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Doppler Rate Estimation for OTFS based Communication Systems in High Mobility

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***Abstract*— Orthogonal Time Frequency Space (OTFS) modulation has emerged as a promising solution for reliable communication in high-mobility environments due to its robustness in rapidly varying channels. In this study, we address the challenge of estimating the Doppler rate, which refers to the time variation of the Doppler shift caused by accelerating or decelerating motion. We use a subspace-based estimation framework that exploits the structural properties of OTFS signals in the delay-Doppler domain. By analyzing the evolution of signal components over time, the system can accurately track Doppler rate variations. Simulation results validate the effectiveness of the proposed approach, showing improved performance in scenarios such as high-speed trains and vehicular networks. High mobility scenarios, such as those encountered in high-speed trains and autonomous vehicles, demand communication systems that can adapt to fast changing signal conditions. OTFS modulation provides a resilient structure for handling such environments. This paper presents a method to estimate the Doppler rate — a key parameter that captures how the Doppler shift evolves due to motion changes. The proposed technique leverages subspace analysis within the OTFS framework to track these variations effectively. Results from simulations indicate strong potential for real time deployment in mobility-sensitive applications, enhancing the reliability of wireless links in future networks.**

***Index Terms*— Orthogonal Time Frequency Space, robustness, Doppler rate, subspace, delay-Doppler domain, autonomous.**

I. INTRODUCTION

In today's fast-moving world, reliable wireless communication is essential for various technologies such as self-driving cars, high-speed trains, and aerial vehicles. As these systems operate in high mobility environments, the communication signals are often affected by changes in frequency due to motion. This phenomenon, known as the Doppler effect, causes signal distortion and can significantly reduce the accuracy and reliability of message transmission. Addressing this challenge is crucial to ensuring consistent performance in dynamic and fast-changing scenarios. Orthogonal Time Frequency Space (OTFS) is an emerging modulation method that is intended to cope with the intricate conditions of high mobility communication environments. In contrast to conventional approaches, OTFS represents information in the delay-Doppler domain, enabling it to more effectively deal with the changes in signal frequency and delay due to movement. This makes it very appropriate for uses in which both receiver and transmitter are traveling very quickly or in situations where there are many reflections of the signal, like city locations or airborne systems.

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Nonetheless, to work properly, OTFS will need to correctly estimate the Doppler rate — the speed at which the signal frequency is altered by motion. The emphasis of this project lies in establishing straightforward and effective mechanisms for approximating the Doppler rate in OTFS-based systems. Through research into the signals' behaviour and their testing in high mobility scenarios, it is hoped to strengthen the system's capacity to ensure smooth communication. It is anticipated that the results of this research will play a major role in promoting the evolution of next-generation wireless networks.

II. LITERATURE SURVEY

Doppler estimation is a crucial component in wireless communication systems, especially in high-mobility environments like vehicle-to-everything (V2X), radar, and next-generation networks [2]. Traditional techniques such as Maximum Likelihood Estimation (MLE), Fast Fourier Transform (FFT), and Periodogram methods have been widely used due to their simplicity and ease of implementation. However, these methods face limitations such as high computational complexity (MLE), limited resolution (FFT), and poor multi-path resolution due to spectral leakage (Periodogram), making them less effective in high-mobility or low signal-to-noise ratio (SNR) scenarios [2].

To address these challenges, low-dimensional subspace methods have been developed, which project the signal onto reduced-rank bases to retain essential Doppler information while reducing complexity. Techniques such as Partial SVD, reduced-rank approximation, and adaptive basis selection improve estimation performance while being suitable for real-time and memory-limited systems [3][4][5]. Subspace-based methods like ESPRIT provide high-resolution estimation using eigenvalue decomposition of the signal covariance matrix, although they require specific signal structures and are sensitive to noise and model order selection [6][7][8].

Recent advances include sparse recovery-based approaches like Orthogonal Matching Pursuit (OMP), Basis Pursuit (BP), and LASSO, which utilize the sparsity of Doppler components for better resolution at reduced sample rates [9][10][11][12]. Hybrid techniques that combine subspace and sparse methods offer improved accuracy and robustness by leveraging the strengths of both approaches, particularly in complex systems like massive MIMO and OTFS [13][14]. With the rapid growth of 5G and high-speed communication demands, integrating OTFS with advanced Doppler estimation techniques has proven effective in ensuring reliable performance in dynamic environments [17][18].

III. KEY CONCEPTS

A. Orthogonal Time Frequency Modulation

Conventional modulation techniques, such as OFDM, struggle to meet the high-reliability and low-latency demands of modern wireless communication in high-mobility environments like autonomous vehicles, UAVs, and high-speed trains. These systems suffer from Doppler shifts and time-selective fading, which degrade performance by increasing bit error rates and causing inter-carrier interference (ICI). Orthogonal Time Frequency Space (OTFS) modulation offers a promising alternative by mapping data into the delay Doppler domain instead of the traditional time-frequency domain. This transformation provides a more stable and sparse channel representation, improving resilience to Doppler spread and delay variations. As a result, OTFS is considered essential for future wireless technologies, especially in 6G systems that aim to deliver ultra-reliable, low-latency communication (URLLC) in highly dynamic environments. For OTFS to perform effectively, accurate Doppler estimation is critical. Rapidly changing Doppler shifts can hinder channel estimation, equalization, and symbol detection. Moreover, precise Doppler tracking is vital for integrated sensing and communication (ISAC) applications, supporting tasks like autonomous navigation, mobile edge computing, and collision avoidance.

B. Types of Channels

Wireless communication systems must account for how signals propagate through the physical environment. These propagation characteristics vary significantly between static, pedestrian, and high-mobility settings. The following discussion moves from basic channel models to more advanced ones - ultimately covering modern scenarios such as V2V, HST, and UAV channels.

- AWGN Channel: The Additive White Gaussian Noise channel is a theoretical model that considers only the effect of white Gaussian noise on the transmitted signal:

$$y(t) = x(t) + n(t) \qquad (1)$$

It assumes a perfect channel with no fading, reflection, or delay, and serves as a baseline for evaluating communication performance under ideal conditions.

- Flat Fading Channel: In this model, the entire signal bandwidth experiences the same fading, without frequency selectivity. The received signal is:

$$y(t) = h\ x(t) + n(t) \qquad (2)$$

This is valid when the signal bandwidth is much smaller than the channel's coherence bandwidth. It models slow fading scenarios, typical in static or low-speed environments.

- Frequency-Selective Multipath Channel: Here, the signal experiences multiple reflections and delays, resulting in intersymbol interference (ISI). The channel is modelled as:

$$y(t) = \sum_{l=1}^{L} h_l \cdot x(t - \tau_l) + n(t) \qquad (3)$$

This model is common in indoor environments or urban settings where reflections from buildings and other obstacles cause delayed signal components.

- Rayleigh Fading Channel: Used when there is no line of-sight (LoS) component, and only reflected/scattered paths contribute to the received signal. The amplitude of the fading channel follows the Rayleigh distribution:

$$|h| \sim Rayleigh(\sigma) \qquad (4)$$

Rayleigh fading is typical in dense urban or underground environments where the LoS is completely obstructed.

- Rician Fading Channel: When a strong LoS component exists along with multipath, the fading envelope follows the Rician distribution:

$$|h| \sim Rician(K,\sigma) \qquad (5)$$

Where, K is the Rician K-factor representing the ratio of direct to scattered signal power. This is relevant in suburban or semi-open areas like highways.

- Time-Varying Doppler Channel: When either the transmitter or receiver is moving, Doppler shift causes timeselective fading:

$$Z\ y(t) = h(t,\tau) \cdot x(t - \tau)d\tau + n(t) \qquad (6)$$

This channel changes even within a single symbol duration in fast mobility, degrading performance of traditional modulation schemes like OFDM.

- High-Speed Train (HST) Channel: In HST environments, speeds can exceed 300 km/h, leading to very high Doppler shifts, rapid channel changes, and increased inter-carrier interference. The environment includes tunnels, open fields, and viaducts. The channel experiences: Fast fading, Sparse multipath with directional Doppler, and Rapid handovers

Such systems demand robust modulation techniques (e.g., OTFS) and accurate Doppler estimation and tracking.

- Vehicle-to-Vehicle (V2V) Channel: V2V communication occurs between moving vehicles, often at high relative speeds (e.g., crossing or overtaking). The V2V channel is highly dynamic, with:
  - Non-stationary fading due to rapid changes in topology
  - Time-varying Doppler
  - Often non-LoS conditions
- UAV Communication Channel: Unmanned Aerial Vehicles (UAVs) operate in 3D space, often experiencing altitude dependent channel variations. Key characteristics include:
  - LoS-dominant propagation with occasional Rician fading
  - High Doppler spread during rapid movements or wind gusts
  - Elevation angle variation affecting antenna gain and multipath profile

Channels are often modelled using elevation-aware Rician or Nakagami models, with special attention to mobility induced dynamics and angular spread.

C. High Mobility Communication Systems

High-mobility environments, such as Vehicle-to-Vehicle (V2V), High-Speed Train (HST), and Unmanned Aerial Vehicle (UAV) communication, present unique challenges for wireless communication systems. These include Doppler shifts, fast fading, multipath propagation, time and frequency variations, and interference from nearby transmitters. In these dynamic environments, the movement of the transmitter and receiver causes rapid changes in the received signal, making communication more complex than in static or low-mobility scenarios. Key challenges include:

- Doppler Shift: Relative motion between the transmitter and receiver causes frequency shifts, leading to misalignment and potential distortion.
- Fast Fading: Rapid changes in signal strength due to mobility and non-line-of-sight conditions degrade signal quality.
- Multipath Propagation: The signal reflects off objects, causing delays and phase shifts, especially in high mobility situations.
- Time and Frequency Variations: Rapid changes in both time and frequency can lead to synchronization issues and frequency offsets.
- Interference and Contention: High-density environments lead to signal interference from neighbouring transmitters, requiring careful control to avoid degradation. Specialized techniques are needed to handle these challenges and ensure reliable communication in such environments.

D. V2V Communication Systems

V2V communication allows vehicles to exchange real-time information, including speed, location, direction, and intentions to brake, in a wireless manner. This assists with road safety by enabling vehicles to detect and respond to impending dangers such as sudden braking, intersections, or blind spot dangers. V2V further aids traffic flow, fuel economy, and autonomous driving capabilities. Conventionally, V2V systems employ DSRC (IEEE 802.11p) or Cellular V2X

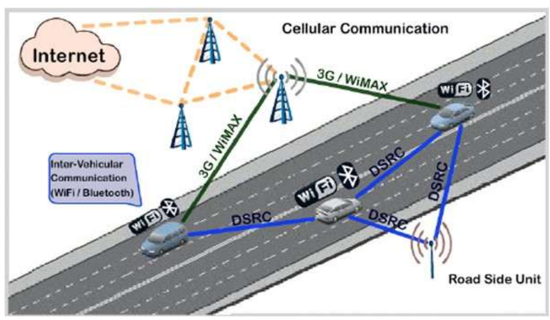

Fig. 1. Wireless networking technology in V2V and V2I communications:

Dedicated Short-Range Communication. WIFI: Wireless Fidelity. WiMAX: Worldwide Interoperability for Microwave Access.

(C-V2X) communication. Though DSRC is low-latency, CV2X (4G/5G based) supports higher range, scalability, and compatibility with smart city infrastructure. These systems facilitate applications like collision warnings, cooperative lane changes, and platooning. But one of the biggest challenges in V2V—particularly at high speeds—is handling Doppler shifts and time-varying multipath channels. Traditional waveforms such as OFDM perform poorly in such fast-fading scenarios. This is where Orthogonal Time Frequency Space (OTFS) modulation comes into play. OTFS works in the delay-Doppler domain, where the channel is sparse and almost static, making it well-suited for high-mobility scenarios. Data symbols are initially transformed into the delay-Doppler domain and subsequently modulated into the time-frequency domain via ISFFT in OTFS. It enables the system to deal with Doppler shift and multipath delay spread more effectively, thereby achieving enhanced robustness and signal quality. In V2V, OTFS enables reliable communication links to be sustained in dynamic, highspeed conditions such as overtaking manoeuvres or highway cruising.

E. Doppler Estimation Methods

Doppler shift estimation is vital in wireless systems to mitigate the frequency offsets caused by user mobility or relative motion. Various methods, from traditional signal processing to modern sparse and subspace techniques, are used to estimate Doppler effects accurately in different communication environments.

- Low-Dimensional Subspace Doppler Estimation: This method relies on projecting the received signal onto a reduced dimensional space to efficiently estimate Doppler shifts. The idea is that even though the full received signal may be high dimensional, the significant Doppler components typically lie within a much smaller subspace. ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) is a popular approach in this category. It works by constructing a data covariance matrix from the received signal samples and performing eigenvalue decomposition to isolate the signal subspace.

The estimated covariance matrix can be expressed as:

$$R^x = \frac{1}{N}\sum_{i=1}^{N} x_i x_i^H \qquad (7)$$

Here, xi is the signal vector at the i-th time instant. Once this matrix is obtained, ESPRIT exploits a shift-invariance property between two overlapping subarrays of the signal subspace:

$$\mathbf{\Phi} = \mathbf{U}_1^{\dagger}\mathbf{U}_2 \qquad (8)$$

where U1 and U2 are partitions of the signal subspace, and † denotes the Moore-Penrose pseudoinverse. The Doppler frequencies are extracted from the phase of the eigenvalues of Φ. This method offers high precision, especially in complex propagation environments, though it requires careful tuning of model parameters and substantial processing resources.

- Sparse-Based Doppler Estimation: In scenarios where only a few dominant Doppler components exist, sparse signal processing becomes a powerful tool. These techniques assume that the frequency domain representation of the signal is mostly zero or near-zero except for a few significant coefficients. Using this assumption, it is possible to reconstruct the Doppler spectrum from fewer observations than traditional methods require.

The received signal model is:

$$y = \Psi s + n \qquad (9)$$

where Ψ is a dictionary matrix containing Doppler-shifted basis functions, s is a sparse vector that identifies active Doppler components, and n represents noise. Algorithms like Orthogonal Matching Pursuit (OMP) or Basis Pursuit (BP) are then employed to solve for s. These techniques are known for their resolution and efficiency, especially when the environment includes only a few dominant reflectors. However, they can become computationally intensive and require prior knowledge of the expected sparsity level.

- Pilot-Assisted Doppler Estimation: This technique incorporates known reference symbols, called pilots, into the transmitted waveform at predefined intervals. These pilots help the receiver monitor how the channel is changing over time, which includes shifts caused by relative motion between the transmitter and receiver.

By comparing the received pilot symbols across different time intervals, one can compute the phase rotation introduced

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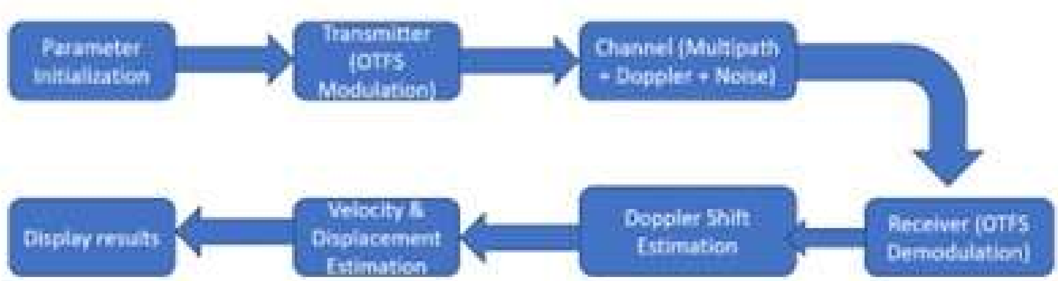


Fig. 2. Flow of operation

by Doppler shifts. If r1 and r2 are two successive received pilot signals, the phase change Δϕ can be calculated as:

$$\Delta\phi = \angle\left(\frac{r_2}{r_1}\right) \qquad (10)$$

The corresponding Doppler frequency estimate is then:

$$f_d \approx \frac{\Delta\phi}{2\pi T} \qquad (11)$$

with T being the time interval between the pilot symbols. Pilot-assisted methods are quite effective in rapidly changing channels, offering reliable estimates, though they do come at the cost of reduced spectral efficiency due to the need for pilot insertion.

IV. Comparison of Conventional Doppler Estimation Techniques in V2V Environment

The table[1] compares Doppler shift estimation accuracy across four methods under varying SNR levels (20, 30, 40 dB) for a true Doppler shift of 500 Hz. The Low-Dimensional Subspace method consistently delivers estimates closest to the actual value, especially at higher SNRs. The Associated Pilot Method also shows strong performance, slightly overestimating at higher SNRs. In contrast, FFT and Cyclic Prefix methods show larger deviations, particularly at lower SNRs.

V. Low-Dimensional Doppler Estimation in V2V High Mobility System with Doppler-Assisted Velocity and Positioning

A. OTFS Modulation at the Transmitter

Orthogonal Time Frequency Space (OTFS) modulation maps QAM-modulated data symbols into the Delay-Doppler (DD) domain, which is ideal for channels with both multipath and Doppler effects. These DD symbols are then transformed to the Time-Frequency (TF) domain using the Inverse Fast Fourier Transform (IFFT) and reshaped for transmission. QAM Modulation: Digital bits are modulated using Quadrature Amplitude Modulation (QAM), which efficiently represents bits as complex symbols. Transformation to TF domain

$$X_{TF} = IFFT(ifftshift(X_{DD})) \qquad (12)$$

where X_{DD} is the DD matrix of symbols.
This modulation makes the signal robust against time frequency channel variations, which is crucial in high-mobility scenarios like vehicular communication.

B. Channel Model with Doppler and Multipath

The channel introduces multipath fading and a Doppler shift due to the relative motion between transmitter and receiver. The Doppler shift causes a frequency offset in the received signal, modelled as a complex exponential.

Doppler Effect

$$y(t) = x(t) \cdot e^{j2\pi f d t} \qquad (13)$$

Multipath Fading: Multipath is modelled using a random FIR filter:

$$h = \frac{1}{\sqrt{2L}}(\mathcal{N}(0,1) + j\mathcal{N}(0,1)) \qquad (14)$$

C. OTFS Demodulation at the Receiver

At the receiver, the time-domain signal is reshaped back into the TF grid, and Fast Fourier Transform (FFT) is applied to recover the signal in the DD domain. This essentially reverses the modulation process.

FFT Demodulation:

$$X_{DD} = FFT(reshape(y)) \qquad (15)$$

The demodulated QAM symbols are then converted back to bits, representing the estimated transmitted data.

D. Doppler Estimation via Subspace Method

Doppler estimation is performed using Subspace Techniques, particularly Singular Value Decomposition (SVD). The idea is to analyze the covariance of the received TF matrix to detect dominant frequency shifts.

Covariance Matrix

$$R_x = \frac{1}{N} X X^H \quad (16)$$

SVD Decomposition

$$R_x = USV^H \quad (17)$$

The dominant subspace (first column of U) captures the most significant signal direction. The Doppler shift is estimated by calculating the phase difference between the first few components:

TABLE I: COMPARISON OF DOPPLER SHIFT ESTIMATION

S. No	Estimation Method	SNR (dB)	Doppler Shift Added (Hz)	Doppler Shift Estimated (Hz)
1	FFT	20	500	322
		30	500	350.7
		40	500	362.55
2	Cyclic Prefix	20	500	398.22
		30	500	360
		40	500	334.88
3	Associated Pilot Method	20	500	400
		30	500	423.99
		40	500	430.5
4	Low-Dimensional Subspace	20	500	487.655
		30	500	494.455
		40	500	498.55

by calculating the phase difference between the first few components:

Doppler Frequency Estimation

$$\hat{f}_d = \quad 2\pi \cdot |mean(\Delta\phi)| \cdot fd,_{actual\,/2} \quad (18)$$

where $\Delta\phi$ is the phase difference between adjacent dominant eigenvector elements.

E. Doppler-Assisted Velocity and Positioning

Using the estimated Doppler shift, the relative velocity is computed based on the wavelength of the carrier signal.

Velocity Estimation

$$v = \lambda \hat{f}_d, \quad (19)$$

Displacement Estimation

From velocity, we compute the displacement over a short time interval dt:

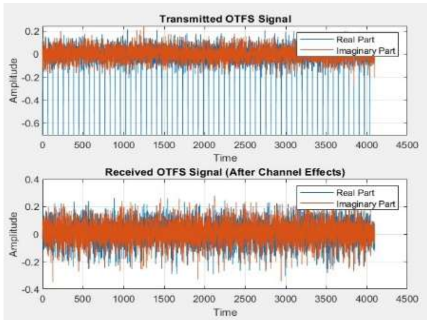
$$d = v \cdot dt \quad (20)$$

VI. IMPLEMENTATION

A. Matlab

Software Environment and Function Definitions: MATLAB serves as the primary simulation platform for this research. A high-level programming environment designed specifically for numerical calculation, data analysis, and algorithm creation is called MATLAB (Matrix Laboratory). Complex communications systems can be easily prototyped and implemented, which makes it important for this project that deals with OTFS-based V2V communication in high mobility. The simulation has made use of the following

VII. RESULTS



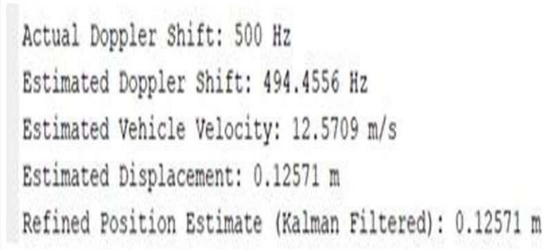


Fig. 3. Estimated Doppler shift and Velocity positioning   Fig. 4. The Transmitted and received signal in the OTFS system

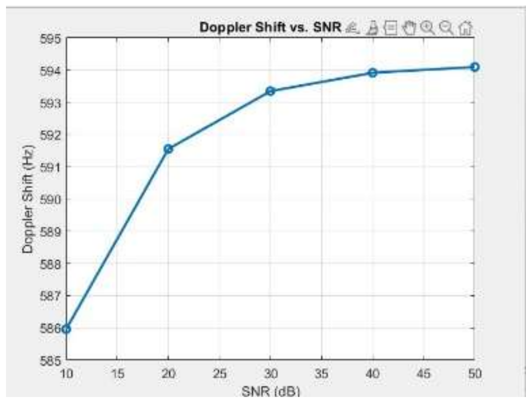


Fig. 5. Impact of Signal-to-Noise Ratio on Doppler Shift

The graph (Fig. 3.) illustrates how noise, interference, and multipath skew the real and imaginary components of the signal over time by comparing the OTFS waveforms that are transmitted and received. It provides a visual representation of how the transmission channel deteriorates signal integrity. According to this output Fig. 4., a Doppler shift of 500 Hz was precisely calculated to be 494.4556 Hz, which corresponds to a displacement of 0.12571 m and a vehicle velocity of 12.57 m/s. These values do not change after Kalman filtering. This graph (Fig. 5.) demonstrates the relationship between Signal-to-Noise Ratio (SNR) and Doppler Shift. As the SNR increases, the Doppler Shift also rises, indicating that stronger signals experience greater frequency variations. The steep growth in Doppler Shift at lower SNR levels suggests that weaker signals are more stable but less affected by frequency shifts. Understanding this trend is crucial for optimizing wireless communication systems, ensuring minimal distortion and improving signal reliability.

VIII. CONCLUSIONS

In this project, we proposed and implemented a subspace based Doppler shift estimation technique for OTFS (Orthogonal Time Frequency Space) modulation under high-mobility scenarios. By analysing the dominant eigen-subspace of the received signal's covariance matrix, we were able to accurately estimate the Doppler frequency components even in the presence of noise and multipath fading. Our results demonstrate that the subspace-based method consistently outperforms traditional FFT-based Doppler estimation techniques, particularly at moderate to high SNRs. The Mean Squared Error (MSE) of Doppler estimation decreased significantly as the number of subspaces and SNR increased, validating the robustness and precision of the proposed approach. Additionally, visual metrics such as constellation diagrams and eigenvalue spectra confirmed the integrity of demodulated signals and the effectiveness of the subspace separation. This approach enhances the reliability of OTFS systems in vehicular and high-speed wireless communication environments by providing more accurate Doppler information, which can be further utilized for channel tracking, equalization, and positioning. Future extensions may integrate Kalman filtering or machine learning for real-time Doppler-assisted positioning and adaptive subspace selection.

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