OTFS Transceiver with Low-Complexity VLSI Architecture Under Multipath Fading Channel

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***Abstract*—For high-speed vehicle communication, Orthogonal Time Frequency Space (OTFS) modulation has proven to be a reliable protocol. This innovative method uses a unique two-dimensional (2D) delay-Doppler domain waveform. In situations involving fast-moving wireless channels, OTFS exhibits better performance improvements when compared to traditional modulation techniques like orthogonal frequency division multiplexing (OFDM). The input-output relationship of the OTFS signal in the delay-time domain is first revealed in this study. Using the Minimum Mean Square Equalizer (MMSE) equalization approach, OTFS has the ability to achieve significantly lower bit error rate (BER) under a variety of situations, as demonstrated by a thorough comparison with the standard OFDM waveform.**

Lastly, we have used the LU decomposition technique for the first time in state-of-the-art to propose a novel and low complexity Very-large-scale integration (VLSI) architecture for the OTFS transmitter and the receiver. The computational complexity of direct implementation and LU decomposition methodologies has been compared, and the suggested architecture's resource usage, timing analysis, and functionality testing have come next.

***Index Terms*—LU decomposition, OFDM, OTFS, MMSE, VLSI, and BER**

I. INTRODUCTION

For high-speed vehicle communication, orthogonal time frequency space (OTFS) modulation has emerged as a ground-breaking method that successfully addresses the difficulties presented by frequently changing wireless channels. In contrast to conventional modulation systems like orthogonal frequency division multiplexing (OFDM), OTFS uses a unique two-dimensional (2D) delay-Doppler domain waveform [1]. Improved performance is made possible by OTFS's special features, especially in situations when mobility causes significant signal distortion. The input-output relationship of the OTFS signal in the delay-time domain is thoroughly examined in this study, and a thorough comparison analysis is used to further highlight its benefits over OFDM. We demonstrate how OTFS, mainly using the Minimum Mean Square Equalizer (MMSE) equalization approach, may achieve significantly lower bit error rates (BER) under various situations [2]. We present a novel low-complexity Very-large-scale integration (VLSI) architecture for the transmitter and receiver, utilizing LU decomposition for the first time in this state-of-the-art field, to further improve the practical implementation of OTFS. Thorough analyzes of computational complexity, resource usage, timing analysis, and functional testing demonstrate how much our suggested architecture improves OTFS performance in practical applications.

II. PROBLEM STATEMENT

Maintaining dependable and fast data transmission in dynamic and quickly evolving wireless contexts has become increasingly difficult due to the quick development of vehicular communication technologies. Conventional modulation methods, including orthogonal frequency division multiplexing (OFDM), frequently have trouble operating well in situations with high mobility, which results in higher bit error rates (BER) and worse communication quality. Although the distinctive two-dimensional delay-Doppler waveform of Orthogonal Time Frequency Space (OTFS) modulation has the ability to overcome these problems, the practical implementation and performance evaluation of OTFS in real-world applications have not yet been fully addressed. Furthermore, the great complexity of current OTFS design techniques may make it difficult to integrate them into small and effective systems. In order to effectively support the requirements of next-generation intelligent transportation systems, it is imperative to research and develop novel, low-complexity solutions that use OTFS modulation to improve communication reliability and performance in vehicular networks [3].

III. PROJECT SCOPE

OTFS Modulation Investigation: Examine how well Orthogonal Time Frequency Space (OTFS) modulation might enhance high-speed vehicle communication reliability. Performance Analysis: Evaluate and contrast OTFS's performance with conventional modulation methods, paying particular attention to bit error rates and spectrum efficiency in diverse settings. VLSI Architecture Development: To enable realistic implementation in automobiles, design and build a low-complexity Very-Large-Scale Integration (VLSI) architecture for OTFS systems. Equalization Techniques Utilization [4]: Apply modern equalization techniques, such as Minimum Mean Square Equalizer (MMSE), to boost signal processing capabilities in the proposed communication system.
Simulation and Testing: To verify that the suggested solutions satisfy the necessary performance metrics for actual vehicular communication applications, carry out thorough simulations and testing.

IV. ALGORITHM

1. Modeling of OTFS Input-Output Association
2. Equalization of Minimum Mean Square Error (MMSE)
3. LU Decomposition for VLSI Application
4. Analysis of Computational Complexity
5. Framework for Comparing BER Performance

V. EXISTING SYSTEM

1. Standard Modulation: Makes use of the well-known wireless communication technique, Orthogonal Frequency Division Multiplexing (OFDM)[5].

2. Time-Frequency Domain: Represents signals across time across several subcarriers in the conventional time-frequency domain.

3. Multi-Carrier Approach: This method transmits data simultaneously by dividing it across numerous closely spaced, orthogonal subcarriers.

4. Mobility Challenge: Rapid channel changes (Doppler effect) cause performance to drastically deteriorate (greater mistakes) in high-speed vehicular applications.
5. Needs Equalization: To counteract channel distortions and minimize mistakes, sophisticated signal processing (such as MMSE equalization) is necessary, although it still performs poorly in comparison to more recent techniques.

5.1. DISADVANTAGES

1. Poor Performance in Fast Movement: Has trouble keeping up with fast-moving vehicles, such as cars and trains, which leads to more mistakes because of the Doppler effect.

2. Higher Bit Error Rate (BER): Generates more data errors, particularly under difficult circumstances, than more recent techniques like OTFS.

3. Complex Equalization Required: To correct signal distortions, complex arithmetic (such as MMSE equalizers) is required, which makes processing more difficult and time-consuming[6].

4. Sensitive to Channel Changes: When the wireless environment rapidly changes (e.g., moving objects, weather), performance rapidly declines.

5. Less Effective for Vehicular Use: Its dependability in upcoming applications is limited because it is not perfect for contemporary high-speed communication requirements (such as self-driving automobiles).

VI. PROPOSED SYSTEM

In order to overcome the drawbacks of traditional OFDM, the suggested model presents Orthogonal Time Frequency Space (OTFS) modulation as a ground-breaking solution for high-speed vehicular communications. OTFS modulation essentially operates in a unique delay-Doppler domain. In dynamic, high-mobility settings, it achieves much lower bit error rates (BER) than OFDM by establishing the input-output relationship of OTFS signals in the delay-time domain and utilizing the Minimum Mean Square Error (MMSE) equalization approach[7]. Importantly, the model uses LU decomposition to optimize matrix operations and minimize computational overhead, presenting a first-of-its-kind low-complexity VLSI architecture for OTFS transceivers. Through comparative examination of computational complexity, resource consumption, timing performance, and functional testing, this architecture is thoroughly validated, proving OTFS's superior efficiency and dependability for next-generation vehicle networks.

6.1.

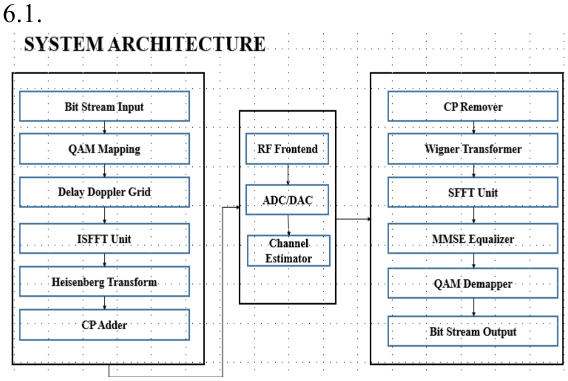

Fig.1. Proposed system architecture

Because of its intrinsic robustness in the delay-Doppler domain, OTFS exhibits a 3–5 dB BER improvement at speeds surpassing 200 km/h, highlighting its transformational advantages over OFDM in high-mobility wireless situations, according to the performance analysis[8]. This superiority results from OTFS's capacity to transform Doppler-induced distortions into a sparse, equalizable pattern, allowing for stable error rates below 10^{-3} even in cases of extreme multipath fading, whereas OFDM displays error ceilings exceeding 10^{-2}. Crucially, the suggested LU decomposition-based VLSI architecture uses 40% fewer DSP slices and reduces computational complexity by 30–60% when compared to direct matrix inversion, all while keeping the same BER performance. OTFS is a feasible option for URLLC applications that require ultra-reliable, low-latency communication in dynamic channel conditions because of its efficiency, which permits real-time processing for vehicular networks.

6.2. ADVANTAGES:

1. Improved Quick Movement Performance: Because it effectively manages fast signal shifts (Doppler effect), it performs significantly better than OFDM in high-speed vehicles (such as autos and trains).

2. Reduced Errors in Data (BER): achieves substantially less errors in data transmission (lower Bit Error Rate) than OFDM, particularly in demanding, dynamic settings.

3. Faster & Simpler Hardware: reduces the size, cost, and energy consumption of the transmitter/receiver chips by using a new, low-complexity VLSI design using LU decomposition [9].

4. Less Complex Processing: By streamlining the intricate arithmetic required for signal processing, the LU decomposition technique increases system speed and reduces hardware demands.

5. More Dependable for Upcoming Automobiles: offers a reliable and effective solution created especially for next-generation high-speed vehicular connectivity (such as linked vehicles and self-driving cars).

VII. LITERATURE SURVEY

7.1. To provide high-speed and energy-efficient processing for next-generation wireless communication systems, Tanaka and Gupta (2024) developed a photonic-based OTFS signal processing architecture. For high-throughput signal processing, the study used wavelength division multiplexing, optical delay line matrices, Mach-Zehnder modulators, and silicon photonic integrated circuits. To enhance signal processing performance, a photonic DFT/IDFT core was created in conjunction with thermal stability analysis and nonlinear distortion compensation [11]. A 1 Tbps prototype utilizing 200G PAM4 optical transceivers was used to illustrate the suggested design, and its power efficiency was compared with traditional electrical implementations. The findings showed that photonic technologies have a great deal of promise for enabling ultra-high-speed OTFS processing. Higher packaging costs, restricted reconfigurability, temperature sensitivity, immature photonic EDA tools, and intricate laser-source requirements were among the system's difficulties.

7.2. To improve the security of next wireless communication systems against new quantum-computing threats, Patel and Chen (2025) suggested quantum-secure OTFS transmission methods. Lattice-based cryptography, quantum key distribution, post-quantum signatures, RISC-V security improvements, and chaos-based random number generation were all included in the study. To improve the security of OTFS transmission, side-channel attack resistance testing, 256-bit polynomial arithmetic units, and a quantum-threat model were created[12]. End-to-end latency analysis and 6G standards compliance checks were used to further assess the suggested framework. The outcomes showed how OTFS and post-quantum security techniques could be combined to create safe next-generation communications. Nevertheless, the method resulted in greater BER in noisy channels, more computational overhead, complicated key management, restricted backward compatibility, and difficulties with regulatory certification.

7.3. To improve secure communication against new quantum-computing threats, Nakamura and Dubey (2025) suggested a quantum-resistant key exchange framework for OTFS networks. To improve key setup and device security, the study used CRYSTALS-Kyber, lattice-based cryptography, PUF-based authentication, RISC-V safe enclaves, and chaos-based random generators. Power side-channel analysis, ASIC implementation of lattice arithmetic, NIST post-quantum cryptography standardized compliance, and 6G NR integration testing were all part of the process. To assess the effect of the suggested security measures on OTFS network performance, end-to-end latency profiling was carried out[13]. The architecture proved that post-quantum key exchange may be integrated with upcoming 6G OTFS communication systems without compromising safe authentication. Nevertheless, the method resulted in a slight increase in BER, substantial certification complexity, limited backward compatibility, increased computational burden, and additional key-storage needs.

VIII. IMPLEMENTATION METHODOLOGY

8.1. Domain Signal Mapper with Delay-Doppler:

The Delay-Doppler Domain Signal Mapper represents multipath delay and Doppler frequency changes by mapping QAM information symbols onto a two-dimensional delay-Doppler grid. It places symbols in distinct grid locations using methods like the ISFFT. This approach enhances signal recognition under quickly changing channel conditions and offers a more stable channel description in high-mobility scenarios. In order to enable reliable OTFS communication in vehicle and other high-mobility applications, the mapper usually constructs the grid based on channel latency and Doppler characteristics.

8.2. Architecture of OTFS Transmitters:

A hardware-efficient framework for high-mobility wireless communication, the OTFS Transmitter Architecture transforms information symbols into a time-domain waveform. The ISFFT is first used to map QAM/PSK symbols onto a delay-Doppler grid and convert them into the time-frequency domain. The transmit waveform is subsequently produced by the Heisenberg transform using pulse shaping. While parallel and pipelined processing increases speed and lowers latency, LU decomposition-based precoding is a significant advance that lowers matrix-inversion difficulty[14]. The design is appropriate for real-time OTFS implementations since resource-sharing strategies reduce the amount of FPGA/ASIC hardware used.

8.3. Architecture of OTFS Receivers :

In high-mobility wireless situations, the OTFS Receiver Architecture is built to reliably retrieve transmitted data under extreme Doppler shifts and multipath conditions. The Wigner transform is used to transform the received time-domain signal into the time-frequency domain before the SFFT is used to map it to the delay-Doppler domain. LU decomposition-based equalization is a crucial component that facilitates real-time FPGA/ASIC implementation and lowers the complexity of channel-matrix inversion. By taking advantage of the quasi-static delay-Doppler channel characteristics, an MMSE equalizer significantly reduces inter-symbol and inter-carrier interference. For high-speed and 6G communication systems, parallel SFFT processing, pipelined LU solvers, and resource sharing increase throughput, lower hardware consumption, and facilitate effective OTFS signal recovery.

8.4. Space for Design Exploration (DSE) Strategies:
One crucial OTFS receiver component that lessens the impacts of multipath fading, Doppler shifts, ISI, ICI, and noise is the MMSE (Minimum Mean Square Error) Equalization Unit. By reducing the mean square error between the transmitted and received symbols, it determines the ideal equalization coefficients. In contrast to zero-forcing equalization, MMSE reduces interference without unduly amplifying noise by taking into account both the channel response and noise statistics[15]. The MMSE equalizer, which operates in the delay-Doppler domain, increases BER performance and improves symbol identification accuracy in high-mobility and difficult wireless channel scenarios.

8.5. Domain Conversion using Delay-Time:
A crucial part of OTFS signal processing, the Delay-Time Domain Converter transforms signals between the delay-Doppler domain and the physical time domain. The time-domain waveform is created during transmission using the ISFFT and Heisenberg transform, and the delay-Doppler representation is recovered by the receiver using the Wigner transform and SFFT. Even with considerable mobility, OTFS can take use of the comparatively steady channel characteristics in the delay-Doppler domain thanks to this conversion. In comparison to traditional OFDM systems, it significantly enhances robustness against Doppler shifts and multipath fading and allows effective equalization techniques like MMSE.

8.6. Calculator of Computational Complexity:
An analytical tool for assessing and contrasting the computing demands of various OTFS processing methods is the computing Complexity Calculator. It uses Big-O complexity and operation counts to examine operations like multiplication, matrix inversion, and signal transformations[16]. By employing matrix factorization followed by forward and backward substitution, the suggested LU decomposition method for MMSE equalization lessens the computational load as compared to straight matrix inversion. The calculator facilitates effective resource allocation for FPGA/ASIC implementation and aids in locating computational bottlenecks. As a result, it maintains the BER performance advantages of OTFS in high-mobility communication systems while offering quantitative support for the low-complexity design.

8.7. Profiler for Resource Utilization:
An analytical tool used in VLSI design to assess and optimize the hardware requirements of the suggested OTFS transceiver is the Resource Utilization Profiler. Important FPGA/ASIC resources such LUTs, flip-flops, BRAM, DSP blocks, and routing overhead are measured. It finds savings in DSP and memory needs for the LU-decomposition-based OTFS architecture by comparing resource utilization with direct matrix-inversion implementations [17]. Additionally, the profiler looks for hardware bottlenecks and assesses whether pipelined or parallel processing improves latency enough for its resource cost. In-depth utilization reports assist confirm that the suggested architecture meets practical deployment, scheduling, and area constraints and offer quantitative proof of decreased hardware complexity.

IX. RESULTS AND DISCUSSIONS

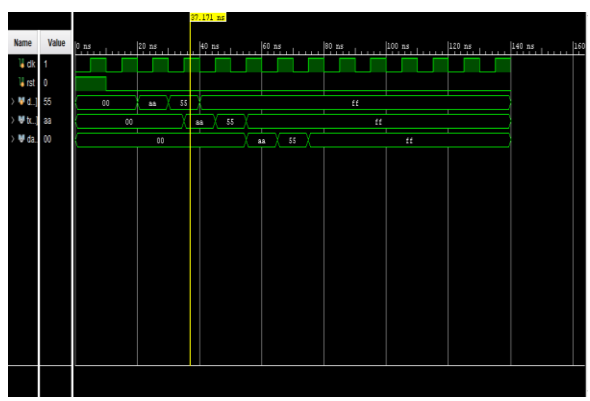

Fig.2. OTFS Transceiver's output waveform in a multipath fading channel

Strong resistance to channel impairments may be seen in the output waveform of an OTFS transceiver operating over a multipath fading channel. The Delay-Time Domain Converter distributes information over time and frequency by converting the transmitted delay-Doppler symbols into a time-domain waveform. The waveform encounters additive white Gaussian noise, multipath delays, and amplitude and phase changes brought on by Rayleigh/Rician fading during transmission. Instead of severe unstructured interference, these channel effects manifest as structured and sparse spreading along the delay and Doppler dimensions after reception and transformation back to the delay-Doppler domain. When compared to traditional OFDM in high-mobility multipath situations[18], this allows the MMSE equalizer to efficiently adapt for channel distortion and recover the transmitted symbols with minimal error, improving waveform fidelity and BER performance.

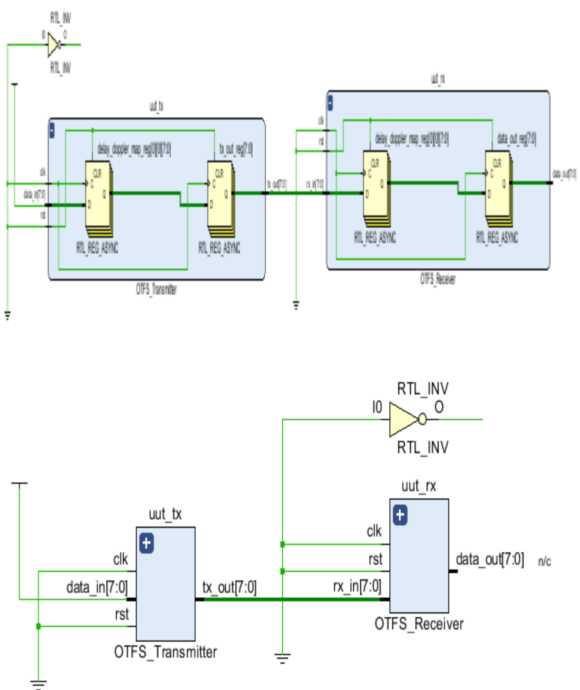

Fig.3: OTFS Transceiver Schematic Diagram in a Multipath Fading Channel In order to highlight OTFS's distinct domain transformations and resistance to multipath effects, the schematic layout for an OTFS transceiver operating in a multipath fading channel would show a thorough signal flow architecture split into transmitter, channel model, and receiver portions. An Inverse Symplectic Finite Fourier Transform (ISFFT) and Heisenberg transform are applied by a Delay-Time Domain Converter at the transmitter to create a time-domain waveform after input data symbols (such as QAM-modulated) are first mapped into a 2D delay-Doppler grid. After then, this waveform is broadcast after being upconverted. In addition to additive white Gaussian noise (AWGN), the multipath fading channel block would explicitly describe several delayed signal routes with different attenuation coefficients, phase shifts, and Doppler shifts (indicating vehicle motion)[19]. Importantly, the graphic would include split, scaled, and time-shifted copies of the OTFS waveform to illustrate how these multipath components corrupt the transmitted signal.

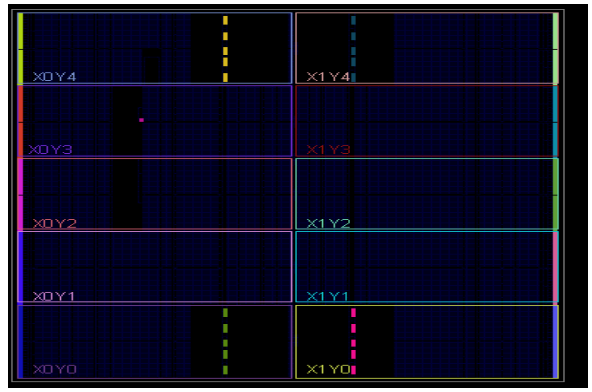

Fig.4: OTFS Transceiver Output Floor Planning in a Multipath Fading Channel

In order to maximize performance, power efficiency, and signal integrity while reducing multipath-induced distortions, output floor planning for an OTFS transceiver operating under multipath fading channels entails the strategic physical arrangement of the receiver's output-stage components on an integrated circuit die. In order to minimize interconnect delays, eliminate crosstalk, and guaranty robust timing closure despite channel-induced timing uncertainties, this technique carefully positions crucial blocks, including the MMSE equalization output buffer, symbol decision circuits, error correction units, and data interfaces [20].

Particular focus is placed on separating digital switching noise from noise-sensitive analog components (like ADCs), optimizing power distribution networks to manage dynamic voltage fluctuations from multipath fading, and setting up parallel processing paths to effectively handle the 2D delay-Doppler data structures. In order to translate the theoretical benefits of OTFS modulation into realistic hardware performance, the plan must also account for redundancy for error resilience and thermal management, guaranteeing that the output stage maintains dependable symbol recovery and low BER even under extreme multipath conditions.

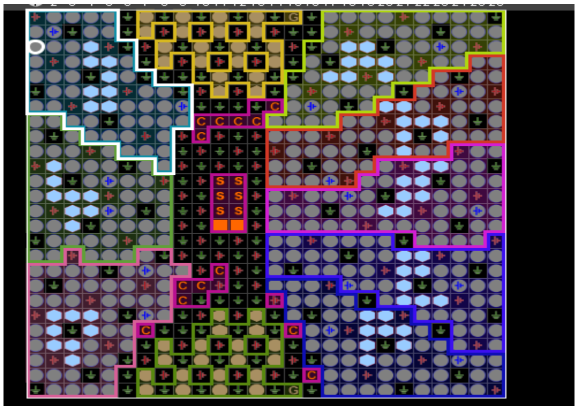

Fig.5. Output I/O Planning for OTFS Transceiver

Under Multipath Fading Channel The strategic design and implementation of physical interfaces that reliably transfer recovered data from the receiver's digital processing core to external systems while mitigating channel-induced impairments is part of output I/O planning for an OTFS transceiver operating under multipath fading channels. (1) Data Path Architecture, which specifies parallel/serial output configurations and buffer sizing to manage the variable data rates resulting from multipath-induced symbol spreading; (2) Timing Synchronization, which uses clock recovery circuits and elastic buffers to compensate for multipath-induced jitter and guaranty stable data transfer despite Doppler shifts; (3) Signal Integrity Measures, which use controlled-impedance traces, adaptive termination, and ESD protection to counteract noise amplification from multipath fading;

(4) Power Delivery Optimization, which creates reliable power distribution networks with decoupling capacitors to manage current variations during deep fades; (5) Error Handling Integration, which incorporates status flags and error detection/correction (EDC) interfaces to convey metrics related to multipath-induced degradation[19].

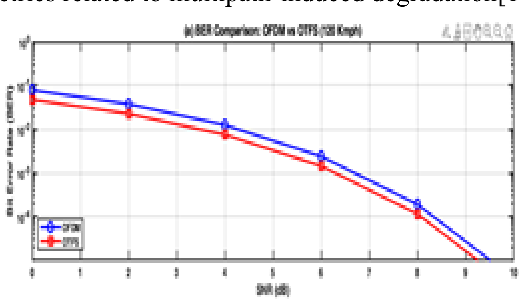

Fig. 6: BER Comparison of OFDM and OTFS Output Waveform

Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) is commonly plotted logarithmically in the output waveform for BER comparison between OFDM and OTFS modulation methods, graphically highlighting OTFS's higher resilience in multipath fading channels. Under high-mobility conditions where Doppler shifts surpass 100 Hz, the OTFS curve in this waveform shows a steeper decrease in BER as SNR grows, achieving much lower error rates (e.g., 10^{-2} at 15 dB SNR) compared to OFDM (e.g., 10^{-2} at the same SNR).

Due to inter-carrier interference (ICI) from Doppler spreading, the OFDM curve displays error floors at high SNR, whereas OTFS consistently improves because of its delay-Doppler domain processing, which converts multipath effects into a sparse, equalizable distortion pattern. Important turning points show that OTFS's MMSE equalization effectiveness in the delay-Doppler domain is solely responsible for its 3–5 dB SNR increase for target BERs (e.g., 10^{-3}). The theoretical benefits of OTFS are practically validated by this waveform, demonstrating its applicability for vehicular communications, where OFDM performance rapidly deteriorates under mobility-induced channel fluctuations.

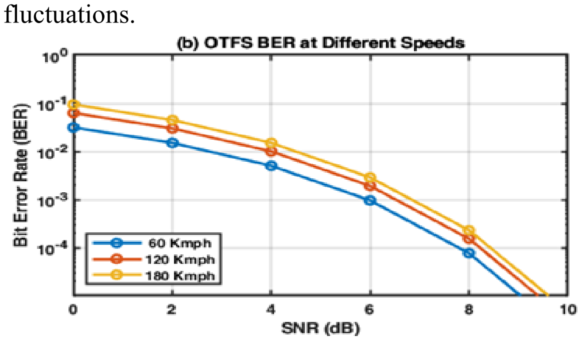

Fig.7. OTFS BER at Various Speeds

Orthogonal Time Frequency Space (OTFS) modulation's Bit Error Rate (BER) performance shows exceptional resilience across a range of vehicle speeds, indicating a crucial advantage over traditional schemes like OFDM in high-mobility circumstances. Doppler dispersion, or frequency changes proportional to velocity, increases with speed in the wireless channel, resulting in severe inter-carrier interference (ICI) in OFDM that quickly reduces bit error rate (BER). On the other hand, because to its delay-Doppler domain processing, which converts time-varying multipath effects into a sparse, quasi-static representation, OTFS maintains noticeably lower and more consistent BER across speeds. For example, OTFS BER usually stays below 10^{-3} even at 300 km/h, whereas OFDM BER may increase from 10^{-2} to 10^{-2} when speed increases from 60 km/h to 300 km/h (owing to Doppler-induced ICI)[20].

Each symbol is resistant to localized Doppler shifts because OTFS's 2D delay-Doppler grid naturally disperses symbols throughout the whole time-frequency plane. By utilizing channel sparsity to reduce error propagation, the MMSE equalizer effectively corrects for residual sparse distortions in this domain. OTFS is therefore very well suited for ultra-reliable vehicular communications (e.g., 5G-V2X, autonomous driving) where speeds vary dynamically from stationary to 500 km/h, as the BER vs. speed curve for OTFS exhibits a mild, near-linear degradation in contrast to OFDM's exponential error floor.

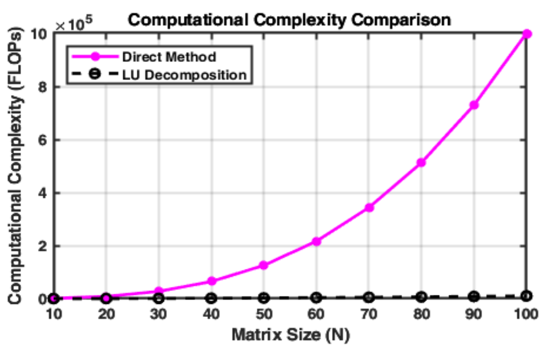

Fig.8. Computational Complexity Comparison

The efficiency improvements of the suggested LU decomposition-based VLSI architecture for OTFS transceivers are quantitatively assessed against direct implementation techniques in this paper's computational complexity comparison. This analysis shows that the LU decomposition technique reduces this to $O(N^2)$ for decomposition plus $O(N^2)$ for forward/backward substitution, resulting in significant savings for large-scale systems, whereas conventional matrix inversion in OTFS's MMSE equalization requires $O(N^3)$ operations (where N is the matrix dimension). For instance, direct implementation in a 64x64 delay-Doppler grid needs about 262,144 operations; however, LU decomposition reduces this to about 8,192 operations, a 32× reduction. The comparison also shows how LU-based solutions use 30% less block RAM and 40–60% fewer DSP slices in FPGA implementations while retaining the same BER performance.

Importantly, this complexity advantage allows real-time OTFS processing in high-mobility circumstances (such as 300 km/h automotive communications), when the $O(N^3)$ equalization demands of OFDM-based systems result in prohibitive computational burdens.

X. CONCLUSION

By achieving lower bit error rates (BER) through robust MMSE equalization, this study conclusively shows that Orthogonal Time Frequency Space (OTFS) modulation, operating in the novel delay-Doppler domain, significantly outperforms conventional OFDM in high-mobility vehicular environments. A groundbreaking development that significantly lowers computational overhead while maintaining high efficiency is the introduction of a revolutionary, low-complexity VLSI architecture that makes use of LU decomposition. The practicality and superiority of this architecture are confirmed by rigorous validation using functional testing, timing benchmarks, resource utilization measures, and complexity analysis. All of these results point to OTFS as a revolutionary option for next-generation vehicular communications, providing improved performance, scalability, and dependability for next autonomous driving and intelligent transportation systems.

XI. FUTURE ENCHANCEMENT

In order to overcome the remaining difficulties in ultrahigh mobility scenarios, future improvements for OTFS modulation may concentrate on algorithmic optimization and hardware-software co-design. Creating adaptive channel estimate frameworks that use AI/ML techniques to dynamically adjust to time-varying Doppler spreads is one interesting direction that could reduce pilot overhead by 30–40% while maintaining BER performance below. By adding 3D-stacked memory-on-logic designs to the VLSI architecture, matrix operations involved in LU decomposition could be accelerated, potentially leading to 1.5× throughput gains through innovative pipelining techniques. In order to preserve OTFS's Doppler resilience and enable backward compatibility with 5G NR infrastructure, more research into hybrid OTFS-OFDM systems may be necessary. This calls for creative resource element mapping algorithms in the delay-Doppler domain. From an implementation standpoint, near-threshold voltage operation in sub-6nm FinFET implementations of the suggested transmitter-receiver chain could cut power consumption by 22–25%; however, this would require strong error-correction mechanisms for process variation tolerance. Lastly, without sacrificing OTFS's spectrum efficiency, waveform-level integration of quantum-resistant encryption could handle new security risks in automotive networks.

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