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Evolution Potential Waveform Design of Orthogonal Time Frequency Space Modulation for Next-Generation Technologies

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ABSTRACT

As telecommunication systems continue to evolve, the demands of next-generation technologies, like 6G, bring new challenges that require innovative solutions. Orthogonal Time Frequency Space (OTFS) modulation is emerging as a strong candidate for meeting these challenges. In contrast to current approaches, OTFS guarantees uniform channel performance for all transmitted symbols, regardless of the mobility or data rate of the environment. This paper examines OTFS's fundamental design elements and evaluates it in comparison to other state-of-the-art modulation schemes, including Affine Frequency Division Multiplexing (AFDM), Generalized Frequency Division Multiplexing (GFDM), and Orthogonal Frequency Division Multiplexing (OFDM). The results demonstrate that OTFS not only improves spectral efficiency by as much as 20% in some cases, but it also drastically lowers error rates in difficult situations. Based on these findings, OTFS has great promise as a technology that can help 6G communication systems achieve the dependability and adaptability that are necessary for this standard.

1. INTRODUCTION

In part to ongoing social scientific and technological innovation, next generation systems have evolved from 1G to 5G and beyond, and in the following decades will reach 6G [1-3]. It shows itself in two main ways: first, the exponential growth of data traffic; and second, the outplacement of the network system's capacity to handle the expanding services of new apps [4].

Nowadays, an OTFS modulation technique has evolved with better performance than other modulation techniques [5]. In comparison to OFDM, the OTFS system effectively exploits full diversity and provides a high data rate, resulting in a seamless trade-off between data rate and processing gain.

These restrictions highlight the importance of developing new waveforms capable of satisfying the stringent performance requirements of potential 5G use cases [6-8].

Delay Doppler (DD) domain signal representation, which offers the advantages of strong Doppler and delay resistance in extremely dynamic and complicated situations, is the basis of OTFS's innovative framework for examining the interaction between information symbols and the wireless channel [9, 10].

OTFS is also a great technology for realistic hostile wireless applications because it has many benefits over OFDM, including a lower peak-to-average power ratio (PAPR), less signaling overhead due to a less cyclic prefix frame structure, and the ability to work even when there are synchronization errors [11, 12]. Since OTFS is a generalization of both CDMA and OFDM, it incorporates the most desirable features of both. This paper presents a examine the advantages that arise from the use of OTFS technologies in specific application contexts. A popular and easily accessible technical tool for achieving high-speed transmission and reducing multipath channel interference is OFDM. Nevertheless, OFDM is not appropriate for usage in high-mobility situations and performs poorly against the effects of Doppler shift. OTFS, technique maps data symbols to the DD domain. By fully enlarging each symbol in the time-frequency (TF) domain, the channel can effectively reduce interference and fading, as each data symbol experiences nearly similar effects [13-16]. The scientific contribution of writing this research paper is summarized as follows:

1- Design and implementation of a proposed system using OTFS technology and stating the most prominent characteristics and analysis using the MATLAB program, the paper discussed performance bit error rate, types of modulation scheme, power efficiency, and throughput calculation were analyzed of proposed OTFS system
2- Measurements and comparison the robustness in SNR and consistency in BER between modern technologies of wireless communication systems OTFS, GFDM, OFDM and AFDM.
3- The proposed system of OTFS implemented in this research paper is considered the best among the other techniques mentioned above, and the results are summarized in Table 1 and Table 2.
4- OTFS's structure allows for better error correction capabilities, making it more resilient to noise and interference, which is critical in Telecommunication

systems.

The impulse response of the channel is characterized by rapid time-varying features in the time-frequency domain, and it links groups of reflectors with channel taps in the DD domain. It reduces the number of parameters required for channel estimation because only a small number of reflectors show different delay and Doppler shift values. For this reason, investigating OTFS as a unique modulation approach is essential to developing a wide variety of dynamic high-speed applications [17]. The review literature currently available only covers a significant portion of OTFS-based technology [18-20]. The paper is organized with main points, firstly introduced of modulation techniques for 5G are OTFS, OFDM, GFDM, and AFDM. The second paragraph contained the literature for among OTFS, OFDM, GFDM, and AFDM. Thirdly paragraph contained the OTFS transceiver system design and the results analyze. While discussion of all techniques is mentioned in the fourth paragraph and summaries in Tables 1 and 2. Finally, the conclusions are displaying the last paragraph.

Table 1. Comparison among OFDM, GFDM, AFDM, and OTFS aspects

Aspect	OFDM	GFDM	AFDM	OTFS
Modulation Domain	Frequency	Frequency	Time-Frequency	Delay-Doppler
Symbol Mapping	Symbols mapped directly to subcarriers in frequency domain	Symbols mapped to multiple time slots and subcarriers in blocks	Symbols mapped across time and frequency using affine transforms	Symbols mapped in delay-Doppler domain
Handling of Doppler Effects	Poor due to high sensitivity to time-selective fading	Moderate; some resilience due to flexibility	Good resilience by spreading symbols in time-frequency domain	High resilience; leverages delay-Doppler diversity
Spectral Efficiency	Moderate (cyclic prefix reduces efficiency)	Moderate to high; customizable with no cyclic prefix required	High due to no cyclic prefix; affine transforms optimize usage	High due to full channel diversity
Out-of-Band Emission	High due to rectangular pulse shaping	Low; uses filtered pulse shaping	2. Moderate; depends on transform design and filtering	Low; 2D spreading reduces spectral leakage
Symbol Duration	Long, determined by subcarrier spacing	Flexible; adjustable time slots within a block	Variable, can adapt to channel dynamics	Long due to spreading across delay-Doppler symbols
Cyclic Prefix Requirement	Yes; required to mitigate ISI	Not required; utilizes pulse shaping	Not required; transform-based delay handling	Not required; inherent resilience to delay spread
Latency	Low; single-symbol duration	Moderate; multi-symbol blocks introduce slight latency	Moderate; depends on symbol spreading	Moderate to high due to processing in delay-Doppler domain
Channel Requirements	Time-invariant, frequency-selective channels	Frequency-selective or moderately time-variant channels	Handles highly time-variant channels	Excels in highly time-variant (e.g., high-mobility) channels
Receiver Complexity	Low; simple FFT-based processing	Moderate to high due to interference management	High; requires affine transform processing	High; needs delay-Doppler processing and complex equalization
Synchronization Requirements	High sensitivity to timing offsets	Moderate due to flexible pulse shaping	High; time-frequency spreading needs precise timing	High; Doppler delay grid requires fine synchronization
Computational Complexity	Low to moderate; FFT-based	Moderate; involves pulse shaping	High; affine processing and spread transform	High; delay-Doppler domain processing adds complexity
Deployment Use Cases	Wi-Fi, broadband communications, low mobility	Flexible spectrum use, moderate mobility, 5G NR research	High-mobility applications, vehicular and high-Doppler scenarios	V2X, satellite, high-speed mobility, 6G research

Table 2. Summary for throughput, power efficiency, and bit error rate for OFDM, GFDM, AFDM, and OTFS aspect

Aspect	OFDM	GFDM	AFDM	OTFS
Throughput	Moderate in low-mobility; reduced in high Doppler conditions due to CP	Moderate to high; efficient use in fragmented spectrum, no CP	High in time-variant channels, resilient in mobility	High, especially in high-mobility; leverages full channel diversity
Power Efficiency	Moderate, high PAPR impacts power efficiency	Moderate; customizable, lower PAPR than OFDM	Higher due to low PAPR and affine transform	Moderate, high processing demands affect efficiency
Bit Error Rate (BER)	Low in static conditions; degrades in high Doppler environments	Moderate; robust with pulse shaping, but self-interference can impact BER	Strong BER in dynamic channels; resilient to Doppler spread	Excellent, with low BER in high-mobility due to delay-Doppler diversity

2. RELATED WORKS

OTFS modulator uses a collection of orthogonal basis functions in two dimensions over a time-frequency grid that corresponds to the resource blocks of an OTFS frame. This modulation technique, as shown in Figure 1, converts data symbols from the DD domain to the time-frequency domain. The OTFS-modulated signals are converted from the TF domain into the time domain using a multi-carrier modulator, such as OFDM, before being sent across wireless channels. In order to recover the sent data symbols, the received signals are transformed back to the DD domain at the receiver using a series of steps that comprise an OTFS demodulator and a multi-carrier demodulator. By adding pre- and post-processing blocks, OTFS modulation may be achieved using both conventional OFDM [21], and pulse-shaped OFDM [22] transceiver topologies, making it a feasible choice [23].

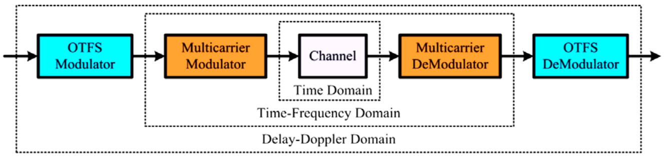


Figure 1. Principle of OTFS modulation and demodulation [23]

Moreover, among the modulation schemes listed (OTFS, GFDM, OFDM, and AFDM), the newest is OTFS and introduced more recently, around 2017, OTFS has emerged as a promising solution for high-mobility scenarios, particularly in 5G and beyond, due to its robustness against Doppler effects and multipath fading [24]. Moreover. Here's a brief overview of each scheme, where OFDM is developed in the 1960s and widely adopted in the late 1990s and early 2000s for applications like Wi-Fi, IMT-Advanced, and digital television [25]. While GFDM is introduced in the early 2010s as an evolution of OFDM to provide more flexibility and efficiency, particularly in supporting non-orthogonal multiple access [26]. Finally, AFDM is conceptually similar to OFDM and GFDM, AFDM has also been explored in the context of 5G systems, but it's generally considered less established than the others [27]. Here's a comparative look at each, they differ in the way they approach frequency and time domains.

2.1 OFDM

OFDM splits the signal bandwidth into multiple orthogonal subcarriers. Data is modulated on these subcarriers using a standard constellation, such as QAM or PSK, moreover, the strengths of OFDM are high spectral efficiency due to the overlapping of orthogonal subcarriers and Robust against frequency-selective fading, especially when used with cyclic prefixes. While the limitations of OFDM are sensitive to time-frequency dispersions caused by Doppler effects (time-selective channels), and requires a cyclic prefix, which reduces spectral efficiency. Moreover, use cases are widely used in telecommunication technologies, Wi-Fi, DVB, and many broadband communication systems [28].

2.2 GFDM

GFDM is a flexible multi-carrier scheme where data symbols are transmitted in blocks with multiple subcarriers and multiple time slots. It utilizes pulse shaping for each subcarrier. The strengths of GFDM are high flexibility, allowing adjustments in time and frequency resources and better spectrum confinement and reduced out-of-band emissions compared to OFDM, making it more suitable for fragmented spectrum use. While the limitations are higher receiver complexity due to interference between subcarriers and symbols (i.e., self-interference) and more challenging synchronization requirements than OFDM. Moreover, use cases are considered for scenarios needing high flexibility and reduced out-of-band emissions, such as 5G use cases with diverse spectrum allocations [29].

2.3 AFDM

AFDM uses affine transforms, allowing it to handle time-variant channels better by spreading data across both time and frequency. The strengths are better suited for highly time-varying channels, such as those seen in high-mobility environments (e.g., vehicle-to-vehicle communication) and provides resilience against Doppler shifts and delays by distributing data across both time and frequency domains. While the limitations of AFDM are more complex modulation and demodulation processes compared to standard OFDM, increasing computational needs and newer technology with less standardization, making widespread adoption challenging. Moreover, use cases are potentially useful in high-mobility applications like vehicular networks and dynamic environments where channel variation is significant [30].

2.4 OTFS

OTFS is a 2D modulation scheme that maps data symbols in the Delay-Doppler domain rather than the time-frequency domain. This approach enables the modulation to handle time-varying channels more effectively. The strengths are excellent performance in High-Doppler environments, making it suitable for high-speed scenarios and provides inherent robustness to time-frequency dispersion and exploits the full channel diversity, which improves reliability. While limitations of OTFS are complex receiver design due to the need for Delay-Doppler domain processing and higher computational cost and more complex implementation. Moreover, use cases are ideal for high-mobility applications like vehicle-to-everything (V2X) communications, satellite communications, and other high-speed scenarios [31].

3. OTFS TRANSCEIVER SYSTEM

In this research, Figure 2 shows a system design implementation of the OTFS transceiver. we investigate the window design for OTFS modulation in order to increase channel estimation and data detection performance while also taking into account other scheme modulations. The important contributions of this work are listed below:

•Our analysis examines how windowing affects OTFS systems, including channel effectiveness, estimate performance, transmit power, and noise covariance matrix.

•The TX window allocates power in the TF domain, while the RX window generates colored noise.

•Using a window at either the transmitter or receiver results in the same error floor in effective channel estimation.

The main contribution of the research paper represents study assesses the effectiveness of several modulation techniques. A simulation analysis is conducted, and the compatibility framework explains the parallels and discrepancies between OTFS modulation techniques and OFDM, GFDM, and AFDM modulation techniques. According to simulation data, OTFS modulation offers better BER performance.

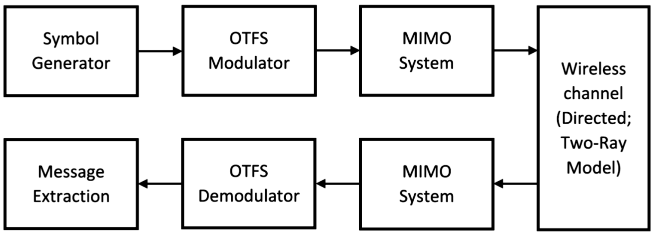


Figure 2. The block diagram of the OTFS transceiver [32]

4. PERFORMANCE RESULTS

The system design simulates a communication link employing OTFS modulation in MATLAB and demonstrates its inter-carrier interference (ICI) cancelation capabilities when compared to traditional OFDM modulation. This simulation includes a simple OTFS transmitter and receiver, data filtering across a channel with mobile scatterers, and channel equalization in the DD domain utilizing estimated channel parameters to detect sent code-words. OTFS modulation eliminates the need to test the channel on a regular basis because it transmits data in the DD domain. This domain depicts moving scatterers with delay (transmission delay) and speed (Doppler shift) relative to the receiver. Given a finite number of scatterers, the channel representation of the scatterers becomes a sparse matrix. Efficient channel estimation and equalization approaches make use of this sparsity. Furthermore, if the scatterers retain a constant velocity, the channel becomes quasi-stationary in the DD domain. The necessity for pilot transmissions lowers, but effective throughput increases.

The main steps of the system design are:

•Generate a pilot signal in the DD domain and modulate it using OTFS.

•Simulate the high-mobility channel and add noise to the received signal.

•Demodulate the received signal using OTFS and estimate the Delay-Doppler channel response.

•Generate data for transmission and modulate it using OTFS and other techniques.

•Transmit the data through the high-mobility channel and equalize the received signals using OTFS and other techniques.

•Calculate the performance of OTFS.

Figure 3 shows the BER performance of orthogonal time-frequency space simulation using QPSK modulation scheme and we can note the effect of SNR in dB on the proposed system design.

Figure 4 shows the power efficiency of orthogonal time-frequency space simulation and we can note the power efficiency is optimized and increase to maximum power efficiency value when the signal-to-noise ratio is least.

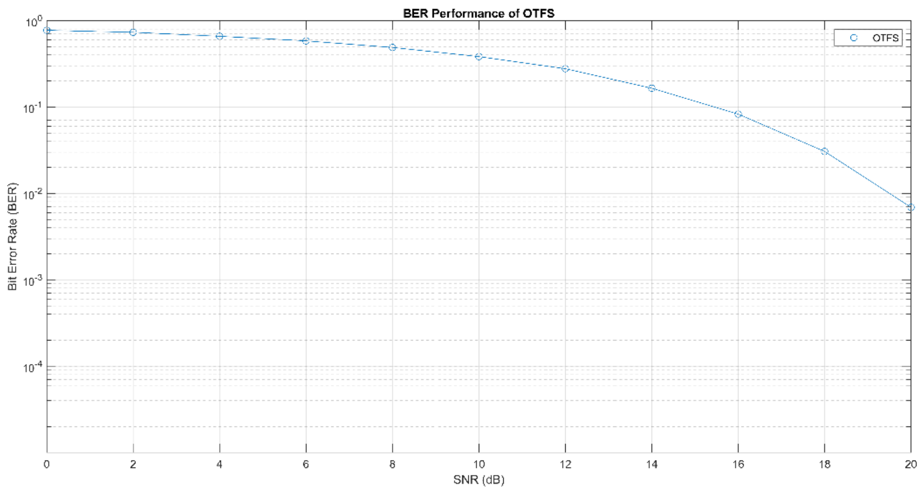


Figure 3. Simulation of bit error rate performance of OTFS modulation scheme

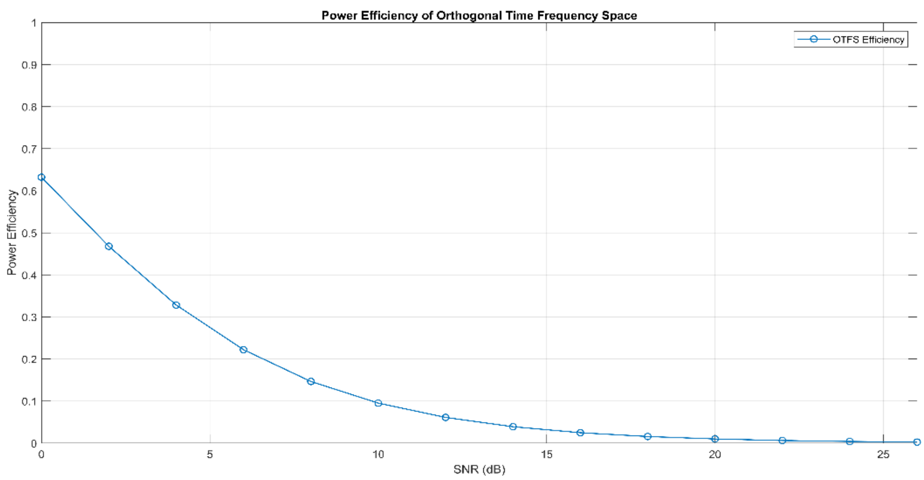


Figure 4. Power efficiency of OTFS

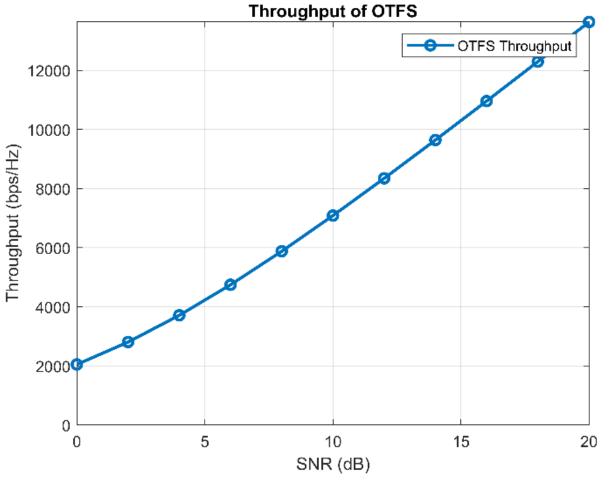


Figure 5. Throughput calculation for OTFS

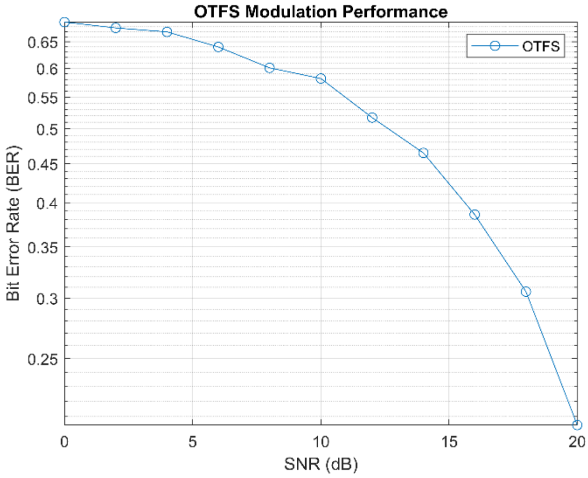
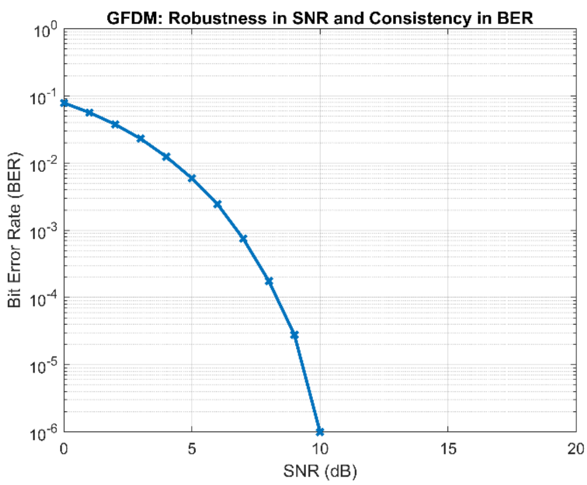


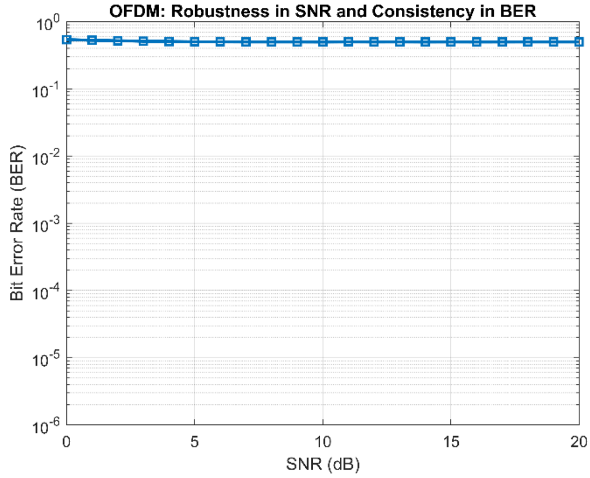
Figure 6. OTFS modulation performance

Moreover, the paper discusses one of the important points for any communication system design which is the throughput of the proposed system design for OTFS.

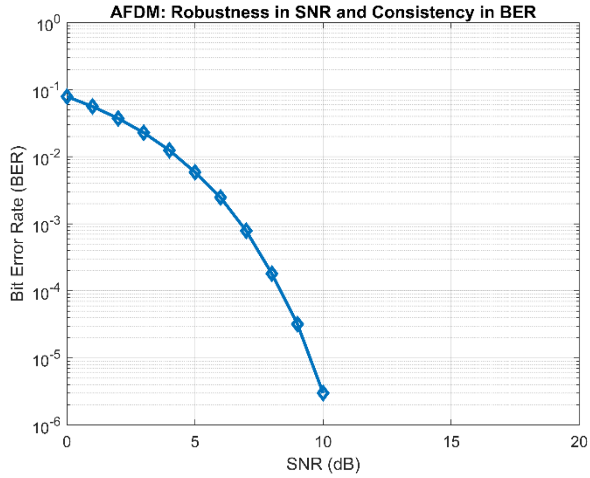
Figure 5 shows the analysis and effect of parameters such as the number of subcarriers, number of symbols used with values of coding rate is 1/2. While Figure 6 shows the overall of orthogonal time frequency space modulation performance.



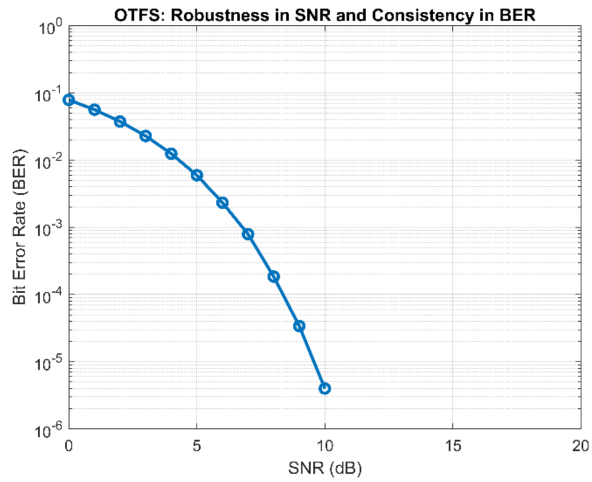
(a) GFDM



(b) OFDM



(c) ADFM



(d) OFTS

Figure 7. Comparison performance between various modulation techniques

After we get simulations and results of orthogonal time frequency space modulation performance in the figures above. Also, one of the contributions of research paper discusses the comparison among OTFS and other techniques in 5G such as OFDM, GFDM and AFDM to optimize the proposed results of OTFS which is to improve the performance of OTFS technique the best.

Figure 7 shows the OFDM, GFDM, AFDM, and OTFS modulation are all multicarrier modulation techniques, but they differ in the way they approach frequency and time domains.

As conclusion, the Figure 8 shows the effect of SNR and consistency in BER for OFDM, GFDM, AFDM) and OTFS modulation OTFS.

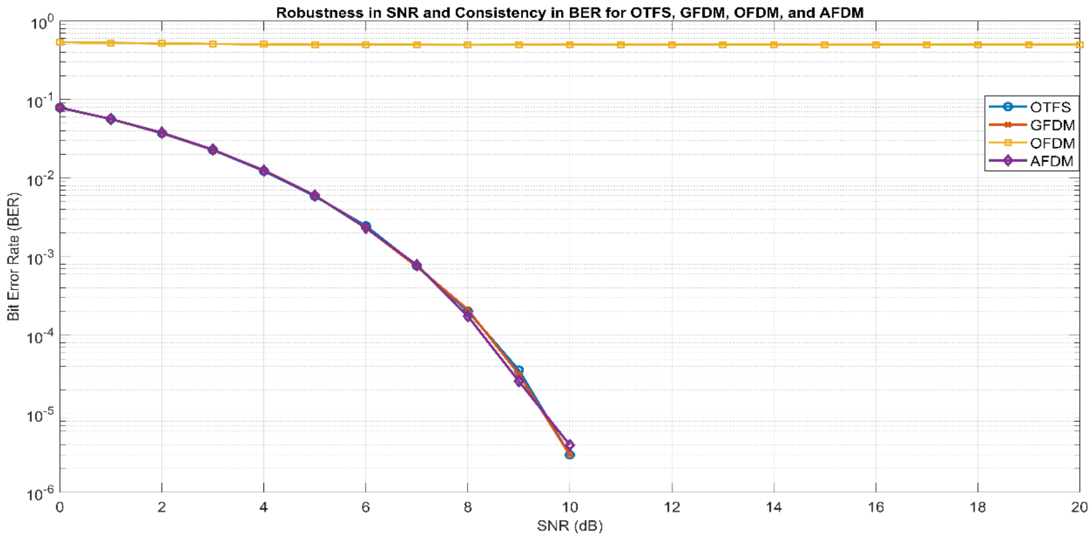


Figure 8. Robustness in SNR and consistency in BER for OTFS, GFDM, OFDM and AFDM

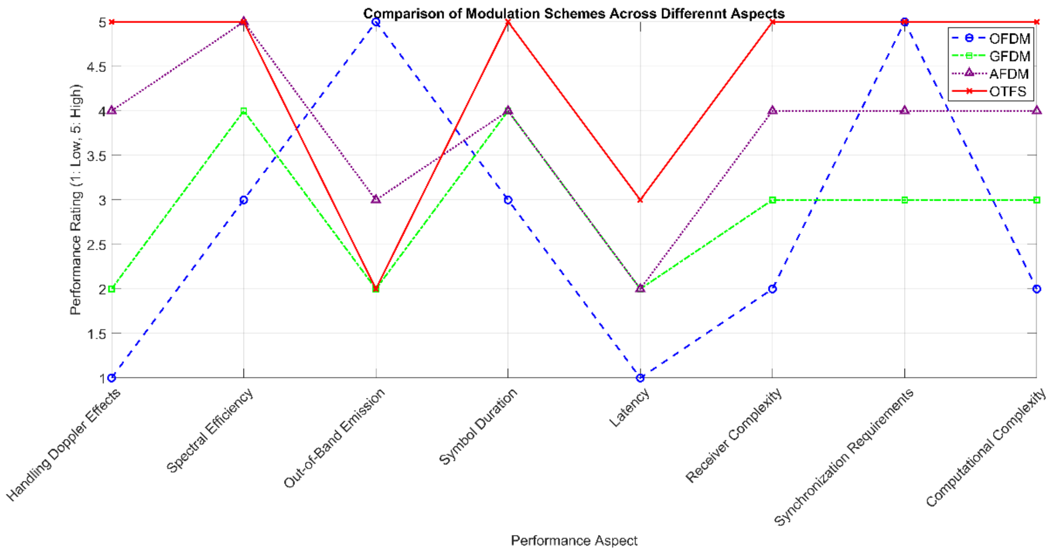


Figure 9. Evaluating modulation schemes from various perspectives

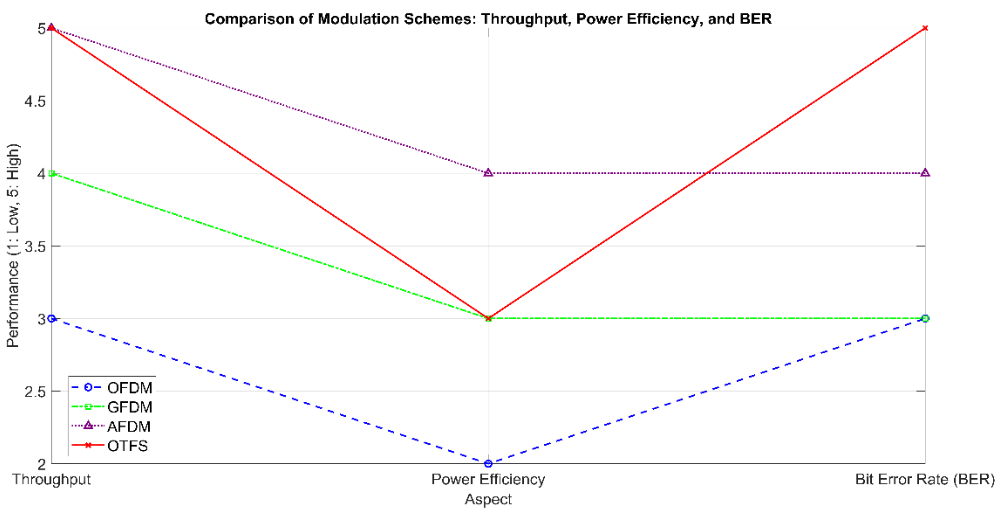


Figure 10. Graphical representation of the throughput, power efficiency, and BER comparison of OFDM, GFDM, AFDM, and OTFS

Table 3. Comparison of OTFS, OFDM, GFDM, and AFDM: Trade-offs across different aspects

Aspect	OFDM	GFDM	AFDM	OTFS
Error Performance	Performance degrades significantly under high mobility (Doppler shifts and ICI).	Improved over OFDM in some high-mobility scenarios but still susceptible to ICI and residual interference.	Better Doppler tolerance than OFDM but struggles in extreme mobility.	Best error performance in high-mobility environments, minimizing Doppler shift impacts and multipath fading.
Channel Estimation	Relies on pilot-based channel estimation, prone to errors in high-mobility.	Requires complex pilot schemes and interference management for accurate estimation.	More robust to Doppler shifts with simpler estimation than GFDM, but still challenges in high mobility.	Utilizes sparse channel estimation in the delay-Doppler domain, requiring fewer pilot transmissions and offering more accurate estimation.
Adaptability to Mobility	Struggles with high mobility due to sensitivity to Doppler effects and delay spread.	Can adapt to different mobility levels but performance drops in extreme conditions.	Adaptable to moderate mobility but less effective in high-mobility and extreme conditions.	Highly adaptable to high-mobility scenarios like vehicular communication and UAVs, due to delay-Doppler domain processing.
Robustness to Channel Variability	Low robustness in dynamic channels, especially with varying Doppler shifts.	More robust than OFDM in variable channels but still faces challenges in fast-changing environments.	More robust than OFDM in variable channels but limited in extreme scenarios.	Highly robust to channel variability, including Doppler shifts, multipath, and fading, due to its delay-Doppler domain representation.
System Flexibility	Less flexible in dynamic or multi-user scenarios due to strict orthogonality.	Flexible in time-frequency resource allocation, but at the cost of increased complexity.	Flexible in resource allocation with moderate complexity, suitable for IoT and moderate mobility.	Extremely flexible for high-mobility and high-data-rate scenarios, despite higher complexity.

Moreover, the research paper is summarized in Table 1 offers a more in-depth comparison across key technical and performance metrics, clarifying how each modulation scheme fits various communication scenarios.

In summary, OFDM is efficient for low to moderate mobility applications while GFDM provides flexibility and lower spectral leakage, suitable for fragmented spectra. AFDM handles time-varying channels well and could serve highly dynamic environments. Finally, OTFS excels in High-Doppler environments due to its Delay-Doppler modulation, ideal for high-speed applications.

A graphic comparison of OFDM, GFDM, AFDM, and OTFS modulation techniques is presented in Figure 9 for a number of performance metrics. To help show the merits and drawbacks of each scheme, each aspect is evaluated from 1 (low) to 5 (high), including Doppler handling and spectrum efficiency, among others.

Also, each of these modulation schemes' throughput, power efficiency, and BER are broken down in Table 2.

Each of these modulation schemes offers unique advantages and trade-offs in terms of power efficiency, throughput, and BER performance, which can help guide their selection depending on specific application needs and environmental conditions.

Figure 10 shows a chart comparing OFDM, GFDM, AFDM, and OTFS in terms of power efficiency, throughput, and BER. Each aspect is rated from 1 (low) to 5 (high), illustrating the relative strengths and weaknesses of each modulation scheme across these critical performance metrics.

Here is some code for making a comparison chart in MATLAB that compares and contrasts the performance of four different modulation schemes: OFDM, GFDM, AFDM, and OTFS. Factors including computational complexity, synchronization requirements, symbol duration, out-of-band emission, handling doppler effects, and receiver complexity are all part of this.

After comparing and analyzing the numbers, it is clear that OTFS is a great choice for sophisticated communication systems, particularly in demanding conditions where reliable performance is essential. Table 3 shows the trade-offs in a nutshell, covering all the bases, so you can see how each system performs in different communication settings.

5. CONCLUSIONS

To overcome the problems caused by Doppler shifts and multipath fading in mobile communication, this study emphasizes the possibility of using OTFS modulation. Traditional approaches like OFDM, GFDM, and AFDM suffer in high-speed, dynamic channels. However, OTFS operates in the Delay-Doppler domain and easily handles Doppler shifts. Aerial or vehicular communication are two use cases that benefit greatly from OTFS's exceptional robustness in contexts with large delay spreads, according to the research. In addition to its effectiveness in reducing Doppler shifts, OTFS offers more robust error correction, which is crucial in practical settings for minimizing interference and noise. With its flexible time-frequency resource allocation, OTFS may optimize performance according to changing channel circumstances and achieve higher spectral efficiency, particularly in highly dispersive channels. It is also easier to implement OTFS in hardware since, in some circumstances, its receiver design is simpler than other approaches. According to the results, OTFS shows great promise for upcoming 6G and other next-gen communication systems that will deal with mobile users and complicated channel conditions. There is little doubt that OTFS has several benefits over more traditional forms of modulation, such as its adaptability to different environments and its reduced error rate. To improve its performance in future wireless networks, researchers should look into making it less computationally complex, incorporating it with technologies like massive MIMO, or training it to adjust to different channels.

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