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Enhancing the WLAN OFDM-PHY by OTFS Precoding

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Abstract—**Reliable communication in high-mobility scenarios is considered a significant challenge. For such a problematic task, the Orthogonal Time Frequency Space (OTFS) modulation technique has come up as an efficient solution, providing promising results in doubly selective time and frequency channels. In this paper, we have simulated and compared OTFS and a complete Orthogonal Frequency-Division Multiplexing (OFDM) system in a multipath environment at different mobile speeds under the presence of a synchronization impairment, i.e., timing offset (TO). Firstly, we have modelled the OTFS system according to the active subcarriers in the OFDM system and then modified the OTFS frame in the time-frequency (TF) plane in compliance with the OFDM symbol. This modification kept a similar bandwidth for both systems, eliminated the need for multi-rate processing and allowed OTFS to be used as a precoder to the targeted OFDM transceiver. Our simulation results show that, with increased mobility, the OFDM Error Vector Magnitude (EVM) performance is degraded abruptly, whereas the OTFS link remains stable.**

Keywords— OTFS, OFDM

I. Introduction

Several modulation schemes were contenders for the final waveform in the 5th-generation wireless mobile networks (5G). These included Universal Filtered Multicarrier (UFMC), Filter-Bank Multicarrier (FBMC), Filtered-OFDM (f-OFDM), and some others [1]. Due to its high flexibility in almost every aspect, such as multipath robustness, simple equalization, and low complexity, all the aforementioned waveform candidates for 5G were based on OFDM. High peak-to-average power ratio (PAPR) and high out-of-band emissions (OOBE) were the main challenges considered [1]. Reliability in high-mobility scenarios due to Doppler effects is also one of the biggest challenges, as the subcarriers lose orthogonality in such scenarios. The simplest solution for mitigating the Doppler spread problem in multicarrier systems is to utilize large subcarrier spacing, which the aforementioned modulation schemes also perform [2]. However, this can reduce spectral efficiency.

Reliable communication under high mobility was considered one of the key performance indicators for user experience in 5G [3]. Multiple high-mobility scenarios, such as High-Speed Trains up to a speed of 500 km/h, and three-dimensional (3D) connectivity, were included in 5G [3]. In 6th-generation (6G) wireless mobile networks, unmanned aerial vehicles, satellites, and High-Speed Trains are also among the targeted use cases [4]. The coherence time of the channel with increased mobility is significantly reduced. This poses an immense challenge for the whole system, as the equalizer needs to be more complex, and channel estimation has to be performed more frequently. The time-frequency (TF) plane changes abruptly, and the low complexity-based one-tap equalizer solution of OFDM would not be able to work in such scenarios. Frequent channel estimation will also reduce the overall performance.

High mobility scenarios demand new solutions, because Doppler effects in a multipath environment change the single-dimensional time-invariant channel into a two-dimensional (2D) time-variant channel. For such 2D cases, there is an inherent need for a 2D channel model. Delay-Doppler (DD) processing is an efficient tool that can be utilized for such fast-fading channel scenarios, and it is the baseline for the proposed 2D waveform known as Orthogonal Time Frequency Space (OTFS) [5, 6]. OTFS waveform is specifically developed for such challenges as it represents the information corresponding to the actual geometry in a physical radio environment. Due to the geometric representation of the radio environment, the DD channel changes much slower than the TF channel [5]. Channel estimation in the DD domain is also more straightforward and can be easily estimated via embedded pilots [7]. The channel effect on the whole DD plane can be calculated via simple interpolation [8]. The estimated channel is valid for the whole frame, as all of the symbols experience nearly the same channel effects [9].

Synchronization challenges are critical for multicarrier waveforms. Carrier Frequency Offset (CFO) needs to be compensated before processing. All the benefits of multicarrier waveforms are only realized when they are perfectly synchronized. However, in the OTFS system, CFO appears as a Doppler shift in the DD domain, and DC offset appears on the zero Doppler column, which can be easily mitigated [10 - 12]. Joint timing offset (TO) and CFO estimation were proposed in [13]. The Sampling Time Offset (STO) can also be alleviated by utilizing multi-rate processing [11] or by utilizing some post-processing [12].

To achieve maximum data rate, multi-rate processing stages should not be large. An OFDM system efficiently utilizes a single sampling rate for the whole processing system, which is done by assigning zeros to the subcarriers at the edges. The OTFS frame occupies the whole TF plane, thus multi-rate processing or sharp filtering is an inherent requirement. However, a relation exists between the TF and DD planes. Via Symplectic Finite Fourier Transform (SFFT) [5] and some post-processing, the same OFDM modulator can be utilized for OTFS. Therefore, with some increased complexity, a single sampling rate can be utilized for OTFS as well.

In this paper we simulate and compare a complete OTFS system with a complete OFDM system [14] under the presence of multipath propagation, timing offset (TO), and different Doppler spreads. Both OFDM and OTFS frames are transmitted simultaneously to make a collective frame. Both frames utilize roughly the same transmission power and equal occupied bandwidth. We investigate both systems' resulting Error Vector Magnitude (EVM) performance at different vehicular speeds. Our results show significant performance gain of the OTFS system under high Doppler spread conditions.

II. System Model

This section discusses a few background concepts related to OFDM and OTFS [5-8].

A. Basic OFDM System Model

With respect to the chosen modulation scheme (e.g. QPSK), bits are mapped into $d_{m,n}$ and then placed on an OFDM frame $\mathbf{X_{OFDM}}$ of size $M{\times}N$. M is the total number of subcarriers, such that total bandwidth B_T is equal to $M\Delta f$, where Δf is the subcarrier spacing. N is the number of symbols in time with $T = 1/\Delta f$ is one symbol duration, and NT is the total frame duration. $\mathbf{X_{DT\text{-}OFDM}}$ is the equivalent delay-time matrix obtained by the N number of M-pt. IFFT:

$$X_{DT-OFDM}\,[k,l] = \frac{1}{\sqrt{M}}\sum_{m=0}^{M-1} X_{OFDM}\,[m,n]e^{j2\pi\left(\frac{mk}{M}\right)} \tag{1}$$

where n is equal to l, not all the entries of $\mathbf{X_{OFDM}}$ are non-zero. At fixed tones $\mathbf{f_{pilots}}$, pilots $x_{p,m}$ are placed, and around the maximum of positive and negative frequencies $\mathbf{f_{nulls}}$, zeros are placed. This placement of zeros allows OFDM to run at a single sampling rate without the need for sharp filtering. $\mathbf{X_{OFDM}}$ is represented as:

$$X_{OFDM}\,[m,\ n] = \begin{cases} x_{p,m},\ \ 0 \le n \le N-1, m \in \mathbf{f_{pilots}} \\ 0,\ \ 0 \le n \le N-1,\ \ m \in \pm\mathbf{f_{nulls}} \\ d_{m,n},\ \ \text{otherwise} \end{cases} \tag{2}$$

With null subcarriers, the occupied bandwidth B_O becomes $M'\Delta f$, where M' is the number of active subcarriers. Serialization is performed on $\mathbf{X_{DT\text{-}OFDM}}$ and then cyclic-prefix (CP) is prepended before each OFDM symbol. At the receiver, the reverse operation is performed after CP removal.

B. OTFS System Model

For an OTFS frame $\mathbf{X}$, the size of the matrix is $M'{\times}N'$, where N' is the number of Doppler bins and M' is the number of delay bins [6, 8]. Mapped symbols $c_{m,n}$ from input bitstream are placed on $\mathbf{X}$ in the DD domain. With considering fractional Doppler, a pilot x_{pilot} is also embedded with data and it is surrounded by a zeros region [7]. The surrounding zero region should account for maximum delay spread for accurate channel estimation. We place the pilot on the zero Doppler column at location m_{pilot}, such that $\mathbf{X}$ becomes:

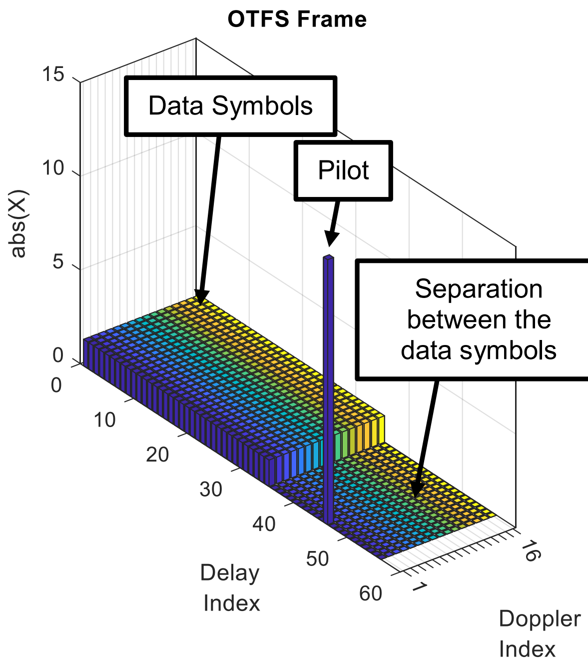


Fig. 1. OTFS frame **X** in a view of delay-doppler (DD) domain.

$$X[m,\ n] = \begin{cases} x_{pilot},\ \ m = m_{pilot},\ \ n = 0 \\ 0, m \in \left[m_{pilot} \pm l_p\right],\ 0 \le n \le N'-1 \\ c_{m,n},\ \ \text{otherwise} \end{cases} \tag{3}$$

$\mathbf{X}$ with $M' = 56$, $N' = 16$ and $l_p = 10$ paths is illustrated in Figure 1. Equivalent delay-time matrix $\mathbf{X_{DT\text{-}OTFS}}$ is obtained by M'number of N-pt. IFFT [8]:

$$X_{DT-OTFS}\,[k,l] = \frac{1}{\sqrt{N'}}\sum_{n=0}^{N'-1} X\,[m,n]e^{j2\pi\left(\frac{nl}{N'}\right)} \tag{4}$$

where $N' = N$ and m is equal to k. Bandwidth relation is equal to $M'\Delta f$, which is equal to the occupied bandwidth B_O in OFDM. Equation (4) is the low-complexity Zak-Transform-based implementation of OTFS [5, 8]. The inherent need for sharp filtering in this implementation involves multi-rate processing [11, 12]. However, SFFT-based OTFS also exists with increased complexity. $\mathbf{X_{TF}}$ is an inverse SFFT (ISFFT) processed OTFS frame such that [8]:

$$X_{TF}[k,l] = \frac{1}{\sqrt{N'M'}}\sum_{n=0}^{N'-1}\sum_{m=0}^{M'-1} X[m,n]e^{j2\pi\left(\frac{nl}{N'}-\frac{mk}{M'}\right)} \tag{5}$$

Applying IFFT over (5) yields [8]:

$$X_{DT-OTFS}\,[k,l] = \sum_{m=0}^{M'-1} X_{TF}\,[m,n]e^{j2\pi\left(\frac{mk}{M'}\right)} \tag{6}$$

where n is equal to l. The resulting $\mathbf{X_{DT\text{-}OTFS}}$ is similar to that in (4), and it also has an inherent need for sharp filtering. Fig. 2a illustrates the full bandwidth utilization of $\mathbf{X_{DT\text{-}OTFS}}$.

III. OTFS SYSTEM BASED ON SINGLE PROCESSING RATE

The occupied bandwidth of both $\mathbf{X_{TF}}$ and $\mathbf{X_{OFDM}}$ are the same. However, for $\mathbf{X_{TF}}$, there is no difference between occupied and total bandwidth. For a single sampling rate without the need for sharp filtering or multi-rate processing, $\mathbf{X_{TF}}$ needs to have a relation between BO/BT similar to that of OFDM. SFFT-based OTFS implementation can provide such benefits. This relation can be established by appending and prepending null subcarriers at $\mathbf{f_{corner}}$ to the $\mathbf{X_{TF}}$, and increasing the number of total samples in the TF plane. Now (6) becomes:

$$X_{DT-OTFS}\,[k,l] = \frac{1}{\sqrt{M}}\sum_{m=0}^{M-1} X_{TF2}\,[m,n]e^{j2\pi\left(\frac{mk}{M}\right)} \tag{7}$$

where n is equal to l. $\mathbf{X_{TF2}}$ is:

$$X_{TF2}\,[m,\ n] = \begin{cases} 0, & 0 \le n \le N' - 1, m \in \pm\mathbf{f_{corner}} \\ & X_{TF}, \text{otherwise} \end{cases} \tag{8}$$

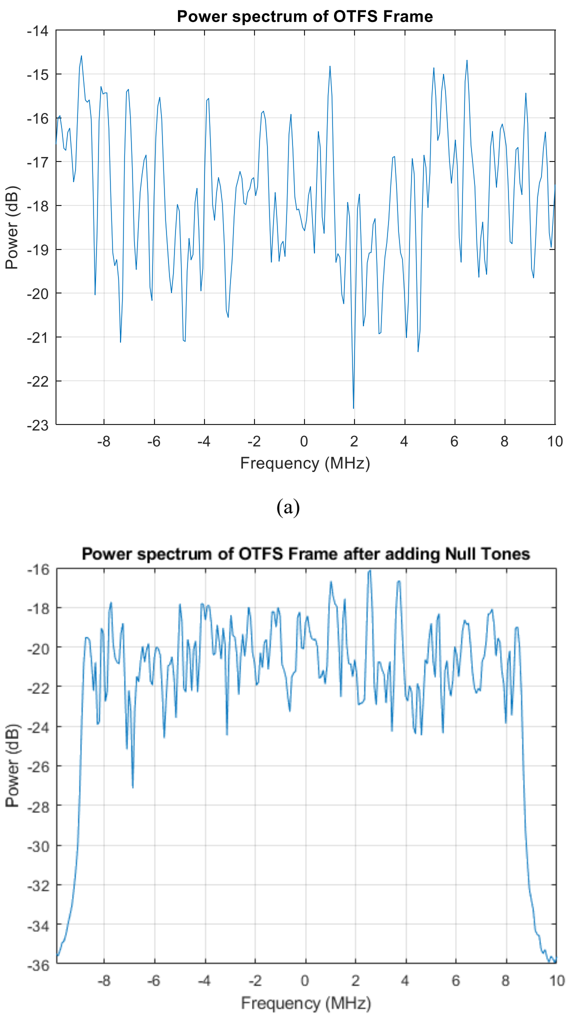
Fig. 3 illustrates the process of (8) clearly for $M' = 56$, $N' = 16$, $M = 64$, and also illustrates $\mathbf{X_{OFDM}}$. Finally, the resulting occupied bandwidth is illustrated in Fig. 2b.

Both $\mathbf{X_{TF2}}$ and $\mathbf{X_{OFDM}}$ have similar sizes, and the same OFDM modulator can be easily used for both cases, hence for practically utilizing OTFS as a precoder to OFDM, the OTFS matrix (delay bins) has to be designed according to the active subcarriers of OFDM and an SFFT-based processing is needed.

Serialization is performed on $\mathbf{X_{DT\text{-}OTFS}}$ and CP is prepended before each symbol. At the receiver, $\mathbf{Y_{DT}}$ is the received delay-time matrix after removing CP. $\mathbf{Y_{TF2}}$ is found by:

$$Y_{TF2}\,[k,l] = \sum_{m=0}^{M-1} Y_{DT}\,[m,n]e^{-j2\pi\left(\frac{mk}{M}\right)} \tag{9}$$

where n is equal to l. The additional M/M' tones are removed to get the matrix $\mathbf{Y_{TF}}$, which is equivalent to $\mathbf{X_{TF}}$ in ideal



(b)

Fig. 2. Power Spectral Density of OTFS frames: (a) original, after Inverse Zak Transform. (b) SFT-based OTFS with addition of Null Tones.

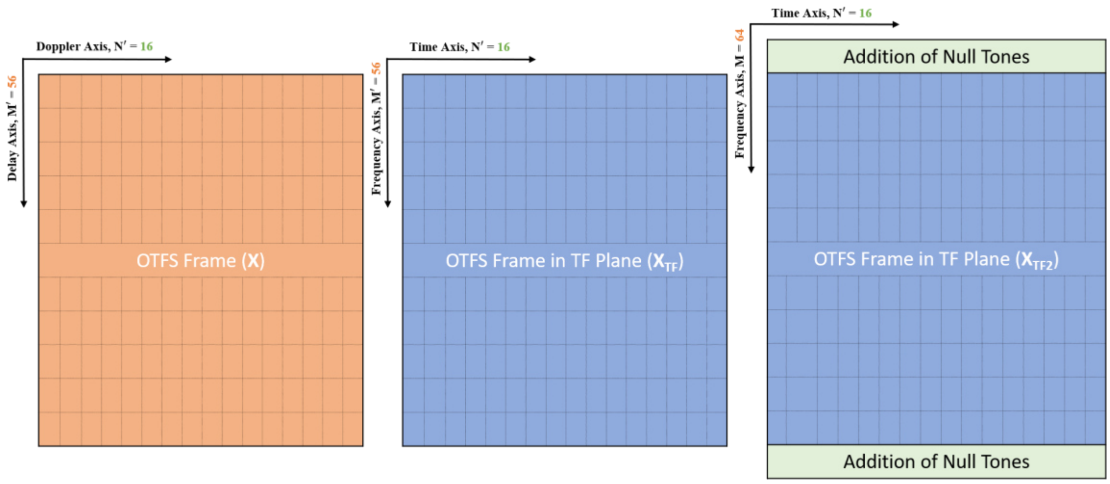


Fig. 3. The original OTFS frame $\mathbf{X}$ in DD domain. Frames $\mathbf{X_{TF}}$ is obtained by ISFFT of $\mathbf{X}$. $\mathbf{X_{TF2}}$ is obtained by appending zeros at the end of both negative and positive maximum frequencies. Zeros appending and formation of $\mathbf{X_{TF2}}$ eliminates the need for separate upsampling and filtering. In the end, $\mathbf{X_{TF2}}$ is serialized column-wise, and IFFT operation is performed, which produces the transmitter baseband signal in the time domain like in an OFDM transmitter.

conditions. Forward SFFT is applied finally to get the resulting matrix $\mathbf{Y}$ [8]:

$$Y[m,n] = \frac{1}{\sqrt{N'M'}} \sum_{k=0}^{N'-1} \sum_{l=0}^{M'-1} Y_{TF}\,[k,l] e^{-j2\pi\left(\frac{nk}{N'} - \frac{ml}{M'}\right)} \quad (10)$$

With OTFS as a precoder to a standard OFDM system, similar techniques can be utilized to compensate for synchronization challenges. An identical preamble is used to find the exact start of the frame (SOF) for frame-level synchronization. As OTFS provides immunity against frequency dispersion, CFO compensation is not necessary. The other remaining synchronization challenge is fractional STO, which can appear as a false multipath [12]. The technique in [12] can also be utilized. However, it is designed for a multi-rate system. Fractional STO appears as a part of channel impulse response (CIR) [15] and can be equalized in TF equalization. However, for OTFS, we utilize a Maximal Ratio Combining (MRC) algorithm of [9] for equalization. Fractional STO is compensated as a pre-equalizer stage via applying calculated opposing linear phase to the received TF matrix, $\mathbf{Y_{TF2}}$. Fractional STO appears like an increasing phase across received subcarriers [15]. This phase increase is linear and can be calculated by sending a known OFDM symbol and observing linear phase change on the subcarriers.

IV. Simulation Results

This section discusses the simulated performance results of the IEEE 802.11n OFDM model and OTFS in a multipath mobile environment. Table I illustrates the constraints for simulation. The OFDM model uses the FFT size 64, with 56 active subcarriers [14]. The total bandwidth of the system is 20 MHz and, to keep the same occupied bandwidth, the value of the OTFS delay bins M' is set to 56. For Doppler bins N', the value is set to 16. This corresponds to a Doppler resolution of 19531.25 Hz and a Delay resolution of 57.1 ns. The carrier frequency is set at 5.85 GHz.

TABLE I. System Constraints

Constraint	Value
Carrier Frequency f_c	5.85 GHz
Bandwidth B_T	20 MHz
Occupied Bandwidth B_O	17.5 MHz
Subcarrier Spacing Δf	312.5 kHz
$M \times N$	64×16
$M' \times N'$	56×16
Delay Resolution $\frac{1}{B_O}$	57.1 ns
Doppler Resolution $\frac{B_O}{M' \times N'}$	19.531 kHz
Modulation Scheme	4-QAM
Tx Power	~0 dB
Simulated Vehicular Speeds	150, 200, 250, 300 km/h
Maximum Doppler Shift	813, 1084, 1355, 1626 Hz

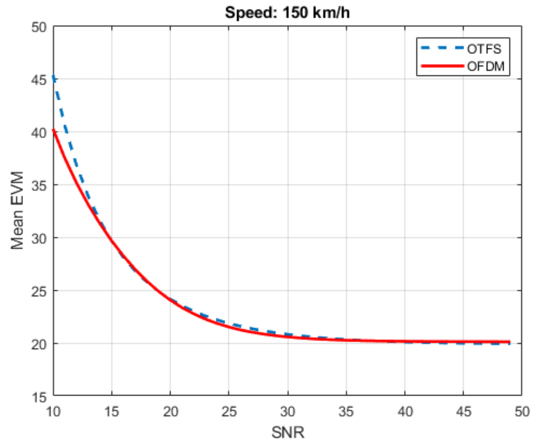
The HT-mixed mode preamble used in IEEE 802.11n for synchronization purposes is also utilized for the OTFS frame [14]. The preamble provides critical information fields such as coarse and fine CFO estimation, integer SOF, estimation of noise variance, and channel estimation. OTFS frame only uses SOF information and channel estimation information. No CFO correction is applied to the OTFS frame, as CFO appears to be a part of channel impairment and does not impact performance [10, 11]. Channel estimation from the preamble is only utilized as a pre-equalizer to correct STO. This pre-equalization resolves the fake paths that arrive due to the sampling rate mismatches.

The performance of both systems is evaluated against different mobility scenarios. The channel delay profile uses seven paths. The path coefficients are taken from the 3GPP specification for an extended pedestrian A channel model [16], with tap delays and power defined as follows {0, 30, 70, 90, 110, 190, 410} [ns], {0, -1, -2, -3, -8, 17, -21} [dB]. We simulated this channel with additional mobility effects at 150, 200, 250, and 300 km/h. The power spectral density (PSD) of the Doppler spectrum is Jakes classical shaped, and Rayleigh fading variates are generated with the sum of sinusoids method. A sampling rate offset of 25 ppm is also applied to consider a high sampling rate mismatch between ADC and DAC clocks.

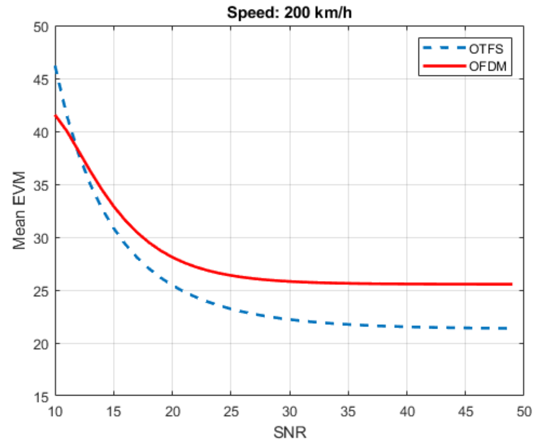
No prior information about the channel is available at the receiver, and it is performed via pilots in both OFDM and OTFS frames. In practical cases, the channel information is either estimated at the receiver or transmitted to it; our simulation is more suitable for practical scenarios. OFDM system utilizes the HT-mixed preamble and four pilots per symbol, and the OTFS system uses a single pilot in the DD domain (surrounded by zeros to avoid interference).

The Minimum Mean Squared Error (MMSE) equalization method significantly gains performance over the Zero Forcing (ZF) equalizer. The MRC algorithm is used to equalize the OTFS system [9]. Due to its reduced complexity, the MRC is operated in the delay-time domain [9]. A maximum of ten total paths are used for channel estimation and equalization. Ten paths account for around 450 nanoseconds of delay spread tolerance (considering fractional delays and residual fractional STO). At higher frequencies, the multipath component becomes weaker, and a smaller number of total paths can be utilized for channel estimation and equalization, thus reducing the complexity even further.

A proper and complete OFDM system was chosen specifically for a fair comparison with the OTFS waveform, which is built for high-mobility scenarios. Fig. 4a illustrates the EVM results between OFDM (with MMSE equalizer) and OTFS waveform at 150 km/h mobile speed. It can be seen that both OFDM and OTFS achieve similar results with the improved SNR. This indicates that OFDM can also work fine in typical high-mobility scenarios, with longer channel estimation validity and good equalizer performance. Fig. 4b demonstrates the results at 200 km/h. The OFDM system's performance has now started degrading, and the performance of the OTFS has not changed much. Fig. 4c and Fig. 4d indicate further degradation of the OFDM system, whereas the OTFS system has slight degradation compared to the OFDM. This shows how the complete OFDM system with efficient equalization can also not accurately manage high-mobility scenarios.



(a)



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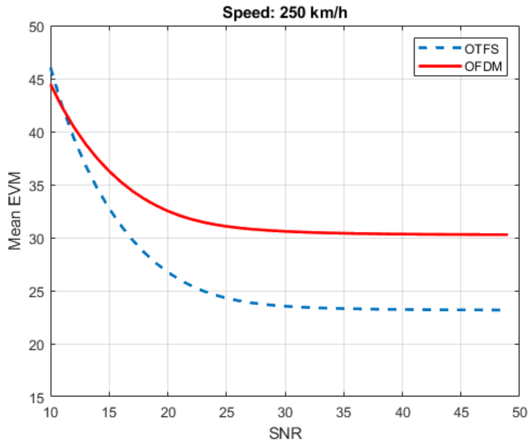
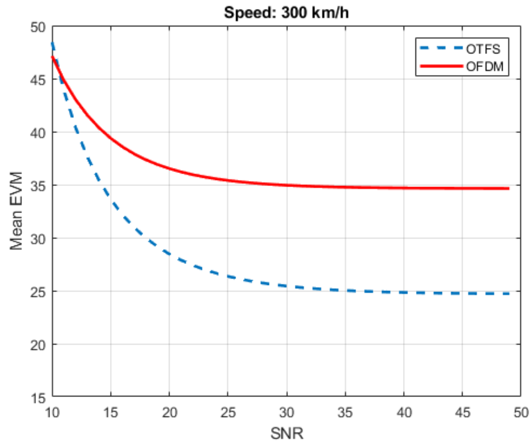
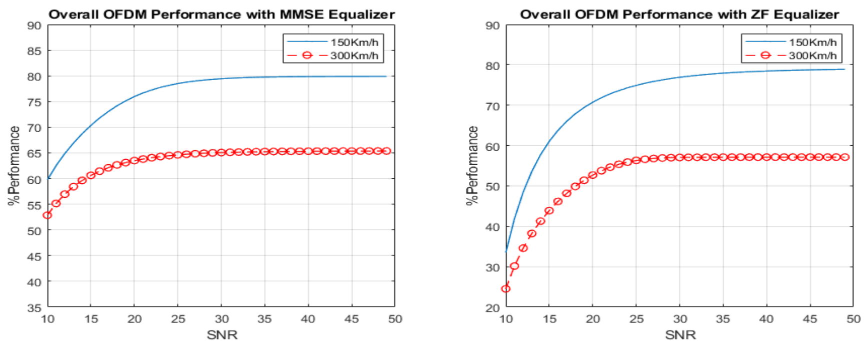


(c)

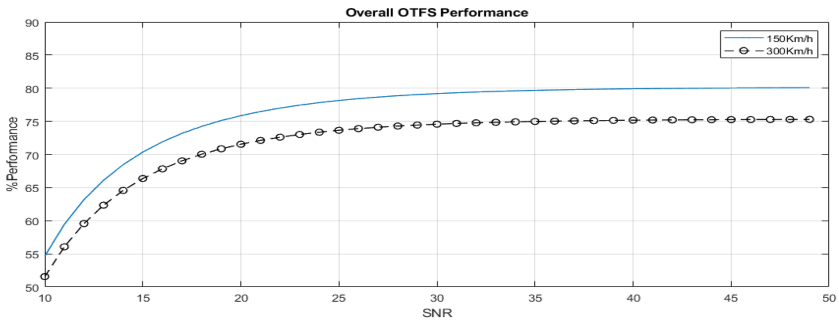


(d)

Fig. 4. Resulting EVM vs. SNR comparisons for different vehicular speeds (a) 150 km/h, (b) 200 km/h, (c) 250 km/h, (d) 300 km/h.



(a)



(b)

Fig. 5. Resulting Percentage Performance vs. SNR comparisons (a) OFDM performance with MMSE and (b) ZF Equalization OTFS performance.

Fig. 5a indicates the total performance degradation of the OFDM system with increased speed. The percentage performance of the system per SNR point is calculated by:

$$P_{SNR}[\%] = (1 - \overline{EVM}_{SNR}) \times 100\% \qquad (11)$$

It is evident that with increased speed, the OFDM system loses significant performance. Fig. 5a also illustrates the poor performance of the ZF equalizer. Fig. 5b indicates slight degradation of the OTFS system as compared to OFDM. The results in Fig. 5 clearly indicate that the OTFS system will outperform the OFDM system in high-mobility scenarios.

V. CONCLUSION

In this work, a complete OTFS system has been compared with the IEEE 802.11n OFDM model. The simulation compared both systems in a multipath environment with different Doppler spread effects at 5.85 GHz carrier frequency. The channel effect also included a high sampling rate mismatch to make simulation results closer to realistic synchronization challenges. For a fair comparison, the bandwidth of both systems was kept at the same level, and both waveforms' frames were sent together in a larger frame to have the same channel impairments. Symplectic Finite Fourier Transform (SFFT) based OTFS allows single rate processing, enables higher data rate prospects, and allows it to be utilized as an OFDM precoder. The simulation results show that the degradation of OFDM with increasing Doppler spread is more abrupt than OTFS, and hence, OTFS can be considered a suitable candidate waveform for high-mobility scenarios. The OTFS shows only a slight EVM degradation as compared to OFDM with the increases in vehicular speed.

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