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Novel Orthogonal Time Frequency Space Based on Universal Filter Multi Carrier for 6G Wireless Networks

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ABSTRACT

Obtaining an efficient multicarrier signalling technique is an essential part in signal processing of the (6G) wireless networks. In order to achieve their intended objectives, the 6G mobile networks needs the utilization of a multicarrier scheme that possesses the ability to withstand multipath fading and inter-symbol interference (ISI), as well as exhibit resilience against inter-carrier interference (ICI) and Doppler spread. In recent research, several filter-based methods have been suggested, including Filter Bank Multicarrier (FBMC), as well as various Orthogonal Frequency Division Multiplexing (OFDM) based techniques such as Universal Filtered Multicarrier (UFMC). Orthogonal Time-Frequency Space (OTFS) technique has been identified as a promising candidate waveform for 6G, particularly in high-mobility scenarios, where it has demonstrated superior performance compared to traditional OFDM-based techniques. The OTFS method offers an advantage in that it can be considered the pre-and post-processing stages for techniques based on OFDM. This papaer presents the design (OTFS) using (UFMC) technique. Additionally, a novel structure is proposed for coded/uncoded UFMC-based OTFS technique, which combines the advantages of both strategies while mitigating their limitations. The results of our analysis demonstrate that the UFMC-based OTFS system exhibits superior performance in terms of error probability and time-spectral efficiency compared to the OFDM-based OTFS system.

1. Introduction

Each generation of communications technology brings about a shift in the primary emphasis of the network. The 2G and 3G periods primarily focused on interpersonal communication facilitated by voice and text. The advent of 4G marked a significant transition towards extensive data consumption, whereas the era of 5G has shifted its attention towards linking the Internet of Things (IoT) and industrial automation systems. During the 6G age, there will be a seamless integration of the digital, physical, and human realms, resulting in the stimulation of extrasensory experiences. The integration of intelligent

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information systems and powerful computational skills would greatly enhance human efficiency and fundamentally transform our lifestyles, work practices, and environmental care. Due to the increased requirements for systems ,6G networks must have a more reliable connection as introduced by Wang *et al*., [1].

The 6G networks encompass various scenarios, such as communication via non-terrestrial networks, high-speed trains, and drones. The rapid movement of a communication endpoint causes rapid changes in the channel, which reduces the coherence time and may negatively impact the effectiveness of traditional OFDM. The candidate modulation technique for massive connectivity is expected to provide enhanced reliability and faster data transfer rates compared to the existing 4G and 5G networks, particularly on user equipment. Furthermore, the utilization of massive Multiple Input Multiple Output (mMIMO) has been recognized as a potential application of 6G technology as introduced by Serghiou, *et al.,* [2].

The presentation of plausible arguments for mitigating lower delay spread, including the implementation of spatial filtering within beamforming and the reduction of cell sizes, was conducted by Zhang,Natarajan and Krishnaswamy, [3]. The aforementioned approaches are anticipated to play a crucial role in future mobile communication networks as a result of developments in network aggregation, management of the extension of the system from point of view of array antennas and subcarriers which leads to more propagation challenges.

Additional determination schemes for low delay spread are presented by several authors [4,5]. The Universal Filter Multicarrier (UFMC) technology is a promising candidate for the upcoming generation of communication networks. As a result, UFMC can effectively allocate the available time-frequency sources for optimal performance. The primary benefit of UFMC technology is demonstrated through its ability to reduce out-of-band emissions (OoBE) in system performance. This reduction significantly decreases the impact of sidelobe interference on adjacent subchannels, thereby enhancing the system's resilience against intercarrier interference (ICI) as presented by Wen, *et al.,* [6]. The UFMC system can be regarded as an intermediary technology that amalgamates the uncomplicated implementation of OFDM and the interference-resistant nature of FBMC. Despite the numerous benefits of the UFMC system, as previously stated, its status as a multicarrier transmission technology results in a significant peak-to-average power ratio (PAPR), as noted by Fathy, *et al.,* [7].

Several multicarrier signalling approaches have been suggested for incorporation in the next generation of wireless mobile networks, each with advantages and disadvantages, has been presented by authors [8 - 10]. The concept of high mobility refers to the ability of a system or entity to move quickly and efficiently. It is often used in the context of transportation, where high mobility is desirable for individuals and goods to reach their destinations promptly and effectively. In other fields, such as military strategy or sports, high mobility can also be a crucial factor in achieving success. Recently, there has been a growing interest in the OTFS technique as presented by Hong, *et al.,* [11].

The delay-Doppler domain's channel sparsity and fixed channel gain contribute to reduced complexity and enhanced resilience. The OTFS technique's complete diversity enables linear throughput scaling with many antennas despite channel Doppler, as stated by Raviteja, *et al.,* [12].

Furthermore, the utilization of OTFS facilitates the efficient and robust compression of signals, a crucial characteristic of the extensive array antennas employed in large MIMO systems [13- 15]. Farhang, *et al.,* [16], used the capability of the OTFS and established a connection between OTFS and OFDM as OFDM-OTFS. Therefore, inspired from the OTFS's capability, we enhance the UFMC by using the OTFS technique to go further than the previous research achievements.The proposed UFMC-based OTFS technique merges the advantages of OTFS with those of the UFMC modulation [17-18].

Pulse-shaping schemes have emerged as a significant factor in recent academic publications. The implementation of new structures is proposed by Strohmer, et al., [19] as a means of enhancing time-spectral efficiency. Baki, et al. discuss the optimization of filtering and pulse shaping, [20] as a means to mitigate the impact of inter-symbol interference (ISI) and inter-carrier interference (ICI), while Das, et al., [21] presented pulse shaping as a technique to enhance the signal to interference-plus-noise ratio (SINR). The scholarly works referenced in the text, specifically [22-25], have delved into the study of channels that exhibit high variability over time, which can be attributed to the presence of carrier frequency offset (CFO) in the context of OFDM technology. Abdel-Atty et al., [26], has introduced a new prototype pulse shaping filter. Zak [27] has introduced the 2D signal representation in mathematics.The utilization of time-frequency diversity transmission has been suggested by many authors in the literature.For instance a RAKE receiver is detailed by Sayeed, et al., [28-30] that operates in the delay-Doppler domain and leverages the temporal and spectral dispersion concurrently while expanding to the multi-antenna scenario. Ma, et al., [32,33] designed precoders and illustrated various ways to design the precoders. The OTFS technique distinguishes itself from previous approaches by operating in the time-frequency domain instead of the delay-Doppler domain, potentially sacrificing complete diversity gain. Hence, the OTFS approach exhibits minimal interference and intersymbol interference, and can attain complete variety by means of appropriate design in the delay-Doppler domain. As a pioneer, Hadani, et al., [33] designed the OTFS technique, and then many researchers started to follow, such as [34-41].

The main contributions of this paper can be summarized as follows:

- **UFMC-Based OTFS**: This paper proposed the concept of UFMC-based OTFS, which combines UFMC and OTFS, offering a novel approach for multicarrier signaling in 6G networks.
- **Improved Performance**: The UFMC-based OTFS structure is shown to outperform traditional OFDM-based OTFS systems, in terms of error performance for high mobility scenario, making it a promising candidate for 6G wireless communication networks.
- **Efficient Frequency and Time Resource Utilization**: The UFMC-based OTFS system is highlighted for its efficient utilization of frequency and time resources, making it suitable for situations with limited frequency bands in future wireless mobile communication networks.
- **Robustness Against Interference**: The UFMC-based OTFS structure is demonstrated to be robust against inter-symbol interference (ISI) and inter-carrier interference (ICI), making it a suitable choice for carrying Ultra-Reliable Low-Latency Communication (URLLC) packets, a key objective of 6G.
- **Extension of OTFS Capabilities**: The paper extends the capabilities of the OTFS technique by integrating it with UFMC, resulting in enhanced resilience and adaptability in high-mobility scenarios and under challenging channel conditions.

The remaining sections of the paper are organized as follows: Section 2 discusses the OTFS Basics and the proposed UFMC-based OTFS system, Section 3 presents the simulation results. Finally, Section 5 contains concluding remarks.

2. OTFS Basics and the proposed UFMC-based OTFS

The system model is shown in figure 1, explaining the difference between the domains.

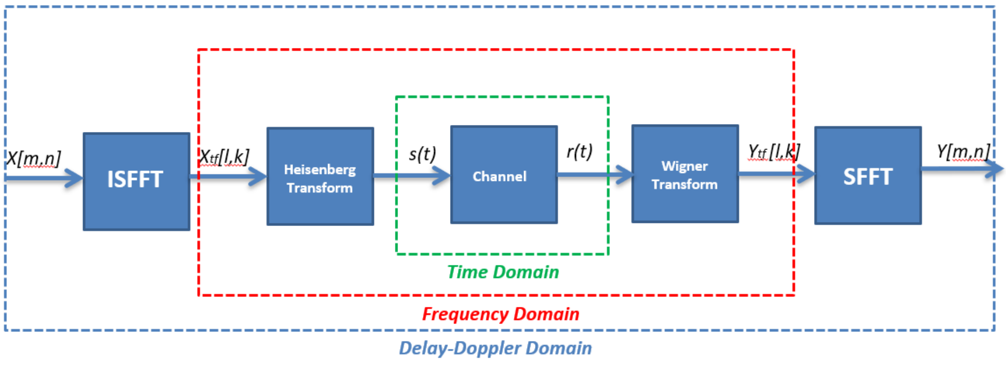

Fig. 1 OTFS system model.

The explanation of the basic model was investigated by Eldemiry et al,[42], exploring the mathematical model of the Basic OFDM based OTFS and the different detection methods. The difference between OFDM, FBMC, and UFMC as promising multicarrier techniques can be illustrated in Figure 2. While OFDM modulates a carrier per the full band, FBMC uses a prototype filter to filter per subcarrier. On the other hand, UFMC can be considered as a technique between OFDM and FBMC, based on filtering per subband (a group of subcarriers), [43].

For a briefing, as shown in Fig.1, the modulator of OTFS modulates $X[m,n]$ in the delay-Doppler domain to the time-frequency domain $X_{tf}[l,k]$ using ISFFT. Then, the **Heisenberg transform** is made to $X_{tf}[l,k]$ for the conversion to the time domain signal $s(t)$, and the **Wigner transform** is used at the receiver to convert $r(t)$ to the time-frequency domain and then to the delay Doppler domain using SFFT before symbol demodulation.

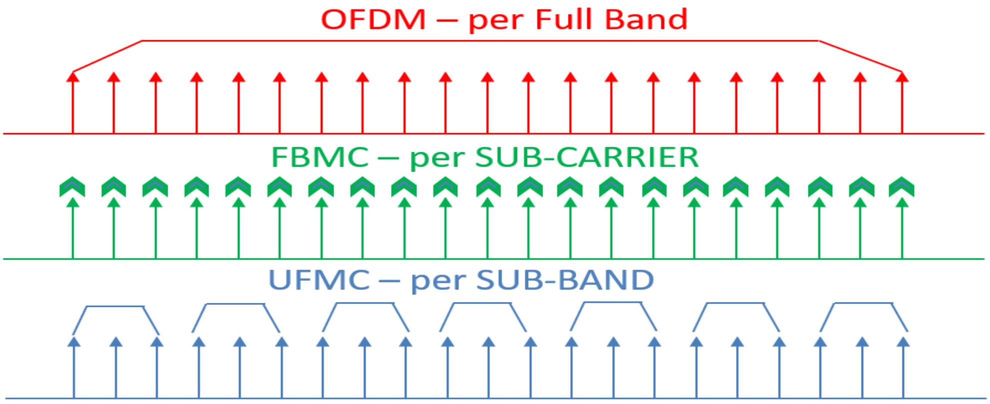

Fig. 2. Filtering methods in OFDM, FBMC and UFMC techniques.

The system model of the proposed UFMC-based OTFS is shown in figure 3,illustrating the different blocks of the system.

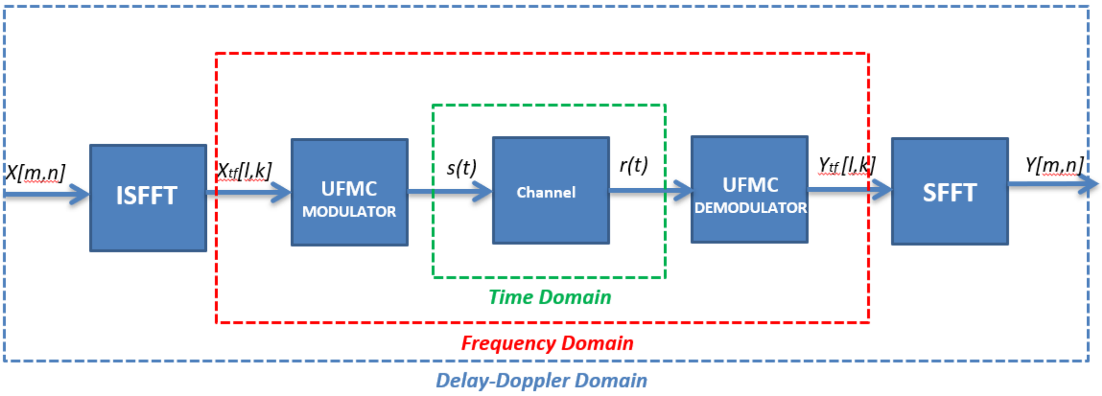

Fig. 3. UFMC-based OTFS system model.

The UFMC-based OTFS is built utilizing five fundamental blocks. The input data undergo conversion into the delay-Doppler domain after being mapped. Afterwards, the 2D delay-Doppler symbols are converted into 2D symbols in the time-frequency domain through the use of the Inverse Short-Time Fourier Transform (ISFFT). The UFMC modulator block utilizes the Fourier transform and filter to convert symbols from the time frequency domain to the time domain. The UFMC demodulator block at the receiver will convert the data at the same reversed sequence of modulator as shown in figure 3.

Considering that $X[m,n]$ in the delay-Doppler domain are transformed into the time-frequency domain employing the ISFFT as follows:

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

for $l = 0,...,M-1, k = 0,...,N-1$ where $X_{tf} \in C^{M\times N}$ stands for the time-frequency domain sent samples matrix.

The ISFFT corresponds to a 2D conversion that takes a *M*-point DFT of the columns of **X** and an *N*-point inverse DFT (IDFT) of the rows of **X**.
Next, a time-frequency modulator, which is the equivalent to **Heisenberg transform** in the basic OTFS, converts the 2D samples $X_{tf}[l,k]$ to a continuous-time waveform $s(t)$ using a transmit waveform $u_{l,k}(t)$ using the UFMC scheme instead of OFDM, as

$$s(t) = \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} X_{tf}[l,k] u_{tx}(t-kT) e^{j2\pi l \Delta f (t-kT)} \quad (2)$$

where $$u_{l,k}(t) = u(t-kT) e^{j2\pi l \Delta f (t-kT)} \quad (3)$$

Including $e^{j\theta k,l}$ which is the phase difference, i.e.,

$$s(t) = \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} X_{tf}[l,k] u(t-kT) e^{j(2\pi l \Delta f (t-kT) + \theta_{k,l}} \quad (4)$$

The received signal at the channel output is written as:

$$r(t) = \sum_{i=1}^{N} h(t,i) s(t-i) \quad (5)$$

The symbols that have been received are decoded, which is equivalent to the **Wigner transform** in the basic OTFS, and converted into the time-frequency domain by projecting the received signal $r(t)$ onto $u_{l,k}(t)$, using the UFMC scheme instead of OFDM, which is

$$Y_{tf}[l,k] = \int_{-\infty}^{\infty} r'(t) u_{l,k}^{*}(t) dt \quad (6)$$

where $r'(t)$ stands for the received signal, and the symbol of * represents the complex-conjugate operator.

The resulted signal, which will transform the symbol from the time-frequency to the delay-Doppler domain as:

$$Y[m,n] = \frac{1}{\sqrt{NM}} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} Y_{tf}[l,k] e^{-j2\pi(\frac{nk}{N} - \frac{ml}{M})} \quad (7)$$

It is important to note that, especially in cases when there are a lot of symbols and time slots, the UFMC-based OTFS is far less difficult than traditional OTFS. The separation of the ISFFT and SFFT from the OTFS modem blocks, where the OTFS modulator integrates the Heisenberg transform and the OTFS demodulator employs the Wigner transform, is the foundation for the OTFS's greater complexity compared to the UFMC-based OTFS. Therefore, by connecting the ISFFT and SFFT to the UFMC modulator and demodulator, respectively, the UFMC-based OTFS significantly reduces the computational complexity.

3. Simulation Results

This section presents the simulation results to demonstrate the significant benefits of the proposed UFMC-based OTFS system. Table 1 displays the parameters used in the simulation. These settings are meant to be comparable to the implementation of OTFS. Therefore, the simulation results provided can be considered as a valid benchmark for comparing OFDM-based OTFS and UFMC-based OTFS.

An OTFS scheme offers a significant advantage in terms of performance in scenarios involving high mobility. In comparison to signaling strategies like OFDM based OTFS, which provide unfavorable outcomes, OTFS scheme proves to be more suited. In regard to this issue, we conducted an analysis of our system using OFDM based OTFS. Subsequently, we compared it to our suggested UFMC-based OTFS, focusing on factors such as the relationship between bit error rate (BER) and signal-to-noise ratio (SNR).

Table 1
Simulation parameters of BER vs. SNR

Name	Symbol	Value
Velocity	V	60 -120 Km/h
Subcarriers Number	M	32
Symbols Number	N	32
Spacing between Subcarrier	Δf	15 kHz
Carrier Frequency	f_c	40 GHz

In Figure 4, the BER against SNR of the OFDM-based OTFS technique and UFMC-based OTFS technique with different velocities of 60 and 120 Km/h Also, applying Chebyshev filter. It is clear that with the higher BER performance of our proposed system as SNR increases with the best performance for the proposed system in both cases of the two velocity scenarios.

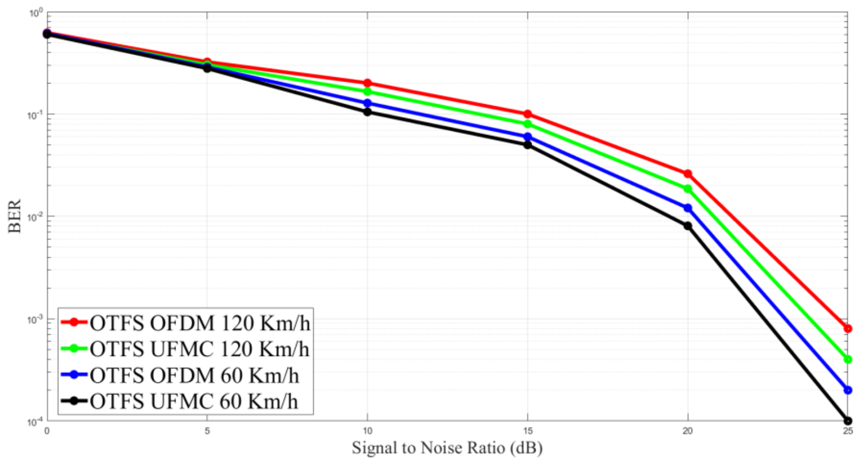

Fig. 4. OFDM-based OTFS versus UFMC-based OTFS with different velocities

In Figure 5, the comparison was held between the different types of filters [44], which can be used in our proposed UFMC-based OTFS; the results clearly show that the best performance was for the

Chebyshev filter, as it has the higher BER performance as SNR increases,with the best performance of the proposed system using Chebychev filter.

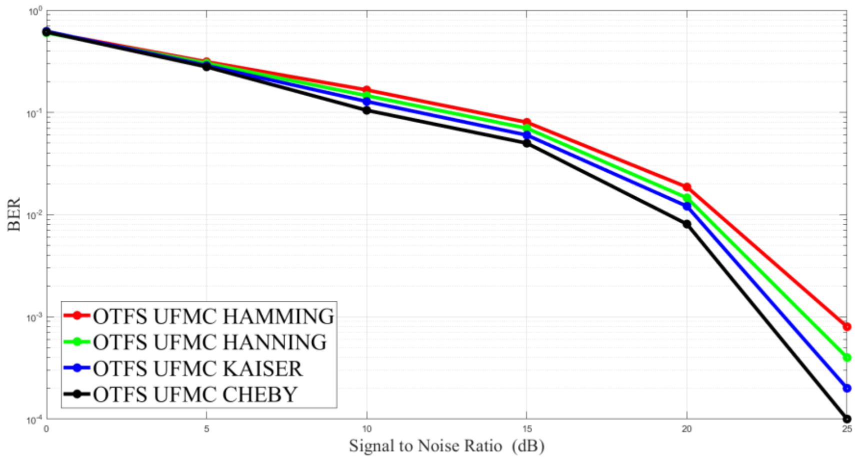

Fig. 5. UFMC-based OTFS using different types of filters

In Figure 6, the comparison was held between the different doppler velocities using our proposed UFMC based OTFS; the results clearly show that the propsed system keeps good performance even in high doppler velocities.

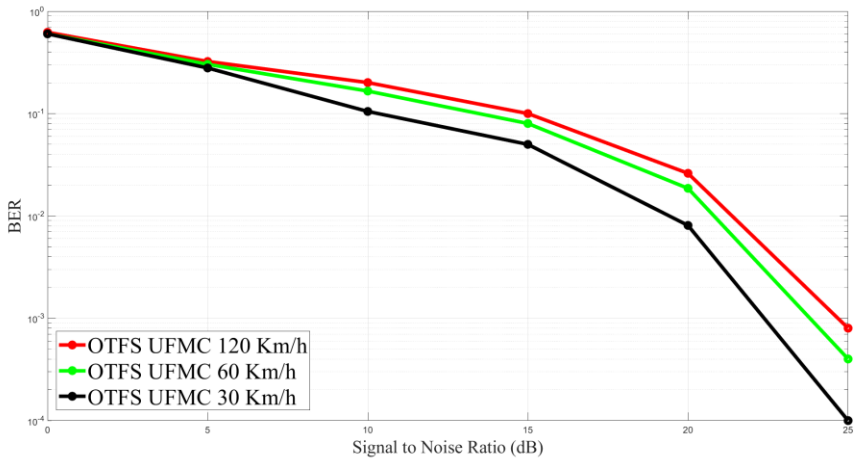

Fig. 6. UFMC-based OTFS with different velocities

In Figure 7, the effect of doppler velocity is clarified with the relation between SNR per bit and BER which shows that the higher doppler the higher BER and vice versa.

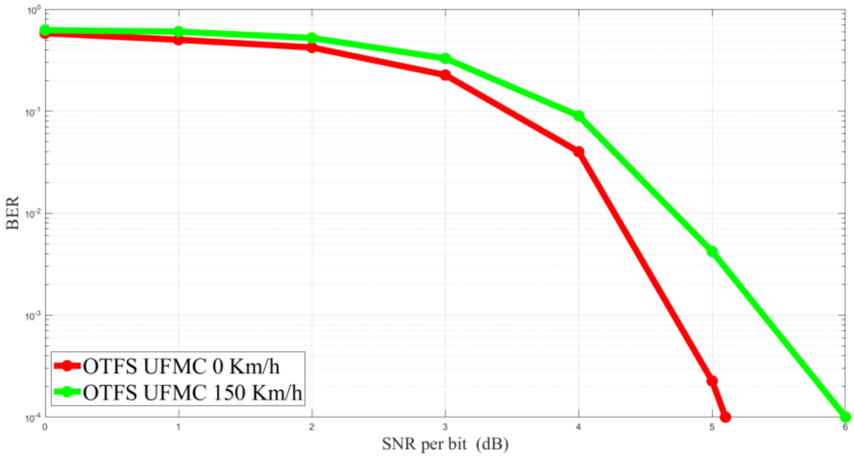

Fig. 7. UFMC-based OTFS Relation between BER and SNR per bit

4. Conclusion

This research paper presents the introduction of UFMC-based OTFS, an enhanced version of the UFMC framework, utilizing OTFS. This proposed system utilizes delay-Doppler and time-frequency domains to augment the achievements of the previous studies. OTFS can be broadly defined as a time-frequency approach that transmits information symbols utilizing a two-dimensional time-frequency lattice. The OTFS can be understood as a method that spreads signals in both time and frequency domains. The computational complexity can be managed by connecting the ISFFT and SFFT with the UFMC modulator and demodulator, respectively.The OTFS technique is a powerful method of transmitting data over channels that change over time. It can be enhanced by combining it with the UFMC multicarrier approach with certain adjustments.

The incoming signal in UFMC-based OTFS is inserted to the UFMC demodulator using a filter. The selection of an appropriate filter relies on the localization of time-frequency and the density of symbols. On the other hand, the Chebychev filter provides more advantageous outcomes in reducing the risk of errors and enhancing the spectral efficiency. OFDM, filtered-OFDM (F-OFDM), and UFMC are multicarrier algorithms that exhibit a significant increase in spectral efficiency with a larger number of subcarriers.

The simulation results have shown that the UFMC-based OTFS optimizes the utilization of the resources more effectively. UFMC-based OTFS demonstrates resilience to both intersymbol interference (ISI) and intercarrier interference (ICI). This makes the proposed system suitable for high mobility systems, as evidenced by comparing its performance with systems operating at varying velocities.

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