importance of symbol length selection in maximizing the performance benefits of OTFS was highlighted in this research as a vital design consideration for its implementation.

Future Research Areas, derive effective methods for channel estimation in these difficult settings and investigate how channel estimate mistakes affect OTFS performance. Advanced equalization techniques and adaptive modulation schemes within the OTFS framework have the potential to further unlock its potential, leading to more efficient, reliable, and spectrally efficient wireless communication systems. A solid groundwork for future research and implementation of OTFS modulation in challenging mobile situations is set in this study.

REFERENCES

[1] J. G. Proakis, and M. Salehi, Digital Communications. New York, NY, USA: McGraw-Hill, 2008.

[2] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch and R. Calderbank, "Orthogonal time frequency space modulation," in Proc. 2017 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), San Francisco, CA, 2017, pp. 74–80, https://doi.org/10.1109/WCNCW.2017.7916761

[3] Y. Zeng, R. Zhang, and T. J. Lim, "Throughput Maximization for UAV-Enabled Mobile Relaying with Optimized Trajectory and Resource Allocation," IEEE Trans. Mobile Comput., vol. 18, no. 10, pp. 2755–2767, 1 Oct. 2019, https://doi.org/10.1109/TMC.2018.2872473

[4 P. Bello, "Characterization of randomly time-variant linear channels," IEEE Trans. Commun. Systems, vol. CS-11, no. 4, pp. 360–393, Dec. 1963.

[5] W. C. Jakes, Microwave Mobile Communications. New York, NY, USA: IEEE Press, 1994.

[6] Gunturu A, Godala AR, Sahoo AK, Chavva AKR (2021) Performance analysis of OTFS waveform for 5G NR mmwave communication system. In: Proc. IEEE Wireless Commun. and Networking Conf., pp 1–6. Nanjing, China.

[7] Liu Y, Gao F, Ma J, Wang X (2019) Uplink-aided high mobility downlink channel estimation over massive MIMO-OTFS system. IEEE J Sel Areas Commun 38(9):1994–2009.

[8] Ramachandran MK, Chockalingam A (2018) MIMO-OTFS in high-Doppler fading channels: signal detection and channel estimation. In: Proc. IEEE Global Commun. Conf., pp 1–6. Abu Dhabi, United Arab Emirates.

[9] Shen W, Dai L, An J, Fan P, Heath RW (2019) Channel estimation for orthogonal time frequency space (OTFS) massive MIMO. IEEE Trans on Signal Processing 67(16):4204–4217.

[10] Li M, Gao F, Fan P, Dobre OA (2021) A new path division multiple access for the massive MIMO-OTFS networks. IEEE J Sel Areas Commun 39(4):903–918.

[11] Gunturu A, Godala AR, Sahoo AK, Chavva AKR (2021) Performance analysis of OTFS waveform for 5G NR mm-wave communication system. In: Proc. IEEE Wireless Commun. and Networking Conf., pp 1–6. Nanjing, China.

[12]. P. H. Moose, "A technique for orthogonal frequency division multiplexing frequency offset correction," IEEE Trans. Commun., vol. 42, no. 10, pp. 2908-2914, Oct. 1994.

[13] F. Hasegawa, A. Taira, G. Noh, et al., "High-speed train communications standardization in 3gpp 5g nr," IEEE Communications Standards Magazine, vol. 2, no. 1, pp. 44–52, 2018.

[14] J. Kim, M. Schmieder, M. Peter, et al., "A comprehensive study on mm-wave based mobile hotspot network system for high-speed train communications, IEEE Transactions on Vehicular Technology, vol. 68, no. 3, pp. 2087–2101, 2018.

[15] M. Zhou, "Analysis on the technical characteristics of wireless communication between vehicles and grounds of Shanghai maglev line," Urban Mass Transit, vol. 13, pp. 26–29, 2010.

[16] F. Lampel, A. Alvarado, and F. M. Willems, "Orthogonal time frequency space modulation: a discrete zak transform approach," arXiv preprint arXiv:2106.12828, 2021.

[17] Hong, Y., Thaj, T., Viterbo, E. (2022). Delay-Doppler Communications: Principles and Applications. Netherlands: Elsevier Science.

[18] Hui Xiao; A.G. Burr: "Simulation of the time-selective environment by 3GPP spatial channel model and analysis on the performance evaluation by the CMD metric" International Conference on Wireless Communications, Networking and Mobile Computing, 2005.

[19] Bentolhoda Kazemzadeh Osgoei. Designing a high data rate wireless communication system in a doubly selective channel: TransPod system. Networking and Internet Architecture [cs.NI]. Université de Limoges, 2024. English.NNT: 2024LIMO0055.

[20] Eldemiry, Ahmed, Abdelazim A. Abdelsalam, Heba M. Abdel-Atty, Ahmed Azouz, and Walid Raslan. "Overview of the orthogonal time-frequency space for high mobility communication systems." In 2022 5th International Conference on Communications, Signal Processing, and their Applications (ICCSPA), pp. 1-6. IEEE, 2022.

[21] Rubio, C. J. V. (2023). "Intelligent sensing and learning for advanced MIMO communication systems". https://doi.org/10.54337/aau596083552

[22] Khuwaja, A. A., Chen, Y., Zhao, N., Alouini, M., & Dobbins, P. (2018). A survey of channel modeling for UAV communications. IEEE Communications Surveys & Tutorials, 20(4), 2804–2821.

[23] Oestges, C., & Quitin, F. (2021). Inclusive radio communications for 5G and beyond. Academic Press.

[24] F. Hlawatsch and G. Matz, Wireless communications over rapidly time-varying channels. Academic Press, 2011.

[25] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions, ETSI TR 102 638, V1.1.1, Jun. 2009.

[26] A. Panagopoulos, P.D.M. Arapoglou, and P. Cottis," Satellite communications at KU, KA, and V bands: Propagation impairments and mitigation techniques," IEEE Commun. Surv. Tuts., vol. 6, no. 3, pp. 2-14, 2004.

[26] P. Chini, G. Giambene and S. Kota" A survey on mobile satellite systems," Int. J. Satell. Commun. Networking, vol. 28, no. 1, pp. 29-57, 2009.

[27] Hu Zhengye, Gu Dekang "ETU calibration instrument" 20 Mar 2013.

[28] H. Asplund, K. Larsson, and P. Okvist, "How Typical is the "Typical Urban" channel model?" VTC Spring 2008 - IEEE Vehicular Technology Conference, Singapore, 2008, pp. 340-343.

[29] Ramachandran, M. K., Surabhi, G. D., & Chockalingam, A. (2020). OTFS: A New Modulation Scheme for High-Mobility Use Cases. Journal of the Indian Institute of Science, 100(2), 315-336.

[30] Aziz Altaf Khuwaja, Yunfei Chen, Nan Zhao, Mohamed-Slim Alouini, "A Survey of Channel Modeling for UAV Communications" arXiv:1801.07359v1 [eess.SP] 23 Jan 2018.

[31] Mohammed Kadhim, Salman Goli, Amer S. Elameer, "Analysis and Simulation of LTE Downlink: EPA and ETU model" 2018 International Conference on Advanced Science and Engineering (ICOASE), Kurdistan Region, Iraq.

[32] Thi My Chinh Chu, Hans-Jurgen Zepernick, Alexander Westerhagen, Anders Höök, Bo Granbom, "Performance Assessment of OTFS Modulation in High Doppler Airborne Communication Networks" Mobile Networks and Applications (2022) 27:1746–1756.

[33] Christoph F. Mecklenbra, Andreas F. Molisch, Johan Karedal, Fredrik Tufvesson, Alexander Paier, Laura Bernado, Thomas Zemen, Oliver Klemp, Nicolai Czink, "Vehicular Channel Characterization and Its Implications for Wireless System Design and Performance" 2011 IEEE.

[34] Wantanee Viriyasitavat, Mate Boban, Hsin-Mu Tsai, and Athanasios V. Vasilakos, "Vehicular Communications: Survey and Challenges of Channel and Propagation Models" arXiv:1505.06004v2 [cs.NI] 26 May 2015.