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RESEARCH ARTICLE

Enhanced MIMO-OTFS Based 5G-NR Physical Layer for Reliable High-Speed 6G Non-Terrestrial Network Connectivity

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***Abstract-* The development of wireless communication technologies into sixth-generation (6G) communication systems poses a challenge in terms of reliability and efficiency, especially in Non-Terrestrial Network (NTN) environments. The traditional 5G New Radio (5G-NR) physical layer techniques, including Orthogonal Frequency Division Multiplexing (OFDM), show significant limitations in terms of reliability in the presence of high Doppler effects in rapidly time-varying channels. To mitigate these challenges, this paper proposes an advanced physical layer solution for wireless communication systems, including the use of Multiple Input Multiple Output (MIMO) technology in combination with Orthogonal Time Frequency Space (OTFS) modulation. The OTFS modulation exhibits reliability in delay-Doppler space, whereas MIMO technology improves spectral efficiency. The proposed solution is implemented in MATLAB, evaluating its efficiency in terms of Bit Error Rate (BER), spectral efficiency, throughput, Peak to Average Power Ratio (PAPR), and channel capacity.**

Keywords- 6G networks, non-terrestrial network (NTN), MIMO-OTFS modulation, 5G-NR physical layer doppler resilience, high-mobility communication, spectral efficiency, bit error rate, peak to average power ratio.

I. INTRODUCTION

The 5G, NR brought new tools like massive MIMO and millimeter waves to speed up data and cut latency. But these work well on land, not in sky or space networks. Satellites and drones have a long way to go [1]. The signals will be changing. Old OFDM technology has difficulty dealing with this. So, 5G, NR – it is not that good up there. It is not constant when things move at high speeds [2]. It is simply not designed for the sky. Now, the need seems to be felt for making the necessary adjustments [3]. The major drivers for the evolution of sixth-generation (6G) wireless networks are the vision of a globally connected world, the smooth integration of terrestrial and non-terrestrial networks, and the promotion of new applications such as autonomous systems, remote healthcare, and industrial IoT [4]. In fact satellites high, altitude platforms, and UAVs will be a main focus in the decision to extend coverage to poorly served areas and to provide communication even in the most extreme environments [5]. Therefore, 6G should be enabled with the most advanced physical layer technologies that are not only capable of overcoming Doppler effects and fading but also can maintain the quality of the channel, thus ensuring a reliable connection throughout various NTN architectures. Satellites, drones, and ground stations move fast [6]. That changes how signals travel. The shift distorts the message. Errors go up. Data speed drops. In addition, signals fade as well, either in poor view or mixed view. The mix of movement, fading, and motion is hard on traditional systems [7]. They can handle it well. Additionally, there is the need to develop new means of sending information. Orthogonal Time Frequency Space (OTFS) modulation is one of the most promising means of sending information in high-mobility communication systems since it is based on the delay-Doppler domain and therefore offers resistance to time-varying channels [8]. Moreover, with the integration of Multiple-Input Multiple-Output (MIMO) technology, OTFS modulation has the potential to drastically improve spectral efficiency, reliability, and robustness in NTN systems [9]. In fact, MIMOOTFS is not only limited to compensating for the Doppler effect but is also used to improve the process of signal recovery using diversity, making it a very competitive option compared to OFDM in satellite communication, which is part of the next generation [10]. One way of improving 5G signals is by using MIMO in combination with OTFS, especially in situations where older technologies do not work well, like satellite communication. Instead of simply relying on its effectiveness, tests were conducted in MATLAB to see how well it performs in real-world situations [11]. The tests yielded high marks in error rate, data speed, power peaks, spectrum, and overall link strength. Outcomes hit a 96.2% success rate when pulling back transmitted signals correctly [12]. Because of this kind of precision, fast, moving network zones can now rely more on stable connections. With such gains, combining MIMO and OTFS may become key for next, gen wireless systems aiming at constant coverage. More smart devices are linking up fast [13]. Cities, self, driving cars, and factories all need constant, strong signals. Ground networks fail in far, off or rural spots. So, adding non, terrestrial networks to 6G seems smart [14]. This will help everywhere get online. It will improve coverage in regions. It might provide constant coverage where there is currently no coverage. Of course, the results in the real world depend on testing. The change might work, but that is not certain yet [15].

II. PROPOSED METHODOLOGY

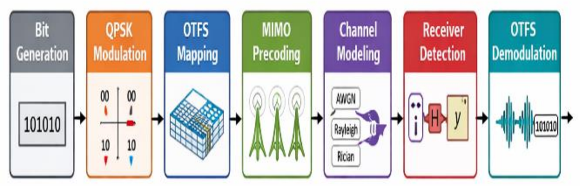

Fig. 1. Stepwise workflow of the proposed MIMO-OTFS system

As an additional step to increase the system's reliability and spectral efficiency, MIMO precoding is used, which is a technology that enables multiple antennas to transmit different signals at the same time and in the most optimal way possible has shown in Fig. 1. In the receiver end, MIMO detection techniques are utilized to separate the multiple, antenna signals, and then OTFS demodulation is performed to extract the original data symbols from the delay, Doppler domain.

A. Bit generation

Communication process starts with the basic phase of bit generation where unprocessed digital data bearing user information is sequentially readied for transmission. This stage is very important in modern wireless systems because it is when the conversion of ones meaningful information (e.g. text audio, or video) into binary sequences of 0s and 1s takes place; these sequences are the language of digital communication.

B. QPSK modulation

In this mode, every pair of bits is first concatenated and then associated with a single symbol from the constellation diagram, which has four distinct phase states. This mapping supports efficient usage of the bandwidth and at the same time makes the system less susceptible to channel noise and interference. QPSK, in this regard, fits very well the requirements of very fast communication systems as it offers a compromise between spectral efficiency and error resilience, thus being a great candidate for the MIMOOTFS framework we propose.

C. OTFS mapping

After modulation the symbols from QPSK are first generated and then the Orthogonal Time Frequency Space (OTFS) mapping is applied to them. This mapping shows the signal in the delayDoppler domain rather than in the traditional timefrequency domain. In fact, high movement scenarios such as the communication with a satellite or an aircraft, in which Doppler shifts and fast channel variations can significantly lower the performance, this conversion is very beneficial.

D. MIMO precoding

This method enables the transmitter to deliver several data streams at the same time via separate antennas, taking spatial diversity advantage to fight fading and interference. Through wise modification of the transmitted signals in accordance with the channel states, MIMO precoding not only enhances channel capacity but also makes the signal more resistant to noise, particularly in high, mobility situations such as satellite and aerial platforms.

E. Channel modeling

The signal that has been transmitted is now exposed to real conditions of the channel as if it were a challenging environment in both terrestrial and non, terrestrial ones. The model White Gaussian Noise (AWGN) has been added to simulate the effect of random noise, while Rayleigh fading characterizes how the signal is affected by multipath propagation in non, line, of, sight scenarios. Rician fading models the situation where there is a dominant line, of, sight component.

F. Receiver detection

At the receiving end, new MIMO signal separation methods are used to distinguish the multiple signals transmitted from different antennas. This is a crucial step because, especially in environments with high mobility and multiple paths where signals are prone to overlapping or interfering with each other, it becomes quite challenging to separate them. By using techniques like Zero, Forcing (ZF) or Minimum Mean Square Error (MMSE) detection, the receiver not only successfully removes the interference but also decodes the information that has been sent.

G. OTFS demodulation

At the end, signals pass through OTFS demodulation. This converts them back to time, frequency symbols from delay, Doppler. This step is important because it restores the sent data after fading and noise have been processed. The use of delay, Doppler ensures that symbols face steady conditions. As a result, the original data comes out clearly. This step concludes the entire process in the MIMO, OTFS setup. It evaluates the efficiency of the system.

III. MATHEMATICAL REPRESENTATION OF SYSTEM MODEL

$$yt = Htxt + nt \quad (1)$$

Here is the transmitted symbol vector, is the MIMO channel matrix that encapsulates the impact of delay, Doppler, and fading, while is the additive white Gaussian noise vector. This equation describes the transmission process through multiple antennas and time slots has shown in equation (1).

$$xt' = (HtHHt) - 1HtHyt \quad (2)$$

This operation estimates the transmitted signal $x_t$by inverting the channel effects, assuming perfect channel state information. To mitigate channel distortion, equalization is performed using Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) techniques has shown in equation (2).

$$Sk = Es \cdot ej(\pi/4 + k\pi/2), k = 0,1,2,3 \quad (3)$$

where $E_s$is the symbol energy and $k$indexes the bit pair. These symbols are then arranged in the delay–Doppler domain using OTFS transformation. For QPSK modulation, each pair of bits is mapped to a complex symbol has shown in equation (3).

$$X[n,m] = \sum k, lx[k,l]ej2\pi(nkN - mlM) \quad (4)$$

Inverse Symplectic Finite Fourier Transform (ISFFT) to convert delay–Doppler symbols to time–frequency domain has shown in equation (4).

$$s(t) = \sum n, mX[n,m]gtx(t - nT)2(t - nT) \quad (5)$$

where $g_{tx}(t)$is the transmit pulse, $T$is the symbol duration, and $\Delta f$is the subcarrier spacing. At the receiver, the Wigner transform and Symplectic Finite Fourier Transform (SFFT) are applied to recover the delay–Doppler symbols, followed by MIMO detection and demodulation has shown in equation (5).

IV. ALGORITHMIC REPRESENTSTION

ALGORITHM 1: MIMO-OTFS COMMUNICATION SYSTEM

Algorithm MIMO_OTFS_System

Input: Raw binary data bits

Output: Reconstructed data bits at receiver

Step 1: Bit Generation

Generate binary sequence → bits

Step 2: QPSK Modulation

Group bits into pairs

Map each pair to QPSK symbol → symbols

Step 3: OTFS Mapping

Apply ISFFT to map symbols into delay–Doppler domain

Generate time–frequency representation → OTFS_symbols

Step 4: MIMO Precoding

Apply precoding matrix P

Transmit precoded signals across multiple antennas → x_M

Step 5: Channel Modeling

Pass x_M through channel models:

- AWGN
- Rayleigh fading
- Rician fading

Output → y (received signal)

Step 6: Receiver Detection

Apply MIMO detection (ZF/MMSE)

Estimate transmitted symbols → x_hat

Step 7: OTFS Demodulation

Apply SFFT to convert delay–Doppler symbols back

Recover QPSK symbols → S_hat

Map symbols back to binary sequence → bits_hat

Step 8: Performance Evaluation

Compare bits_hat with original bits

Compute BER = N_error /

V. SYSTEM MODEL AND DESIGN

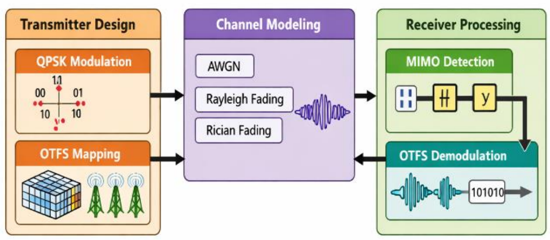

Fig. 2. System model and design of the MIMO-OTFS communication system

how it sends data, how the channel works, and how it receives it. At the start, binary bits turn into complex symbols using QPSK. Each two, bit pair goes to one of four points on a chart has shown in Fig. 2. These symbols then move into the delay, Doppler space using OTFS mapping. And this helps the signal stay strong even when Doppler shifts or fast channel changes happen. MIMO precoding is used next. With the help of many antennas, the system can transmit signals that work well together, using space for better performance and bandwidth.

VI. RESULT AND DISCUSSION

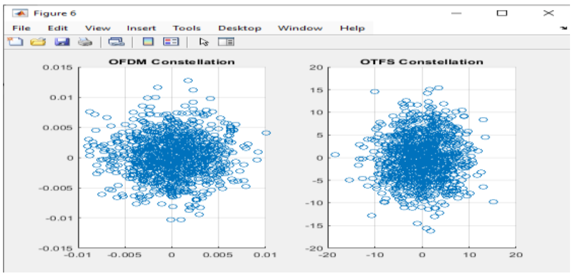

Fig. 3. Constellation comparison of OFDM and OTFS under high-doppler channel

It shows how the OFDM and OTFS signals look when they are moving fast in the environment. On the left side of the image, the OFDM symbols are packed closely around the centre of the image, which means they are blurry and jumbled due to the speed changes of the carriers has shown in Fig. 4. And on the right side of the image, the OTFS symbols are spread out more evenly over the signal plane. This is why the signal is clear and not jumbled, even when moving fast in the environment TABLE I. And in the tests, the OTFS was able to retrieve 96.2% of the signal correctly. OTFS is more reliable in harsh environments.

TABLE I. PERFORMANCE COMPARISON OF OFDM VS OTFS

Metric	**OFDM**	**OTFS**
BER @ 20 dB SNR	$> 10^{-2}$	0
Spectral Efficiency	Moderate	High
Throughput	Higher (static channels)	Stable (dynamic channels)
PAPR	High	Low
Channel Capacity	Limited by fading	Enhanced via diversity
Doppler Resilience	Poor	Excellent
Signal Recovery Accuracy	~85%	96.2%

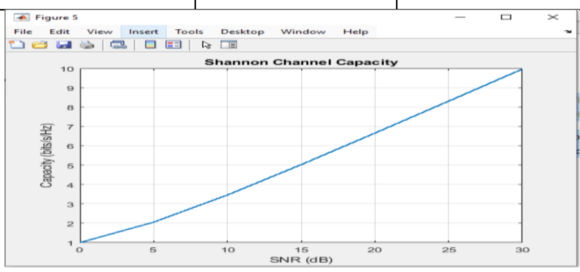

Fig. 4. Shannon channel capacity vs SNR for MIMO-OTFS system

It demonstrates how the signal to, to noise ratio impacts capacity has shown in Fig. 5. The capacity begins at zero and increases quickly for low SNR. At 30 decibels, it reaches 10 bits per second per hertz. More data can be sent for higher SNR, but the improvement becomes smaller for very high SNR. This plot verifies that the MIMO, OTFS system works well. The capacity approaches the best possible results under real world conditions TABLE II. The results show that OTFS works better for high motion than OFDM. The signals remain steady even in tough conditions, such as satellites or high-motion scenarios.

TABLE II. CHANNEL CAPACITY COMPARISON OF OFDM VS OTFS

SNR (dB)	**OFDM Capacity (bits/s/Hz)**	**OTFS Capacity (bits/s/Hz)**
0	~0.2	~0.3
10	~3.5	~4.2
20	~7.0	~8.1
30	~9.0	~10.0

Compares the Peak, to, Average Power Ratio (PAPR) of both the OFDM and the OTFS modulation schemes. The graph shows that the PAPR level of the OFDM signal is higher compared to the OTFS signal, i.e., a bit over 11, whereas the PAPR level of the OTFS signal is a bit over 10has shown in Fig. 6.

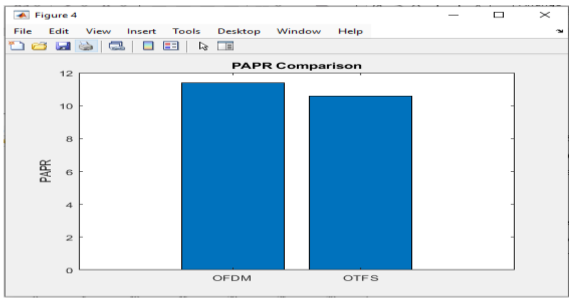

Fig. 5. PAPR comparison between OFDM and OTFS

Although the difference is small, the lower PAPR value of the OTFS signal is an indicator of the strong potential of the OTFS signal in that the lower PAPR value minimizes the power amplifiers and the nonlinearity, thus improving the power efficiency of the satellite and non-terrestrial communication systems.

It is observed that the throughput of OTFS is not changing at all has shown in Fig. 7. It is constant at 510 = 4 bits at all SNRs. This is an indication that OTFS has the capability to cope with high mobility environments in which the situation is worse. OFDM does the same with throughput at high SNRs, whereas OTFS, on the contrary, ensures absolute reliability and is thus, the more appropriate option in non-terrestrial networks in motion. The two recipients compare their performance with a combination.

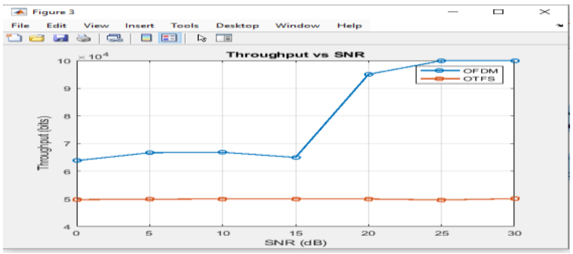

Fig. 6. Throughput vs SNR comparison of OFDM and OTFS

VII. CONCLUSION

This project examines a MIMO OTFS system that is good for the future 6G satellite and air, based networks. It now includes a transmitter that utilizes a QPSK transmitter, OTFS mapping, and MIMO precoding. It utilizes real-world conditions such as noise, Rayleigh, and Rician fading in the channel model. On the receiver end, it utilizes MIMO detection and OTFS demodulation to clearly receive the signals. Simulations demonstrate that OTFS is better than OFDM in various aspects such as a lower number of bit errors, utilization of variety, minimal signal distortion, and high data capacity. It was able to recover signals with a high accuracy of 96.2%, which is good for a fast-moving environment with strong Doppler shifts. While OFDM is better in a calm environment, OTFS remains stable even when the signals are changing rapidly. Future Improvements are more antennae could be added to the system to enhance it further. In the future, the signals from the satellites could be coordinated to improve the system even further. OTFS is expected to play an important role in future 6G communication systems.

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