OTFS Modulation Based Analysis of Varying Doubly Dispersive Wireless Channel

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Abstract

This paper presents a comparative analysis of the bit error rate (BER) performance of Orthogonal Time Frequency Space (OTFS) modulation under three standard 3GPP wireless channel models: EPA, EVA, and ETU. Utilizing a MATLAB-based simulation framework with a zero-padded OTFS system and a linear minimum mean square error (LMMSE) equalizer, the impact of increasing delay spread and Doppler spread on BER is investigated. The results reveal a consistent performance hierarchy where the EPA channel model yields the lowest BER, followed by EVA, and finally ETU with the highest BER. The observed degradation is attributed to the growth in delay spread and power of late taps, which increases the frequency selectivity and complexity of channel equalization in the delay-Doppler domain.

Keywords: Doubly Dispersive Wireless Channel, OTFS Modulation, Propagation Channel Models

Ⅰ. Introduction

High-mobility wireless links (e.g., vehicular and satellite channels) exhibit pronounced time- and frequency-selectivity, posing challenges to traditional orthogonal frequency division multiplexing (OFDM). In such environments, OFDM suffers from inter-symbol interference (ISI) due to its sensitivity to doppler shifts, motivating the exploration of alternative modulation schemes. Orthogonal Time Frequency Space (OTFS) modulation, which operates in the delay-Doppler domain, has emerged as a promising candidate. By transforming doubly-dispersive channels into nearly time-invariant representations, OTFS offers improved robustness under high-mobility conditions [1].

The real-world multipath fading is often modeled using standard 3GPP profiles, namely EPA, EVA, and ETU, each with distinct delay spread characteristics. Understanding the BER performance of OTFS under these models is essential for practical system design. This study evaluates the effect of these channel conditions using consistent OTFS system parameters and highlights the influence of channel selectivity on equalization performance.

II. System Model

A downlink system is considered with single transmit and receive antenna. Each OTFS frame comprises M subcarriers with a spacing of Δf and N symbols with a time of T. This results in a total bandwidth of $B = M\Delta f$ and a frame duration of $Tf = NT$. The respective delay Doppler grid is given by

$$\emptyset = \left(\frac{k}{NT}, \frac{l}{M\Delta f}\right), k \in \{0, \dots, N-1\}, l \in \{0, \dots, M-1\} \quad (1)$$

where $1/NT$ denotes the resolution along the Doppler dimension and $1/(M\Delta f)$ denotes the resolution along the delay dimension. After converting the transmit bits into symbols and placing them in the DD grid, Inverse Symplectic finite Fourier transform (ISFFT) is applied to convert DD domain symbols $x[k,l]$ to Time-frequency (TF) domain symbols $X[n,m]$ and then form TF to time domain signal $s(t)$ using Heisenberg transform.

$$X[n,m] = \frac{1}{MN}\sum_{k=0}^{N-1}\sum_{l=0}^{M-1} x[k,l]e^{j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \quad (2)$$

where $n \in (1,2, \dots N)$ and $m \in (1,2, \dots M)$.

$$s(t) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} X[n,m]e^{j2\pi m\Delta f(t-nT)}g_{\mathrm{tx}}(t-nT) \quad (3)$$

where $g_{tx}(t)$ is the transmit pulse function. The time domain signal will undergo a DD domain channel $h(\tau,\nu)$, given in [2] as

$$h(\tau,\nu) = \sum_{p=0}^{P} h_p\delta(\tau-\tau_p)\delta(\nu-\nu_p) \quad (4)$$

where P is the number of multipaths. The received time domain signal at the receiver is given by

$$r(t) = \iint h(\tau,\nu)e^{j2\pi\nu(t-\tau)}s(t-\tau)d\tau d\nu + z(t) \quad (5)$$

where $z(t)$ is additive white Gaussian noise. The TF domain signal is extracted from the time domain signal using the Wigner transform and is converted to DD domain signal by employing the Symplectic finite Fourier transform (SFFT).

$$Y[n,m] = \int_{-\infty}^{\infty} g_{\mathrm{rx}}^{*}(t-nT)r(t)e^{-j2\pi m\Delta f(t-nT)}dt \quad (6)$$

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

where $g_{\mathrm{rx}}(t)$ is the received pulse function. For equalization a time-domain LMMSE equalizer is used to mitigate the doubly dispersive channel effect.

$$\hat{y} = (G^H G + \sigma^2 I)^{-1} G^H r \quad (8)$$

where G is the $MN \times MN$ channel matrix formed from estimated delay-Doppler taps and r the received vector.

III. Channel Models

The evaluation is based on the 3GPP-defined EPA, EVA, and ETU channel models. Each model is characterized by a unique power delay profile (PDP):

EPA: 7 taps, maximum delay of 410 ns, low delay spread with most energy concentrated in early taps.

EVA: 9 taps, maximum delay of 2510 ns, moderate delay spread with mid-tap power.

ETU: 9 taps, maximum delay of 5000 ns, high delay spread with significant late tap power.

The RMS delay spread and coherence bandwidth for each model inversely correlate. The RMS delay spread can be computed as

$$\tau_{rms} = \sqrt{\frac{\sum_i P_i(\tau_i - \bar{\tau})^2}{\sum_i P_i}}$$

where $\bar{\tau} = \frac{\sum_i P_i \tau_i}{\sum_i P_i}$ is the mean delay, P_i is the power of i^{th} multipath component and τ_i is the delay of that component. EPA's short spread results in a coherence bandwidth sufficient to maintain flat fading across subcarriers. Conversely, ETU's long spread reduces coherence bandwidth, leading to severe frequency selectivity.

III. Results

The simulated system utilizes an OTFS transceiver with M = 8 subcarriers and N = 8 symbols per frame, resulting in a delay-Doppler grid of 64 symbols. QPSK modulation is employed, and a single pilot is inserted for channel estimation. Zero-padding is used to mitigate inter-symbol interference, and a time-domain LMMSE equalizer reconstructs the transmitted data based on the estimated channel. The carrier frequency is set to 5 GHz with a subcarrier spacing of 15 kHz. The system bandwidth is 120 kHz, and channel sampling adheres to the Nyquist rate. UE mobility is modeled at speeds up to 1000 km/h. For each SNR point from 0 to 30 dB, 500 to 1000 OTFS frames are simulated depending on the SNR, ensuring statistical reliability.

In Figure 1, the BER versus SNR performance consistently follows the trend: EPA < EVA < ETU. At an SNR of 15 dB, the BER under the EPA model is approximately 10^-3, while it exceeds to 10^-2 for EVA and reaches around 10^-1 for ETU. This performance degradation corresponds to increasing delay spread and the presence of powerful late taps. In the delay-Doppler domain, the wider support of ETU causes energy to leak further from the diagonal of the channel matrix, reducing the accuracy of linear equalization and increasing residual interference. The following observations are key:

Coherence Bandwidth: With larger RMS delay, the channel's coherence bandwidth narrows, making subcarriers experience frequency-selective fading.

Channel Matrix Spread: More and stronger delayed paths in EVA and ETU increase off-diagonal terms in the channel matrix, complicating inversion and equalization.

Equalizer Limitations: The basic LMMSE equalizer, while computationally efficient, cannot fully mitigate the dispersion in ETU-like channels.

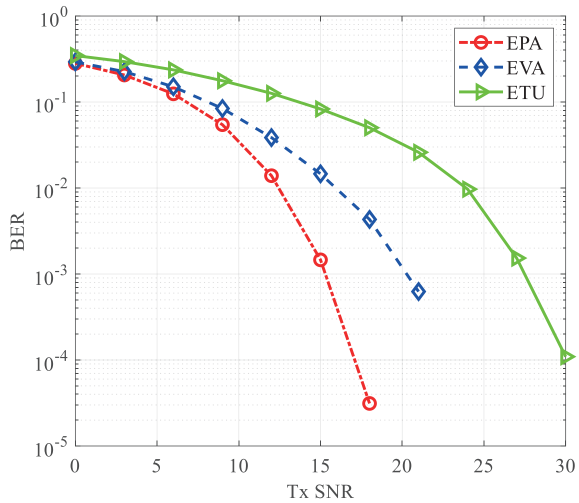

Figure 1: BER comparison of 3GPP wireless channel models: EPA, EVA, and ETU.

IV. Conclusion

We have demonstrated that under identical OTFS parameters and an LMMSE equalizer, 3GPP EPA, EVA, and ETU channels yield progressively worse BER, perfectly matching theoretical expectations based on delay spread and coherence bandwidth. For ETU-like scenarios, designers should increase pilot density or adopt advanced equalizers to combat severe selectivity. Future work will extend to real-world channel measurements and coded OTFS schemes.

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