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An approach for 5G implementation in railways based on orthogonal time frequency space

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Abstract:

Fifth Generation for Railways (5G-R) is a promising technology that seeks to improve safety, efficiency, and passenger experience by supporting a variety of services, such as real-time monitoring, predictive maintenance, autonomous operation, and passenger entertainment by accessing the Internet during trips, thus starting a new era of smart and efficient railway transportations. However, 5G-R suffers from the termed inter-carrier interference (ICI) problem due to the Doppler shift phenomenon especially when operating in high-mobility environments, such as high-speed railway (HSR) as it depends on orthogonal frequency division multiplexing (OFDM) technology. Our aim in this paper is to reduce the Doppler shift effect in the 5G-R system environment by incorporating the orthogonal time frequency space (OTFS) technology. Recently, OTFS was introduced as an effective ICI canceler. We referred to this solution as the OTFS-based 5G-R system. In order to verify the effectiveness of the proposed solution, we compare its performance with that based on OFDM in different HSR environments using quadrature amplitude modulation (QAM) schemes. Further performance evaluation process was conducted including the use of two different equalization techniques at the receiving side. Matlab was used to implement the aforementioned solution. Results confirmed the superiority of the proposed solution since it shows lower BER values. Results also confirmed the effectiveness of the proposed solution in reducing the Doppler effect because it almost shows identical performance regardless the difference in speeds.

Keywords: Fifth generation for railways; High-speed railway; Orthogonal frequency division multiplexing; Orthogonal time frequency space; Future railway mobile communication system

1. Introduction

Several use-case scenarios that need a specific requirement for each lead to great challenges in 5G [1–5]. One of the major challenging issues in this aspect is the communication in the HSR environments in which signals suffer from a significant Doppler effect. A successful railway system greatly depends on wireless communications in many aspects, including controlling trains, exchanging signals between the system components, exchanging data with a control center, performing some operational processes, and providing services to passengers during trips [6]. Until the end of 2009, the Global System for Mobile Communications-Railway (GSM-R) was the most widely spread wireless railway communication system. Besides voice communication service, GSM-R can support data transmission but at a low rate. Along with the fast growth of railway services, the termed long-term evolution of railway (LTE-R) was adopted as the GSM-R successor in 2010. Compared with GSM-R, LTE-R can provide a faster data rate with higher spectrum efficiency [7]. The features of a new era of railway systems began to emerge when the International Union of Railways (UIC) proposed the Future Railway Mobile Communication System (FRMCS) in 2014. In this context, UIC announced the FRMCS user requirements (URS), including seventy-two cases for future railway communications [8]. Since neither GSM-R nor LTE-R could meet these requirements, the need for a new railway communications system became urgent. The 5G-R has been proposed as the next successor. It is characterized by its higher data rates, low latency, and improved reliability [9]. On the other hand, 5G-R is highly sensitive to the effect of Doppler shift when operating in high-speed environments due to its reliance on OFDM technology, which will be the exact case in future railway systems in which speeds may reach 500 km/hour. The Doppler shift, sometimes referred to as frequency-based dispersion, causes a loss of orthogonality between carriers, resulting in significant signal distortion or loss. Several researches were conducted aiming to reduce the effect of the Doppler effect in the HSR environment at the high-frequency band (the millimeter wave band). Some of this research followed the estimation approach, while others followed the compensation approach. For example, researchers in [10] proposed three different Doppler shift estimators, namely: radio environment map (REM)-based, equally divided structure-based estimator (ESBE), and enhanced ESBE (EESBE). The results confirmed the superiority of the proposed estimators over the traditional ones used currently in the millimeter wave HSR environment. Researchers in [11] proposed a data-assisted Doppler compensator, using channel modeling based on taking the second-order Taylor expansion of phase delay. The results confirmed the effectiveness of the proposed solution. Researchers in [12] proposed a low-complex Doppler estimator scheme using machine learning and reference signal received power (RSRP) values. The results confirmed the superiority of the proposed solution over the traditional ones. Researchers in [13] introduced a new algorithm for Doppler and channel estimation. The results confirmed the effectiveness of this algorithm in wireless communication systems especially those supported by an intelligent transparent surface (ITS) when used in the HSR environment. On the other hand, many researches have aimed to reduce the Doppler effect in HSR systems but in lower frequency bands. In this context, researchers in [14] proposed intelligent Doppler spread compensation algorithms for mobile broadband communications considering the HSR environment. The results confirmed the superiority of the proposed algorithm in dealing with the Doppler effect at the link level of HSR mobile broadband communications. OTFS technology has been proposed to overcome the above-mentioned drawback faced by OFDM. While the above-mentioned solutions may lead to increased system complexity or resource consumption, OTFS can be implemented using simple pre- and post-processing steps over OFDM [15]. The performance of OTFS and OFDM was first compared in [16] using the DD domain representation. This work confirmed several important advantages of OTFS, including its potential use with radar, and the capability to reduce interference. Later, the authors in [17] prepared by Cohere Technologies revealed the association of OTFS with traditional modulations, such as TDMA and CDMA. Compared to OFDM, OTFS is another two-dimensional technique that operates in the delay-Doppler (DD) domain rather than operating in the time-frequency (TF) domain. In OTFS, both the channel and information signal are represented in the DD domain. The information symbols are modulated into the DD domain using the inverse symplectic finite Fourier transform (ISFFT). Using the two-dimensional (2D) transformation, i.e., from the DD domain to the TF domain, every information symbol can span over the entire TF domain with an OTFS frame. Thus, achieving full diversity, which eventually leads to realizing ultra-reliable communications [18]. In addition, the time-varying channel is transformed into the time-invariant channel, which leads to all symbols undergoing a nearly constant gain. A worth-mentioning is that the channel response in the DD domain exhibits a sparse property, which leads to reducing the complexity of data detection and channel estimation [19, 20]. A further advantage of OTFS over OFDM is the reduced cyclic prefix which is attributed to its lower peak-to-average power ratio (PAPR) and reduced signaling overhead [21]. Many recent studies have confirmed the effective contribution of the OTFS technology in the field of communications, especially in precoding transmitter design, delay-Doppler channel estimation, multiple accesses design, and detection methods. In this context, researchers in [22] proposed using practical pulse-shaping waveforms to reduce the OTFS cyclic prefix. They created a new OTFS input-output relationship with non-ideal waveforms and confirmed that it shows a simple and sparse characteristics, whereas many studies achieved bi-orthogonality when ideal pulse-shaping is used. Researchers in [23] proposed a channel estimation and data detection solution using the Dolph-Chebyshev (DC) window at the transmitter or receiver in the case of suppressing the channel state information (CSI) at the transmitter. The results showed an improvement in the channel estimation and data detection with the proposed solution as compared with the traditional rectangular window. Researchers in [24] proposed an adaptive scheme for transmission using MMSE and frequency domain precoding techniques. In the proposed scheme, new OTFS signals were re-forming based on previously encoded OFDM signals. The results confirmed the superiority of the proposed scheme by achieving better performance compared to OTFS in fast-fading channels. The results also confirmed the effectiveness of the proposed scheme for channel estimation errors, especially with short signal frames. In [19], researchers proposed a new channel estimation scheme for OTFS based on the embedded pilot-assisted approach using threshold and message passing algorithm (MPA) at the receiver side. The proposed channel estimation scheme achieves acceptable performance compared to the ideal performance in which a channel with previously determined information is used. Researchers in [25], proposed an OTFS channel estimating solution. The solution was based on the existence of fractional Doppler shifts to recover the structured sparse signal. The solution was formulated using the so-called factor graph representation. The results confirmed the effectiveness of the proposed solution. Researchers in [26] investigate the phenomenon of partial delay and partial Doppler shifts that cause the problem of leakage in pulse-shaped OTFS and reduce the efficiency in channel estimation. They proposed a leakage suppression technique by minimizing discrete isotropic gradients in the TF domain. The results confirmed the superiority of the proposed technique in reducing the leakage problem, enhancing the channel estimation, and improving the overall performance. Researchers in [20] aimed to improve OTFS interference cancellation (IC) and symbol detection by proposing a new, simple, and low-complex MPA. Results confirmed the ability of the MPA-based OTFS scheme to achieve the ideal OTFS pulse-shaping waveform performance even when practical rectangular waveforms are used. Researchers in [27] proposed an innovative OTFS detection scheme based on Gaussian Approximate Message Passing (GA-MP) such that it operates in the DD domain. The GA-MP interprets the posteriori probabilities of transmitted symbols in the forms of Gaussian distributions and then estimates the transmitted symbols frequently. The results confirmed the superiority of the proposed scheme over the Message Passing (MP) scheme used previously. Researchers in [28] aimed to reduce the complexity of the OTFS receiver by developing a low-complex OTDS detector using the termed Variational Bays (VB) method. The results confirmed the feasibility of the proposed solution compared to the traditional one based on the MAP detector. Researchers in [29] seek to achieve an upper uplink rate using the 2D OTFS multiple access schemes, which are termed delay division multiple access (DDMA) and Doppler division multiple access (DoDMA). Compared to OFDM, both DDMA and DoDMA can provide higher rates due to their better signal-to-interference-plus-noise ratio (SINR). Researchers in [30] proposed a hybrid scheme to improve the performance of multi-user OTFS systems. The hybrid scheme was based on the integration between the sparse code multiple access (SCMA) and the code-domain non-orthogonal multiple access (NOMA) technologies. It is referred to as the OTFS-SCMA system. The scheme achieved excellent diversity gains compared with the conventional OTFS-OMA hybrid scheme. It exhibits a sufficient tolerance, making it able to work with different SCMA overloading factors (up to 200%) and delay-Doppler plane parameters. Researchers in [31] proposed an innovative multiple access (MA) method to increase spectral efficiency and reduce multi-user interference (MUI) for OTFS systems. The proposed method was examined in wireless channels that exhibit large Doppler and delay. The results show that the proposed MA exhibits an almost free MUI compared to existing MA methods that use guard bands. OTFS was also engaged in the field of HSR communication, albeit with just a little. In this context, researchers in [32] proposed a hybrid scheme aimed to support massive Internet of Things (mIoT) usage in HSR environments. The hybrid scheme is based on OTFS and tandem spreading multiple access (TSMA) technologies. Results confirmed the possibility of providing reliable communications using the proposed solution via time-frequency selective fading channels. Researchers in [33] evaluated the feasibility of using OTFS-based LTE-R technology in the HSR environment considering the characteristics of the channel spreading function. Results confirmed that OTFS needs an additional 5 dB gain when operating in practical channel spreading mode to reach the identical performance when operating in ideal channel spreading mode. In this paper, the authors proposed a hybrid solution to deal with the Doppler shift in the 5G-R environment. This solution is referred to as the OTFS-based 5G-R system. To come up with a fair judgment, the performance of the OTFS-based 5G-R system was compared with the 5G-R system that is based on OFDM technology, considering different HSR environments using 16-QAM and 64-QAM schemes. The performance of the OTFS-based 5G-R system was also examined at different HSR speeds. Further performance evaluation process was conducted including the use of two different equalization techniques at the receiving side.

2. Mathematical modeling of the proposed solution

This part provides the mathematical formulation of the proposed solution including the OTFS system model, OFDM mathematical formulation, HSR channel modeling, and mathematical formulation of the equalization techniques. An analytical approach was used in this paper to evaluate the performance of the proposed OTFS-based 5G-R system in different HSR environments. BER was used as a performance metric. The work includes modeling the OTFS system to estimate its ability to resist the Doppler effect caused by high mobility. Analysis was conducted using the HSR communication model for the 5G-R system introduced in [8]. The 5G-R system key parameters used in this analysis are listed in Table 1. The speeds were carefully chosen such that they emulate real-world high-speed train capabilities [9]. For the OTFS system, the number of delay symbols (M) and Doppler symbols (N) has been chosen to ensure good performance in HSR environments. As for the value of subcarrier spacing, it is given by $\Delta f = B/M$, and the value of symbol duration is given by $T = 1/\Delta f$. The Tapped-Delay-Line (TDL) approach was used for modeling HSR channels in hilly, urban, rural, and viaduct environments. To ensure a fair comparison, the performance of the OTFS-based 5G-R system was compared with the performance of the OFDM-based 5G-R system under identical conditions. That is both systems were examined using the same carrier frequency, bandwidth, and modulation schemes in the same HSR environments. The termed Zero-Forcing Equalizer (ZF) and Minimum mean squared error Equalizer (MMSE) are the two equalization techniques that have been included in this analysis, considering the DD domain. The mathematical formulation of these equalization techniques is provided below.

2.1 OTFS system model

Figure 1 shows an OTFS-based communication system model. To generate data symbols, the input bits undergo a QAM process. In OTFS, each frame contains N symbols with T symbol duration for each, and M sub-carriers with Δf bandwidth for each, resulting in a total frame duration $T_f = NT$, and a total frame bandwidth $B = M\Delta f$. The mathematical formulation of the DD and TF domain grids is

Table 1. 5G-R Key Parameters.

Parameter	Value
Carrier frequency (f_c)	2.1 GHz
Train velocity (v)	350, 500 Km/h
Doppler symbols (N)	32
Delay symbols (M)	32
Subcarrier spacing (Δf)	625 KHz
Symbol duration (T)	1.6 μs
Bandwidth (B)	20 MHz
Modulation Alphabet	16-QAM, 64-QAM
Equalizers	ZF, MMSE

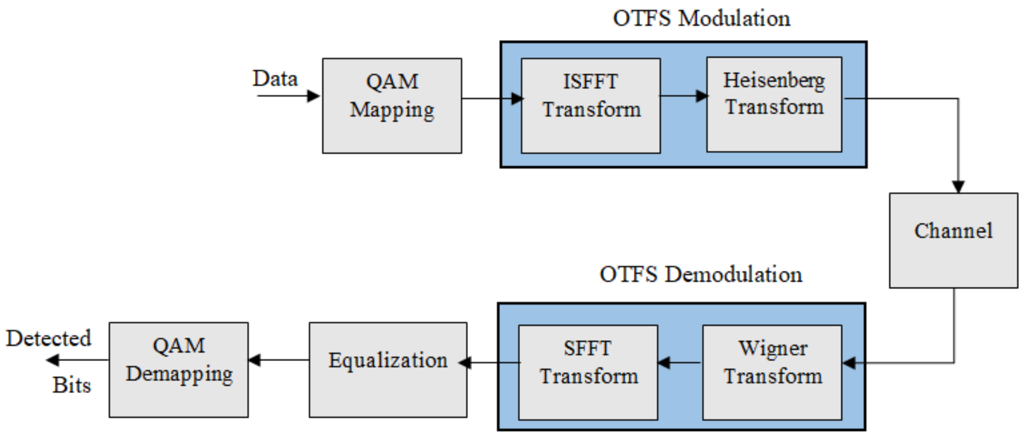

Figure 1. OTFS-based communication system.

written in equations (1) and (2), respectively [16]

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

$$\Lambda = \left\{ (m\Delta f, nT), m = 0, \cdots, M-1, n = 0, \cdots, N-1 \right\} \quad (2)$$

where $1/NT$ and $1/M\Delta f$ represent the resolution of Doppler shift and delay, respectively. The modulated data symbols are arranged onto the 2D DD domain grid Γ as $x[k,l]$, where k refers to the Doppler shift and l refers to the delay shift. In the DD grid, one axis represents the delay (the time a signal spends to move from transmitter to receiver) and the other axis represents the Doppler (the frequency shift due to high motion). Each symbol $x[k,l]$ is located at a specific point to represent a specific combination of delay and Doppler. The DD symbols $x[k,l]$ are then converted to the TF domain grid $\bigwedge$ via the ISFFT as in equation (3) [16]

$$X[n,m] = \frac{1}{\sqrt{NM}} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} x[k,l] e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)} \quad (3)$$

where, $X[n,m]$ are the information symbols in the TF domain.

The next step is to produce a time domain signal suitable for transmission over the wireless channel using the Heisenberg transform. The Heisenberg transform can properly structure the signal in such a way making it suitable for transmission over the dispersive wireless medium, allowing the system to deal with the dynamic properties of that medium which are the delay and Doppler effects. Equation (4) formulates this process [16]

$$s(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X[n,m] g_{tx}(t - nT) e^{j2\pi m\Delta f(t-nT)} \quad (4)$$

where $s(t)$ is the time domain signal and g_{tx} is the transmitted pulse of duration T. The combination of ISFFT and Heisenberg transform is referred to as OTFS modulation.

Finally, the time domain signal is sent over the channel represented in the DD domain. The channel impulse response (CIR) in the DD domain is given as [22]

$$h(\Gamma, \nu) = \sum_{i=1}^{P} h_i \delta(\tau - \tau_i) \delta(\nu - \nu_i) \quad (5)$$

where h_i, τ_i, and ν_i are the channel gain, delay shift, and Doppler shift of the *i-th* path, respectively. P represents the number of propagation paths. The delay and Doppler shift for the *i-th* path are expressed by [22]

$$\tau_i = \frac{l_i}{NT}, \nu_i = \frac{k_i}{M\Delta f} \quad (6)$$

where l_i and k_i are the delay and Doppler index for the *i-th* path. Thus, the received signal $r(t)$ can be expressed as [34]

$$r(t) = \int \int h(\tau, \nu) s(\tau - \nu) e^{j2\pi\nu(t-\tau)} d\tau d\nu + w(t) \quad (7)$$

where $w(t)$ represents the additive white Gaussian noise (AWGN) in the time domain.

At the receiver side, the Winger transform is assigned to convert the time domain signal $r(t)$ back to the Wigner transform is used to convert it back to the TF domain. The cross-ambiguity function is calculated first as in equation 8 [34]

$$Y(t,f) = A_{g_{rx}}(t,f) \triangleq \int r(t') g^*_{rx}(t' - t) e^{-j2\pi f(t'-t)} dt \quad (8)$$

here, g_{rx} is the pulse shape at the receiver. By sampling $Y(t,f)$ the grid Λ, one can create a matrix of received samples in the TF domain signal $Y[n,m]$ as [34]

$$Y[n,m] = Y(f,t)|_{t=nT, f=m\Delta f} \quad (9)$$

for $n = 0, \cdots, N-1$ and $m = 0, \cdots, M-1$. Equations (8) and (9) together are called Wigner transform. Later, the symplectic finite Fourier transform (SFFT) is used to obtain the DD domain signal $y[k,l]$ as [34]

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

The input-output relationship in the DD domain for the considered system can be represented in vector form as [22]

$$y = Hx + w \quad (11)$$

where y, x, and w represent the vector forms of the received symbols, transmitted symbols, and the noise in the DD domain, respectively. H is the effective channel matrix whose size is $MN \times MN$ in the DD domain which can be expressed as [22]

$$H = \sum_{i=1}^{P} h_i (F_N \bigotimes I_M) \prod^{l_i} \Delta^{k_i} (F_N^{\dagger} \bigotimes I_M) \tag{12}$$

where F_N is the discrete Fourier transform (DFT) matrix whose size is $N \times N$, I_M denotes the identity matrix whose size is $M \times M$, $\prod^{l_i}$ represents the $l_i - th$ path step cyclic shift of the permutation matrix $\prod$ which can be expressed as [18]

$$\prod = \begin{bmatrix} 0 & \dots & 0 & 1 \\ 1 & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \dots & 1 & 0 \end{bmatrix}_{MN \times MN} \tag{13}$$

Δ^{k_i} is a diagonal matrix whose size $MN \times MN$ given by $\Delta = diag z^0, z^1, \cdots, z^{MN-1}$ with $z = e^{\frac{j2\pi}{MN}}$. The matrices $\prod^{l_i}$ and Δ^{k_i} are the model of delays and Doppler shifts for the $l_i - th$ delay path [17]. Finally, the process of equalization and detection can be performed in either the TF domain or DD domain [34].

2.2 OFDM mathematical formulation

Since the performance of OTFS will be compared with that of OFDM over delay-Doppler channel, it is essential to review the vectorized formulation of the OFDM input-output relation. The OFDM model to be used in this comparison has been previously studied in [17]. The model considers an OFDM symbols with T duration for each. Each T consists of M subcarriers, resulting in a received signal and noise being sampled over T/M intervals. Using fast Fourier transform (FFT), the frequency domain representation of the vectorized formulation of the OFDM input-output relation can be given as [20]

$$y = F_M H_t F_M^H x + w \tag{14}$$

where y, F_M and x represent received OFDM symbol, an M-point FFT matrix and transmitted OFDM symbol, respectively. H_t is the time-domain channel matrix that model the doubly-selective effect, which described as [20]

$$H_t[p,q] = \sum_{i=1}^{P} h_i \delta \left[\left[p - q - \frac{\tau_i M}{T} \right]_M \right] e^{\frac{j2\pi(q-1)v_i}{M}}, p,q = 1,\dots,M \tag{15}$$

To conduct equalization and detection process in frequency domain using OFDM, equation (14) can be reformulated using the $M \times M$ frequency-domain channel matrix $H_{\text{OFDM}} = F_M H_t F_M^H$ which yields [20]

$$y = H_{\text{OFDM}} x + w \tag{16}$$

2.3 HSR channel modeling

As mentioned above, the TDL approach is used in this paper for modeling the HSR channel environment. TDL is characterized as one of the simplest modeling approaches for estimating the channel impulse response (CIR). TDL characterizes each exist path between transmitter and receiver in terms of delay and attenuation. Table 2 lists the HSR delay and attenuation parameters based TDL modeling approach, considering hilly, urban, rural, and viaduct channel environments [35, 36]. In Table 1, each path is referred to as a tap. The Doppler shift is calculated as $\boldsymbol{f_D}$=$\boldsymbol{f_d} \cos\theta$, where $\boldsymbol{f_d}$ is the maximum Doppler shift given as $\boldsymbol{f_d} = \frac{\boldsymbol{v f_c}}{\boldsymbol{c}}$, where $\boldsymbol{v}$ is the train velocity, $\boldsymbol{f_c}$ is the carrier frequency, $\boldsymbol{c}$ is the speed of light, and $\boldsymbol{\theta}$ is the angle of arrival (AoA) which follows a uniform distribution $\boldsymbol{U[0,2\pi]}$.

2.4 ZFE mathematical formulation

ZFE is characterized as a low-complex linear detection algorithm. ZF indicates to the possibility of achieving zero ISI when transmitting over a noise-free channel, hence recovering the transmitted signal correctly.
The ZF can be formulated mathematically as [37]

$$W_{\text{ZF}} = (H^H H)^{-1} H^H \tag{17}$$

where W_{ZF} and H^H represent the ZF equalization matrix and the complex conjugate transpose of channel matrix H, respectively. Processing the signal in (11), yields an estimated symbols as

$$\hat{x}_{\text{ZF}} = W_{\text{ZF}} y \tag{18}$$

2.5 MMSEE mathematical formulation

MMSEE is used to improve performance in communication systems when transmitting over fading and noisy channels. It performs an optimization process in which the mean squared error between the received and transmitted symbols is reduced, which minimizing the effect of additive noise and ISI distortion.
The MMSEE can be formulated mathematically as [37]

$$W_{\text{MMSE}} = (H^H H + \sigma^2 I_{MN})^{-1} H^H \tag{19}$$

Table 2. HSR delay and attenuation parameters based on TDL modeling approach, considering hilly, urban, rural, and viaduct channel environments.

Tap	Hilly		Urban		Rural		Viaduct	
	Delay (μs)	Relative Power (dB)	Delay (μs)	Relative Power (dB)	Delay (μs)	Relative Power (dB)	Delay (μs)	Relative Power (dB)
1	0	0	0	-3	0	0	0	0
2	0.1	-1.5	0.2	0	0.3	-12.9	0.6	-11.2
3	0.3	-4.5	0.6	-2	0.6	-22.9	1.3	-14.9
4	0.5	-7.5	1.6	-6			2.0	-15.9
5	15.0	-8.0	2.4	-8				
6	17.2	-17.7	5.0	-10				

where W_{MMSE} and σ^2 represent the MMSEE equalization matrix and noise variance, respectively. I_{MN} is called the identity matrix whose size is $NM \times NM$. Similar to the case in ZFE, processing the signal in (11), yields an estimated symbol as

$$\hat{x}_{\text{MMSE}} = W_{\text{MMSE}} y \tag{20}$$

3. Results and discussions

As mentioned above, this paper seeks to evaluate the performance of the OTFS-based 5G-R system, considering hilly, urban, rural, and viaduct HRS environments. In order to obtain meaningful results, the performance of the 5G-R system that is based on OTFS technology was compared with that based on OFDM. In addition, the performance of the 5G-R system was evaluated by employing ZF and MMSE equalization techniques, considering 16-QAM and 64-QAM modulation schemes. This section presents the obtained results in graphical form. BER was used as a reference for performance evaluation. Table 1 lists the 5G-R key parameters that were exploited in this study.

Figures 2 (a-d), show BER versus SNR for the OTFS-based 5G-R and OFDM-based 5G-R systems, considering hilly, urban, rural, and viaduct HSR environments when traveling at 350 Km/h using 16-QAM and 64-QAM modulation schemes. It can be obviously seen that OTFS shows better performance than that of OFDM in all cases. Practically, this means that OTFS-based 5G-R can provide more reliable data transmission, which is important to maintain a stable connection at speeds of up to 350 km/h. On the other hand, the higher error rate in OFDM-based 5G-R can cause communication interruptions, which affects operational efficiency and passenger safety.

Figures 3 (a-d) show BER versus SNR for the OTFS-based 5G-R system, considering hilly, urban, rural, and viaduct HSR environments when traveling at different speeds (350 Km/h and 500 Km/h) using 16-QAM and 64-QAM modulation schemes. It can be obviously seen that OTFS shows an identical performance regardless the traveling speed, i.e., It is not affected by the change in speed. From practical perspective, the consistent performance of OTFS even with increased speed indicates that real-time monitoring and safety alerts can be enhanced by OTFS by reducing data loss and maintaining consistent data flow.

The ZF equalizer has been used in all the aforementioned cases. Figures 4 (a-d) show BER versus SNR for the OTFS-based 5G-R system using ZF and MMSE equalizers, considering hilly, urban, rural, and viaduct HSR environments when traveling at 500 Km/h using 16-QAM and 64-QAM modulation schemes. In all cases the OTFS-based 5G-R that employs the MMSE equalizer shows lower BER, thus providing a better performance. From practical perspective, MMSE can be the best choice that assist to achieve improved and stable communication irrespect of its computational complexity.

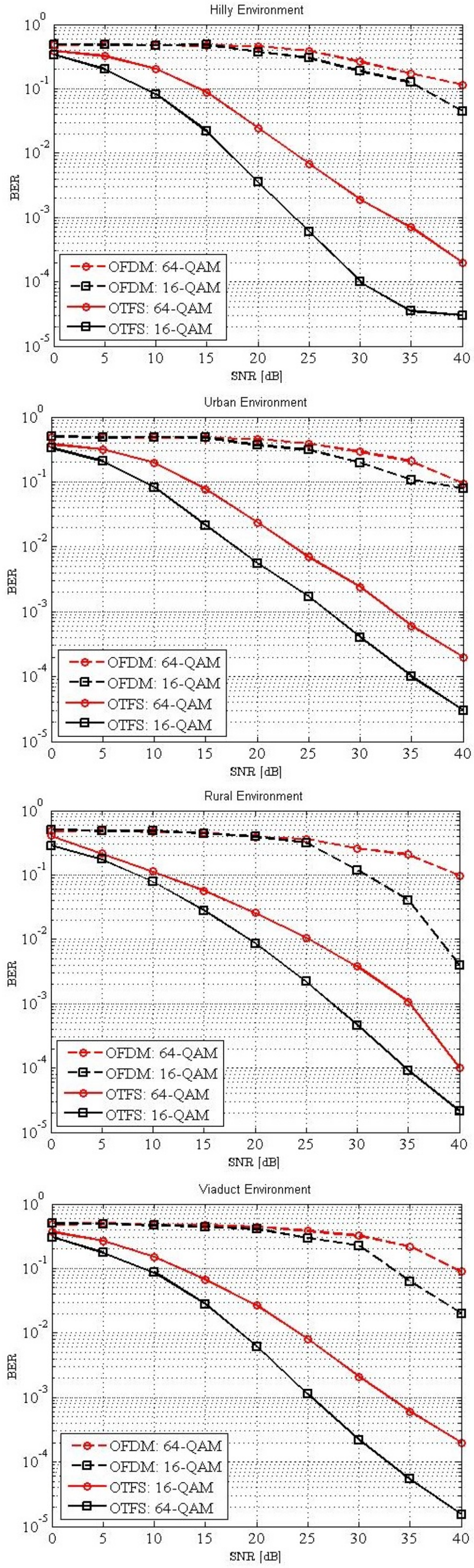

Figure 2. (a) BER VS SNR for the OTFS and OFDM-based 5G-R considering Hilly HSR environment at 350 Km/h; (b) BER VS SNR for the OTFS and OFDM-based 5G-R considering Urban HSR environment at 350 Km/h.; (c) BER VS SNR for the OTFS and OFDM-based 5G-R considering Rural HSR environment at 350 Km/h; (d)BER VS SNR for the OTFS and OFDM-based 5G-R considering Viaduct HSR environment at 350 Km/h.

4. Conclusions

In this paper, the performance of the OTFS-based 5G-R system has been evaluated in terms of its resistance to the

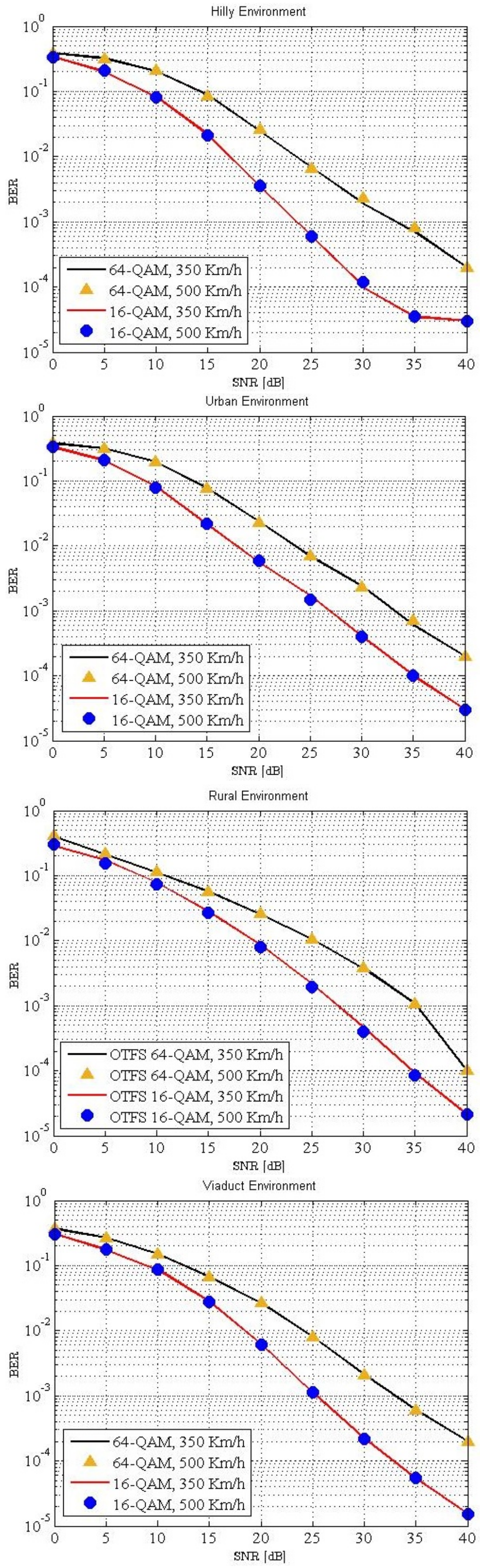

Figure 3. (a) BER VS SNR for OTFS-based 5G-R considering Hilly HSR environment at different speeds using 16-QAM and 64-QAM modulation schemes; (b) BER VS SNR for OTFS-based 5G-R considering Urban HSR environment at different speeds using 16-QAM and 64-QAM modulation schemes; (c) BER VS SNR for OTFS-based 5G-R considering Rural HSR environment at different speeds using 16-QAM and 64-QAM modulation schemes; (d) BER VS SNR for OTFS-based 5G-R considering Viaduct HSR environment at different speeds using 16-QAM and 64-QAM modulation schemes.

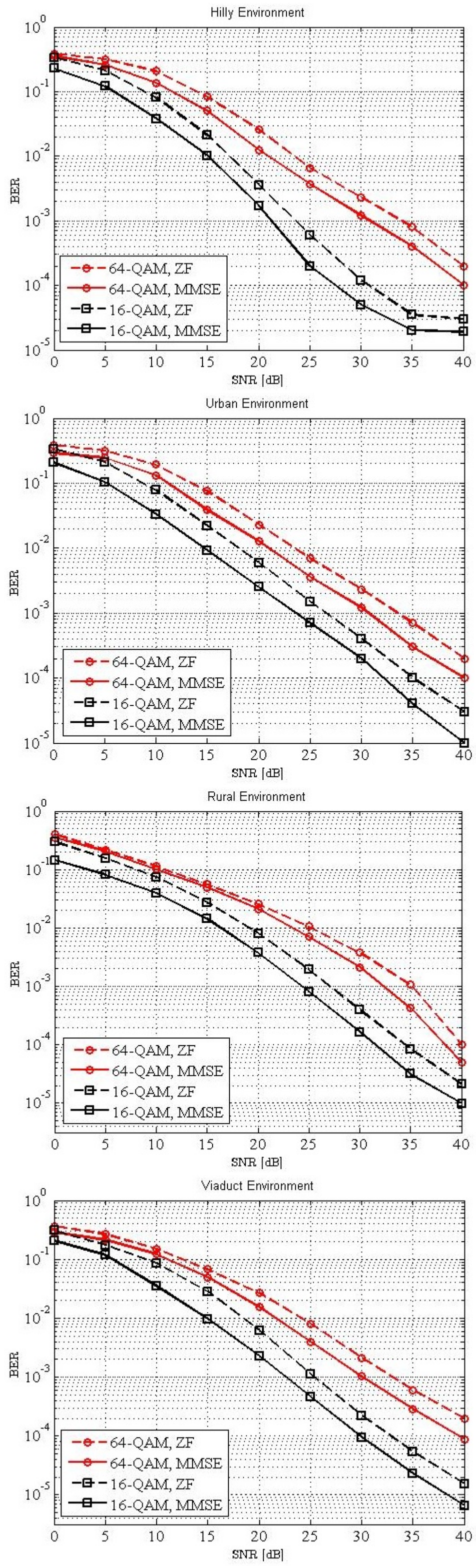

Figure 4. (a) BER VS SNR for OTFS-based 5G-R with ZF and MMSE equalizers, considering Hilly HSR environment at 500 Km/s using 16-QAM and 64-QAM modulation schemes; (b) BER VS SNR for OTFS-based 5G-R with ZF and MMSE equalizers, considering Urban HSR environment at 500 Km/s using 16-QAM and 64-QAM modulation schemes; (c) BER VS SNR for OTFS-based 5G-R with ZF and MMSE equalizers, considering Rural HSR environment at 500 Km/s using 16-QAM and 64-QAM modulation schemes; (d) BER VS SNR for OTFS-based 5G-R with ZF and MMSE equalizers, considering Viaduct HSR environment at 500 Km/h using 16-QAM and 64-QAM modulation schemes.

Doppler effect, considering hilly, urban, rural, and viaduct HRS environments. In order to reach a fair verdict, the performance of the OTFS-based 5G-R system has been compared with the performance of the 5G-R that is based on OFDM technology. The results confirmed the superiority of the OTFS-based 5G-R system in all of the above-mentioned HSR environments because it shows lower BER values compared to the higher BER values obtained using the OFDM-based 5G-R system. The results also confirmed the effectiveness of the OTFS-based 5G-R system in resisting the Doppler effect due to the identical performance it shows regardless the difference in speeds. Further increase in the Doppler effect resistance was realized by using the MMSE equalizer. This is based on the lower BER values achieved with the MMSE equalizer compared to the higher BER values recorded with the ZF equalizer. Based on the robust performance of the OTFS in combating the Doppler effect in HSR systems, one can conclude that it can improve the performance in other high-speed scenarios, such as automotive and drones' communication systems. These systems experience large Doppler shifts due to the high speeds at which vehicles and drones move. The low BER achieved by the proposed OTFS-based 5G-R system makes OTFS a potential candidate for maintaining a reliable communication in the above-mentioned scenarios, which is very crucial.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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