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# ISI and PAPR Immune IEEE 802.11p Channels Based on Single-Carrier Frequency Domain Equalizer

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## Abstract

Doppler Effect is a prominent obstacle in vehicular networks, which dramatically increase the Bit-Error-Rate (BER). This problem is accompanied with the presence of the Orthogonal Frequency Division Multiplexing (OFDM) systems in which the Doppler shift interrupts the subcarriers orthogonality. Additionally, Inter-Symbol Interference (ISI) and high Peak-to-Average Power Ratio (PAPR) are likely to occur which corrupt the received signal. In this paper, the single-carrier combined with the frequency domain equalizer (SC-FDE) is utilized as an alternative to the OFDM over the IEEE 802.11p uplink vehicular channels. The Minimum Mean Squared Error (MMSE) and Zero-Forcing (ZF) are employed in order to study the impact of these equalization techniques along with the SC-FDE on the propagation medium. In addition, we aim to enhance the BER, improve the transmitted signal quality and achieve ISI and PAPR mitigation. The proposed schemes are investigated and we found that the MMSE outperforms the ZF equalization under different Doppler shift effects and modulations.

***Keywords:*** Single-Carrier Frequency Domain Equalizer; Inter-Symbol Interference; Doppler Effect; Vehicular Channels

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## 1. Introduction

The upcoming vision of the communication systems targets higher data rates along with lower latencies. Vehicular networks pave the way for various ITS applications and services in order to fulfill the different vehicles requirements. These networks aim to increase the mobility requirements in order to cover excessive speed scenarios up to 250 Km/h [1]. However, for such high specifications, the IEEE 802.11p channels become extremely frequency-selective and can cause severely degrading the BER performance.

The IEEE802.11p standard has been developed using the bandwidth allocation of the IEEE 802.11a and the wireless access WAVE-IEEE 1609.x [2-5]. Nevertheless, the vehicular networks still suffer from some significant challenges including the insufficient bandwidth, lower packet delivery rate, and the high BER caused by the high vehicular mobility [6, 7]. This Standard is based on the OFDM system that enables the multicarrier transmission of the transmitted signal. Although the OFDM systems have become the best choice for the physical layer in several communication standards, the presence of some drawbacks for using the multi-carrier systems are a persistence challenges. Along these drawbacks are the high PAPR, intolerance to amplifiers nonlinearities, and the high sensitivity to carrier frequency offsets.

Moreover, the high Doppler shift due to mobility can affect the transmitted symbols' orthogonality by increasing the carrier interference. Thus, it is crucial to keep up orthogonality among the transmitted subcarriers to avoid ISI and improve the communication performance [8]. Consequently, the quality of the transmitted signal can be enhanced and guarantee the successful receive of the broadcasted data.

In this paper, we aim to employ the advantage of the single-carrier based on a frequency domain equalizer instead of the OFDM to lower the PAPR and avoid the ISI. The benefits of the SC-FDE along with the insertion of CP are utilized to maintain circuitry and preserve orthogonality. The reduction of the PAPR is necessary for the uplink channel transmissions. For that reason, we intend the uplink channel over the vehicle-to-roadside communications. The primary objective of this work is to investigate the performance of the ZF and MMSE equalization techniques with the purpose of reducing the resulted interference and to know which equalizer is better in determinates conditions.

In Section 2, we review the previous work in single-carrier transmission. Section 3 explains the proposed uplink vehicular channel model. We describe the channel capacity for the IEEE 802.11p standard in Section 4. Section 5 illustrates the feedback decision scheme of the frequency equalization. Section 6 presents the simulation evaluation including the setup configuration and BER performance.

## 2. Literature Review

The first appearance of both the multi-carrier and single-carrier schemes was in 1966 and 1973, respectively [9, 10]. Although the time between their advent is not that far, scientific attentions are mainly subjected towards the multi-carrier solutions and little efforts are devoted for the SC-FDE. However, the Frequency-Domain Equalization (FDE) was initially investigated by Walzman and Schwartz [9] to be adopted as a channel equalization technique that leads to lower complexity and offers better convergence properties compared to the time domain techniques. In 1995, digital TV broadcasting using terrestrial networks attracted researches particularly in North America and Europe [11-14]. The presence of strong echoes drastically affects the propagation medium. The primary aim is to deploy the single-frequency networks in order to increase the number of the broadcasted TV channels in the allocated frequency bandwidth. As a result, the communication research community has paid considerable attention to the use of FDE [15]. This paper pointed out to the use of the frequency-domain channel equalization in the single-carrier systems. The authors stated that the single-carrier transmission with the FDE can provide single-frequency networks as well as prevent the nonlinear distortion and carrier interference of the OFDM. The reason behind the renewed interests in FDE is for being a low-complexity solution especially over a highly-time-dispersive channel.

Recent researches on FDE mainly consider the utilization of the spatial and frequency diversities, design of linear equalizers, and the embedding of FDE in nonlinear modulations. On one hand, decision feedback equalization and Turbo equalization have been recently proposed and they are considered to be the result of integrating nonlinear equalizers with FDE. A frequency domain channel equalization algorithms were introduced by Pancaldi and Vitetta [16]. They are based on linear MMSE and decision-feedback equalizers. In addition, a synthesis technique had been proposed on Levinson-Durbin algorithm [17] mainly designed for the decision-feedback equalizer.On the other hand comes the nonlinear modulation schemes that use the FDE. A novel frequency domain equalizer was derived for the continuous phase modulations (CPMs) using the Laurent decomposition of the CPM signals [18]. Moreover, The CPM signal is obtained by employing the Gram-Schmidt orthonormalization procedure [19] and the Laurent's decomposition of the binary CPM [20]. The FDE has been included in various systems such as code division multiple access (CDMA), ultra-wideband (UWB) networks, and relay-assisted cooperative communications [21].

The linear equalization algorithms which are based on SC-FDE are used in various applications. Benvenuto and Tomasin propose a frequency domain decision feedback equalizer for single-carrier transmission. This model transmits a data block in the same format as OFDM with a cyclic prefix. Nevertheless, it is considered a non-adaptive decision feedback equalizer because the feed-forward relies on the frequency domain whereas the feedback is generated using time-domain [22]. Another suboptimum decision feedback block iterative scheme is also introduced based on single carrier [23]. The proposed scheme has been adopted to the uplink channels in the Third-Generation Partnership Project Long-Term Evolution (3GPP-LTE). Based on the MMSE, this work optimizes the coefficients of the feedback and feed-forward filters. This work shows that the proposed low complexity frequency domain iterative block decision feedback equalization (FD-IBDFE) converges faster and provides better performance compared to the time domain MMSE-turbo equalizer.

A comparison was held among various turbo equalizer algorithms by Aleksandr et al. [24]. This study is applied to single-carrier frequency division multiple access signals in LTE systems. Further, it performs signal processing in frequency domain under MMSE and soft interference cancellation approaches. The SC-FDE for the uplink transmission combined with the OFDM for the downlink transmission was proposed for the broadband wireless transmission systems [25]. Ribeiro et al. presented an extended approach for the base station cooperation system in the C-RAN allowing the deployment of the large scale clusters. This work aims to reduce both the detection complexity and backhaul signaling requirements.

Shortly, the SC-FDE is currently receiving a vast popularity because of its low complexity along with better BER compared to the conventional OFDM.

## 3. SC-FDE Uplink Vehicular Channel

The SC-FDE offers the same overall structure as the OFDM in which single carrier modulation can be done at the transmitter with a frequency domain equalization at the receiver. Nonetheless, an immune transmission system against the high PAPR and inter-symbol interference can be achieved. Recent researches directed to the utilization of the SC-FDE espcially for the uplink channels in order to reduce the cost of the power amplifiers.

Although the SC-FDE and OFDM systems uses the same communication component blocks, the location of the DFT block is different. In SC-FDE, the IDFT/DFT operations are comprised at the receiver side whereas the OFDM system has one IDFT at the transmitter and the corresponding DFT block at the receiver. Nevertheless, SC-FDE outperforms the mulit-carrier OFDM by being low sensitive to the carrier frequency offset, robust to the null spectral channel, and reduce the complexity at the transmitter [26].

In addition, the reduced PAPR feature offered due to avoiding the use of OFDM and utilize the single-carrier transmission is advantageous for the uplink transmissions [27]. The single-carrier equalization which considers the single tap FDE is able to enhance the BER by avoiding the frequency-selective channels. However, the presence of ISI after the FDE process degrades the communication system performance [27-31]. The SC-FDE system preserves the subcarrier orthogonality of the users as each user occupies different subcarriers in the frequency domain. Thus, the high PAPR can be avoided since the overall signal is considered to be a single carrier signal [32].

In this section, the proposed modulation studies the uplink vehicle-to-roadside communication channel using SC-FDE scheme. The FDE is employed to mitigate the ISI effect over a multipath Rayleigh vehicular channel.

### 3.1 System Model

Through this model, an input signal is mapped into consecutive data blocks of $\log_2 M$ information bits. Hence, the generated complex (I,Q) baseband signal is considered to be an M-ary complex constellation (i.e., PSK and QAM). A serial-to-parallel (S/P) conversion is applied to organize the data blocks so that each block consists of $S$ symbols. Afterwards, the cyclic prefix (CP) symbols are inserted in each block. In this case, the transmitted data blocks are cyclically extended (i.e., insert a repetition of the last $S_{cp}$ symbols of each block at its beginning). The addition of the CP helps to maintain orthogonality among the transmitted symbols. Here, the overall block length $S_B$ is defined as:

$$S_B = S + S_{cp} \tag{1}$$

At this moment, the generated blocks $S_B$ go through a parallel-to-serial (P/S) conversion to facilitate the availability of the complex symbols every predefined symbol period $T_s$ for digital transmission. The baseband data is passed through the digital-to-analog block and a frequency up-conversion is taken place to convert the I/Q symbols of the baseband into real signal centered at the carrier frequency $f_c$. This step is essential to prepare the signal for transmission over the IEEE 802.11p vehicular channel. **Fig. 1** demonstrates the SC-FDE diagram of the proposed model.

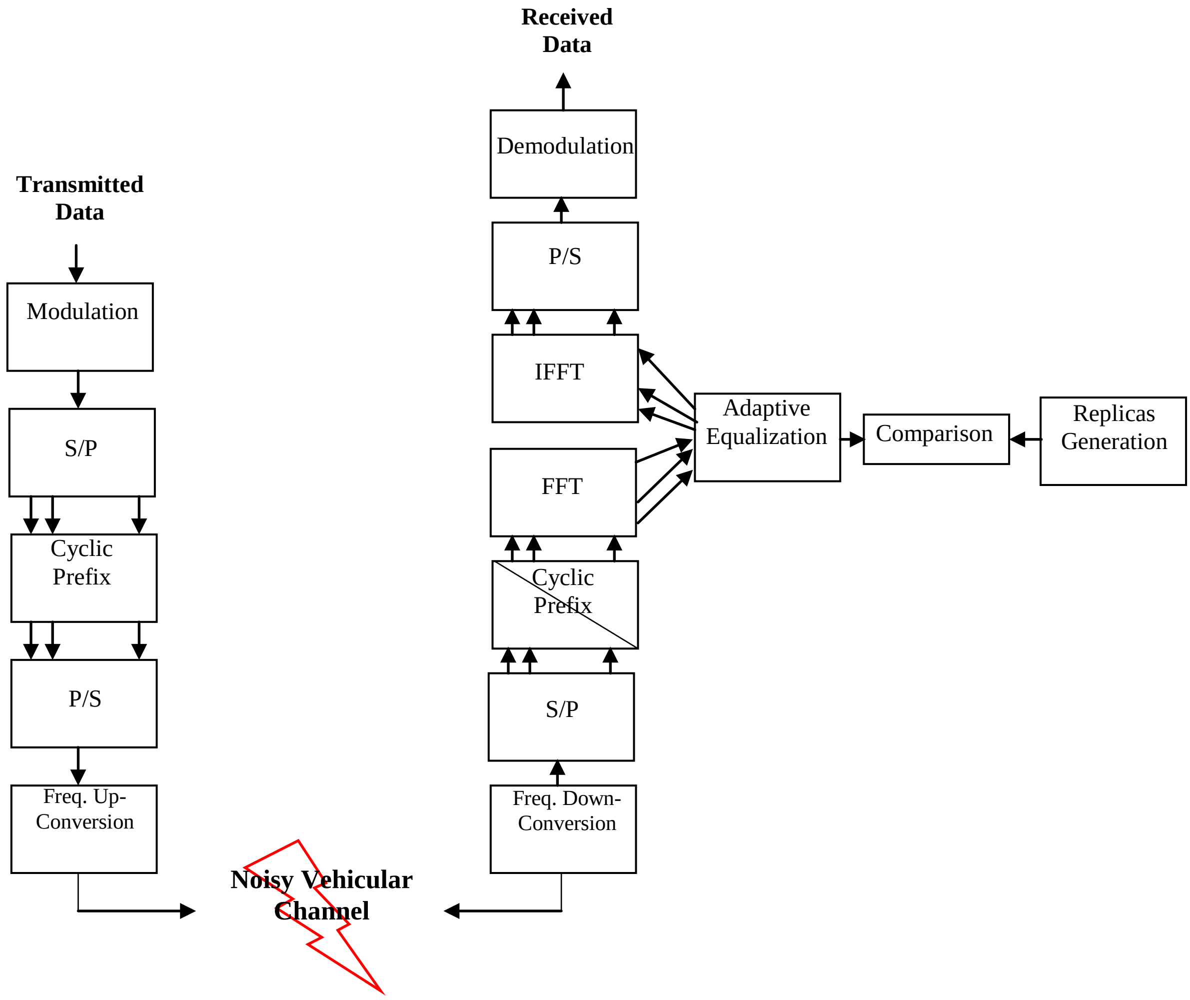


**Fig. 1**. The SC-FDE proposed model for uplink vehicle-to-roadside channel

The transmitted signal is distorted while propagating over the channel due to the expose to the Additive White Gaussian Noise (AWGN). At the receiver side, the received data blocks undergo the frequency down converter. The key idea behind this phase is to re-convert the real-valued signal at the frequency carrier to I/Q baseband symbols. Next, an analog-to-digital conversion is employed to produce a sequence of the noisy samples. These samples are re-grouped into blocks of equal length whereas each block contains the transmitted data block and the cyclic prefix. At this step, the cyclic prefix samples are ready for removal in order to recover the original signal. The received noisy data blocks of size $S$ are converted to the frequency domain using the Fast Fourier Transform (FFT).

In this model, two different adaptive equalizers are applied such as ZF/MMSE equalization in order to compare their impact on the BER. This step is necessary to remove the noise and recover the transmitted data as well as compensate channel distortion. Then, Inverse Fast Fourier Transform (IFFT) is applied to transform the signal back to the time domain. Finally, the received signal is passed through parallel-to-serial converter to be detected and feedback decision made based on the sample-by-sample concept.

### 3.2 Channel Modeling

As mentioned above, the primary target of this work is to deploy the SC-FDE to the uplink vehicular IEEE 802.11p channel in order to overcome the ISI and PAPR drawbacks of the OFDM systems. The quality of the event-triggered messages in vehicular networks depends mainly on the communication links among vehicular components, dynamicity, and propagation conditions. The reliability of the vehicular communications have a strong impact on the ITS applications and services provided [2].

The IEEE 802.11p standard [31] is a key technology that intends both communications vehicle-to-roadside and vehicle-to-vehicle which operates on the 5.9 GHz frequency band. In addition, this standard is a known framework for various packet-exchanges in vehicular environment. The proposed model allows the block transmission of the transmitted signal among various $V$ vehicular users and the roadside unit within their coverage area. Each user has a single antenna based on the single-input single-output (SISO) concept and it follows the transmission structure that is explained in [32].

*Transmitter Side*:

For generality purpose, this model considers a single vehicular user $v_n$ which needs to transmit binary information bits $b_n \in \{0,1\}$. These bits are mapped using $2^M$-ary (i.e., PSK or QAM) symbols. The single carrier symbols are divided into $B$ data blocks; each of length $B_L$. The length of each block defines the number of symbols transmitted over the vehicular channel. Thus, the transmitted data block for the $n^{th}$ vehicular user is defined as $x_n = \{x_{n,0}, x_{n,1}, \ldots, x_{n,B-1}\}$.

In this case, the expected value of the transmitted data block is given by:

$$E\{x_n, x_n^H\} = \sigma_x^2 I_M \tag{2}$$

Where $x_n^H$ is the conjugate transpose of $x_n$, $I_M$ is an identity matrix of size $M \times M$, and $\sigma_x^2$ is the mean transmit power allocated to the $n^{th}$ vehicular user.

The cyclic prefix $S_{cp}$ symbols are inserted at the beginning of each data block which is prefixing the end of $x_n$ in order to relief the inter-block interference. Later, the total baseband signal $s_n = x_n + S_{cp}$ undergoes frequency up-conversion procedure. This allows the I/Q symbols to be converted to real signal centered at the carrier frequency $f_c$. This is done by shifting the frequency of the transmitted signal as follow:

$$s_n(t)e^{j2\pi f_c t} \leftrightarrow S_n(f - f_c) \tag{3}$$

Where $j$ is the imaginary complex number $\sqrt{-1}$ and $s_n(t)$ is the transmitted symbol at time $t$ given that:

$$s_n(t) = s_{n_I}(t) + js_{n_Q}(t) \tag{4}$$

At this time, the resulted passband signal $S_n$ is ready for transmission over the IEEE 802.11p vehicular channel.

### 3.3 Single-Carrier Block Receiver

Since, we assume a multi-path channel with p paths; the channel impulse response $h_n$ can be expressed as:

$$h_n(t) = \sum_{i=0}^{p-1} h_i \delta(t - t_i) \quad (5)$$

where $h_i$ represents the complex path gain such that $E[\sum_{i=0}^{p-1} |h_i|^2] = 1$ and $t_i$ represents the time delay of the $i^{th}$ path. (i.e., $E[.]$ denotes the expectation operation).

At the receiver side, the passband data block is transmitted over the Rayleigh multipath fading vehicular channel. This signal is expressed in the time domain as in equation (6):

$$r_{n,i} = \sum_{i=0}^{B-1} h_{n,i} x_{n,i} + w \quad \text{for } r_n = [r_{n,0}, r_{n,1}, ..., r_{n,B-1}] \quad (6)$$

Where $h_n$ is the vehicular channel impulse response vector for the $n^{th}$ vehicular user with a circular criterion and is defined as $h_n = [h_{n,0}, h_{n,1}, ..., h_{n,B-1}]^T$ such that $[.]^T$ is the transpose. $w$ is the independent and identical distributed (i.i.d) additive white Gaussian noise (AWGN); though this noise should satisfy:

$$E\{w, w^H\} = \sigma_w^2 I_M \quad (7)$$

Where $w^H$ is the conjugate transpose of $w$ and $\sigma_w^2$ is the noise power for the received signal.

At this point, the $r_n$ of the $n^{th}$ vehicular user is transformed to the frequency domain using the N-point FFT using:

$$R_n = \sum_{i=0}^{B-1} r_{n,i} e^{-j2\pi k \frac{i}{B}} \quad \text{for } k = 0,1,..., B-1 \quad (8)$$

Where $R_n = [R_{n,0}, R_{n,1}, ..., R_{n,B-1}]$ represents the frequency domain received signal for the $n^{th}$ user without filtering. Here, the use of the advanced equalization techniques is irreplaceable.

## 4. IEEE 802.11p Channel Capacity

The IEEE 802.11p standard mainly is based on the OFDM scheme [31, 33-35], which was previously specified in the IEEE 802.11a [2]. The use of the OFDM associated with an appropriate adaptive modulation can enhance the channel capacity than using the one-tap single-carrier for signal transmission. Nevertheless, the transmission system is exposed to some drawbacks such as high PAPR and sensitivity to the frequency-selective channels, which requires additive techniques to control the signal transmission. Consequently, the system complexity is increased to avoid the degraded signal quality.

The same channel capacity can be obtained when employing the SC-FDE with a multi-tap channel that achieves better BER. In addition, the transmission system succeeds to mitigate the PAPR and the ISI problems. Improving the signal quality in vehicular networks is vital due to the emergence of the transferred messages. According to [27], the channel impulse response matrix $h$ is given as:

$$h = \begin{bmatrix} h_0 & & \cdots & & & h_{p-1} & \cdots & h_1 \\ h_1 & \ddots & & & & & \ddots & \vdots \\ \vdots & \ddots & h_0 & & & & & h_{p-1} \\ h_{p-1} & & h_1 & \ddots & & 0 & & \\ & \ddots & & \ddots & \ddots & & & \vdots \\ & & h_{p-1} & & \ddots & h_0 & & \vdots \\ & & & \ddots & & h_1 & \ddots & \\ 0 & & \cdots & & \ddots & & \ddots & h_0 \end{bmatrix} \tag{9}$$

At this point, the FFT is applied to the received data blocks $R_n$ so that h is transformed to the diagonal matrix $H$ in order to maintain the circulate feature of the channel impulse response:

$$H = \begin{bmatrix} H_0 & & \cdots & & 0 \\ & \ddots & & & \\ \vdots & & H_i & & \vdots \\ & & & \ddots & 0 \\ 0 & & \cdots & & H_{B-1} \end{bmatrix} \tag{10}$$

Given that $H = FhF^H$ for $F$ is the FFT transform. In addition, the vehicular channel capacity $V_c$ is defined as:

$$\begin{aligned} V_c &= B_w \sum_{i=0}^{B-1} \log_2(1+SNR) \\ &= B_w \sum_{i=0}^{B-1} \log_2(1+\frac{\sigma_x^2}{\sigma_w^2}|H_i|^2) \end{aligned} \tag{11}$$

Where $B_w$ is the channel bandwidth. This channel capacity is computed using the Shannon theorem in the presence of the noise.

## 5. SC-FDE Feedback Decision

### 5.1 Basics of ZF and MMSE

Generally, the equalizers are considered to be a filtering technique which provide an approximation of the channel impulse response. They are employed to reduce the intersymbol interference and tolerate the recovery of the transmitted signal [36]. Typically, the intersymbol interference is one of the major problems in signal processing which negatively affects the transmitted symbols and allow distortion by other transmitted symbols. The reason behind this phenomenon is the limited bandwidth and the multipath effect of the wireless channel. Hence, equalization techniques are frequently utilized to mitigate the impact of the multipath propagation and Doppler spreading of the channel. At the receiver side, the equalizer coefficients are adapted in order to match the output training sequence. This can be done by employing a pre-assigned time slot during the signal training is transmitted which is known in advance by the receiver.

The ZF equalizer is a linear equalizer that is used in wireless communications and was proposed by Robert Lucky [37]. It applies the inverse of the frequency response of the channel to the received signal. This equalizer forces the intersymbol interference to have zero values in a noise free case. Given the channel matrix explained in (10), the ZF equalizer $W_{ZF}$ is defined as:

$$W_{ZF} = (H^* H)^{-1} H^* \tag{12}$$

Another adaptive equalizer is the MMSE which is utilized to minimize the intersymbol interference and control the additive noise effects on the received signal. One of the primary advantages of the MMSE equalizer is that it minimizes the total power of the noise and the intersymbol interference elements in the output signal instead of eliminating them completely [38]. Basically, MMSE is an estimation method that minimizes the Mean-Square Error (MSE) of the fitted values of a vector of a dependent variable. The MMSE equalizer is applied to the channel response as follows:

$$W_{MSE} = (H^* H + \frac{1}{SNR} I)^{-1} H^* \tag{13}$$

For the perivous equation, it is noticable that the MMSE equalization algorithm is based on the SNR values which determine the behavior of the equalizer. For instance, if the SNR values are high, MMSE mimics the ZF equalization. Otherwise, the MMSE equalizer takes in consideration the noise and signal variance. Thus, this equalizer doesn't amplify the received signal just by applying the inverse of the channel. However, it takes into consideration the SNR in order to significantly reduce the noise which is vital when more null values appear in the frequency impulse response. Here, the input signal is multiplied by the reciprocal of this channel.

## 5.2 Iterative Feedback Process

The equalization process is employed to $R_n$ in an iterative feedback decision manner. First, the equalizer needs to generate the previous symbol information in the form of coded bits log-likelihood ratios (LLRs) [24,33] for the transmitted data bits. The key idea of using iterative feedback is to compare each consequent symbol using the result of the previous one as a priori-information. After the last iteration, decision can be made about the obtained information bits.

The probability of the previous symbol in the received signal $R_n$ is calculated as:

$$P(X_{ni} = R_{ni}) = \prod_{k=1}^{M-1} \frac{e^{(-mL'(C_{Mi+k}))}}{1 + e^{(-L'(C_{Mi+k}))}} \tag{14}$$

Such that $m = 0,1,...,M-1$ and $i = 0,1,...,B-1$. Where $M$ is the modulation index, $X_{ni}$ is the $i^{th}$ symbol in the frequency domain original transmitted data for the nth vehicular user, and $L'(C_{Mi+k})$ represents the updated coded bits for the transmitted symbol. The last parameter is obtained by:

$$L'(C_{Mi+k}) = \ln \frac{\sum_{k=0}^{M-1} e^{(-m|R_{ni} - X_{ni}|^2)}}{\sum_{k=1}^{M-1} e^{(-m|R_{ni} - X_{ni}|^2)}} \tag{15}$$

By considering the mean symbol power equal to 1, the expected variance of the received symbol for the n[th] vehicular user can be defined as:

$$E(\text{var}_n) = \sum_{R_{ni}\in R_n} \left| R_{ni} - (R_{ni} X_{ni}) \right|^2 .P \qquad (16)$$
$$= \sum_{R_{ni}\in R_n} \left| R_{ni} (1 - X_{ni}) \right|^2 .P$$

This summation is done over all the symbols of the received symbols $R_n$ for the $n^{th}$ vehicular user. As a consequence, the mean variance of the received symbol is calculated as follow:

$$\bar{v}_n = \frac{1}{BL_n} \sum_{i=0}^{BL_n} \text{var}_n \qquad (17)$$

In this case, the inner parameter of the equalizer is given by:

$$par = \frac{1}{BL_n} \sum_{i=0}^{BL_n} \frac{|H_{ni}|^2}{\sigma_w^2 + \bar{v}_n |H_{ni}|^2} \qquad (18)$$

Where $BL_n$ is the block length for the transmitted symbol of the $n^{th}$ vehicular user. Based on the $par$ value, the estimated symbols in the frequency domain using the channel impulse are calculated as in equation (17):

$$Y_{ni} = \left( \frac{1}{1 + (1 - \bar{v}_n) par} \right) \left( \frac{(H_{ni} R_{ni}) - (|H_{ni}|^2 X_{ni})}{\sigma_w^2 + \bar{v}_n |H_{ni}|^2} + R_{ni}\, par \right) \qquad (19)$$

The interleaved subcarriers are filtered and $Y_n = \{Y_{n,0}, Y_{n,1}, ..., Y_{n,B-1}\}$ represents the received signal in the frequency domain. These received data blocks re-transform to the time domain using the N-point Inverse Fast Fourier Transform (IFFT) (as illustrated in **Fig. 1**) and we denote them as $y_n$:

$$y_n = \sum_{i=0}^{N-1} Y_{n,i} e^{j 2\pi k \frac{i}{N}} \qquad \text{for } k = 0,1,..., N-1 \qquad (20)$$

For $y_n = [y_{n,0}, y_{n,1}, ..., y_{n,B-1}]^T$ .

In this model, the best data block with the MMSE estimation is selected and transformed to the detection step in order to be received at the roadside unit.

## 6. Simulation Results and Discussion

In this section, a comparison between the MMSE and the ZF equalizer in avoiding the ISI and achieve low PAPR based on feedback decision estimation is presented. Through the use of this estimation, the main goal is to reduce the error propagation effects over the uplink vehicular channel in a vehicle-to-roadside environment. This is necessary in order to ensure the efficient and correct arrival of the propagated messages. The conducted simulation performs signal simulation, Rayleigh multipath channel simulation and detection of the transmitted data blocks.

### 6.1 Setup and Signal Constellation

We assume a block transmission for the transmitted signal where different M-ary modulations are applied including $2^1$, $2^2$, $2^4$, and $2^6$ for BPSK, QPSK, 16-QAM and 64-QAM respectively. However, we consider only the QPSK and 16-QAM for simplicity issues and following the work done in [27].

According to [2], the key characteristics of the uplink vehicle-to-roadside channel are defined in which carrier frequency is 5.9 GHz, and the bandwidth of each channel is 10 MHz. The symbol time $T_s$ is defined as 4 µs in which the symbol rate $f_s = 1/T_s$. Furthermore, three different values are set for the maximum Doppler frequency shift $f_D$ equal 1, 40, and 200 in which the first mimics the static movements and the other two values represent the dynamic movements. Further, the path gain and path delay vectors are defined based on the outdoor regulations [39]. For the two taps simulation, the channel paths delayed for $\{0,4\}$ µs with average path gains of $\{0,-3\}$ dB respectively. On the other hand, the channel paths delayed for $\{0,4,8,12,16,20\}$ µs along with average path gain vector of $\{0,-3,-6,-9,-12,-15\}$ dB respectively, using 6 taps multipath vehicular channel.

The constellation diagrams of the transmitted data symbols before and after using the MMSE iterative equalizer are shown in **Fig. 2**. At the first iteration, the symbols are allocated near the center of the I/Q components. Nonetheless, the signal constellation points are uniformly distributed at the last iteration of the equalizer.

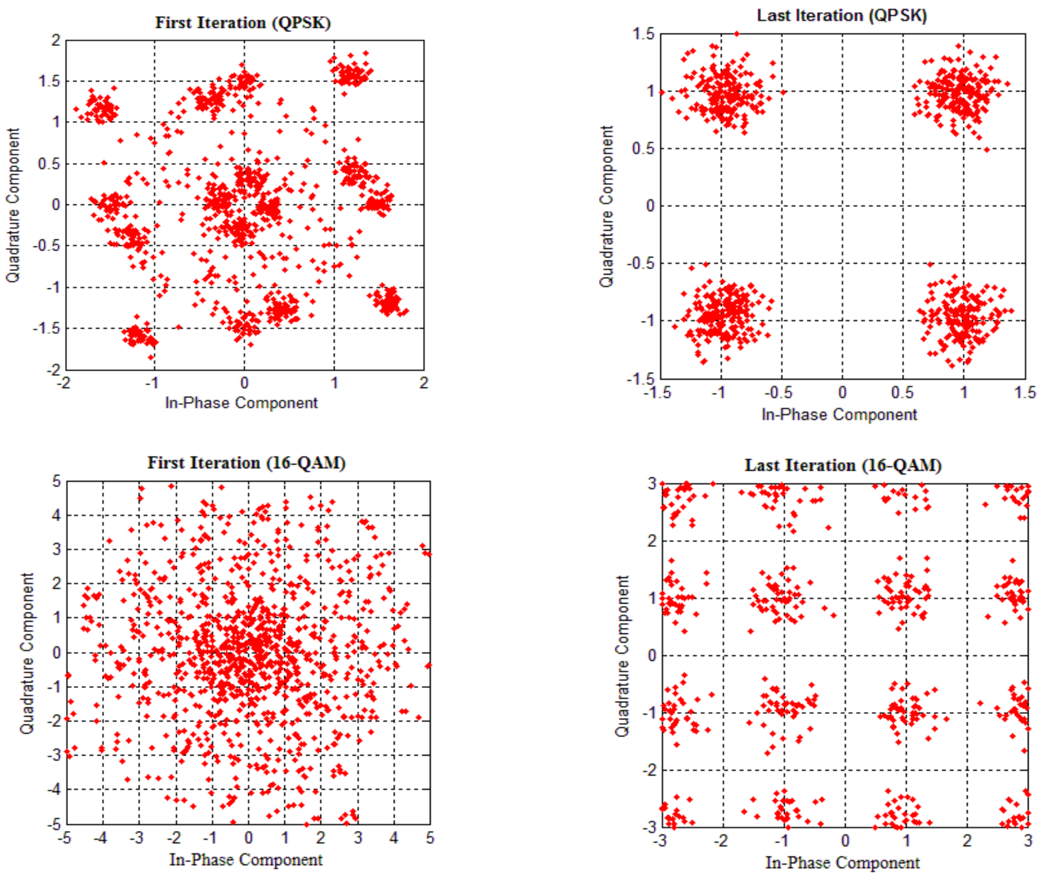


**Fig. 2**. Signal constellation points for the first and last iterations of using the MMSE equalizer under QPSK and 16-QAM modulations

## 6.2 BER Analysis

The BER estimation is done for the static and dynamic channel cases. The Rayleigh multipath frequency-selective fading channel is randomly initialized before the transmission of the generated symbols. The vehicular propagation channel is tested using 2 and 6 taps with different values for the path delay, path gain vectors, and the maximum Doppler shift. The transferred data are divided into 100 data frames.

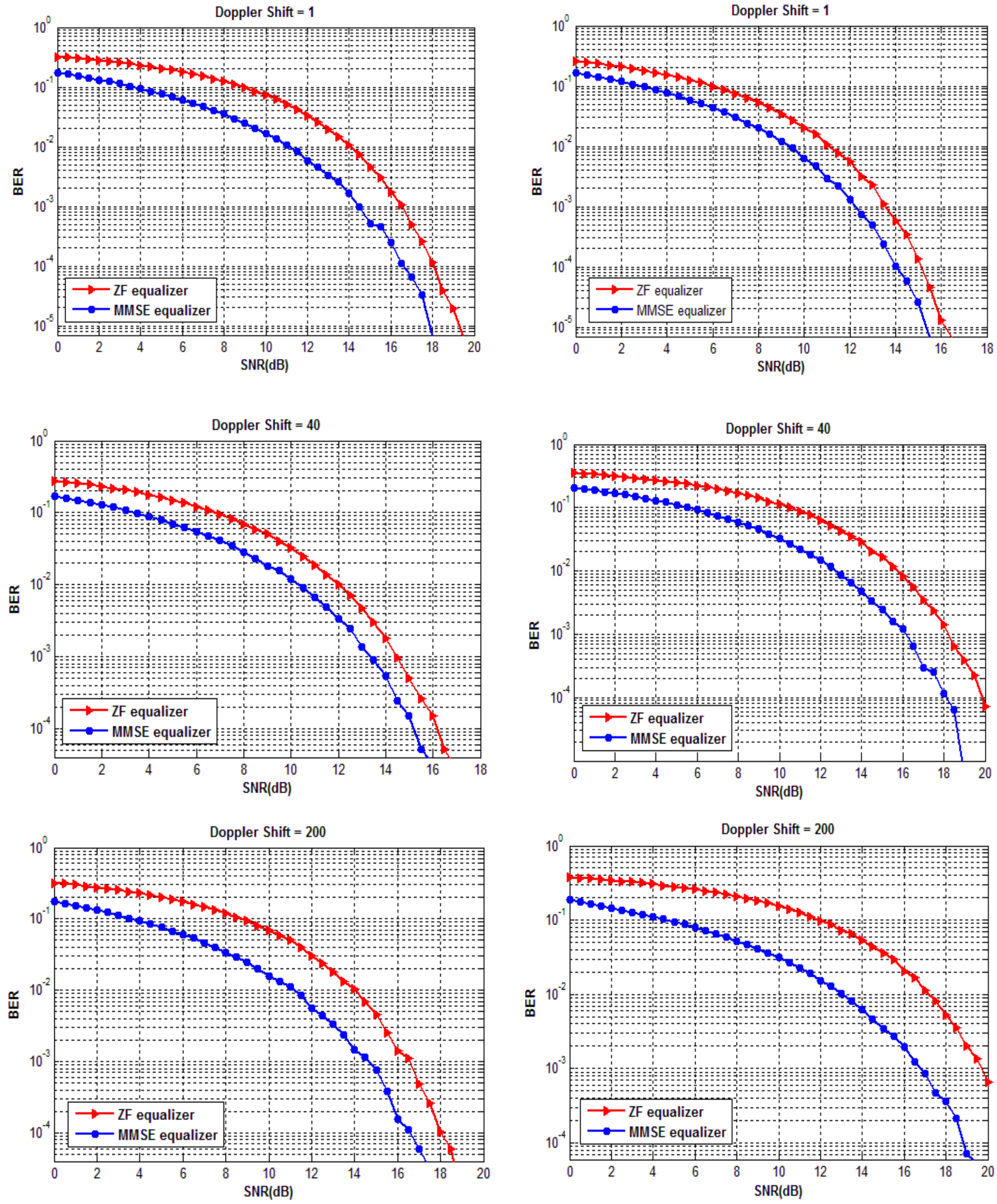


**Fig. 3**. QPSK modulation for 2 and 6 taps for different $f_D$. (a), (c), and (e) represents the 2 taps Rayleigh channel whereas (b), (d), and (f) represents the 6 taps channel.

The MATLAB is used to evaluate the performance of the proposed model. In this simulation, the results for the BER curves are obtained and compared to the SNR. These curves show the probability of the error bits undergoes different conditions including the modulations, maximum Doppler shifts, and number of channel taps.

According to the simulation results, the bit error probability when using the adaptive equalizer MMSE is reduced compared to the linear ZF equalizer. The propagation environment is tested using three distinct values for the maximum Doppler shift which are 1, 40, and 200. In Figure 3, the QPSK is applied to the multipath vehicular channel under two different numbers of taps (i.e., 2 and 6). We observe that the QPSK best fit the 2-tap and 6 tap vehicular channel when using $f_D = 40$ and $f_D = 1$, respectively.

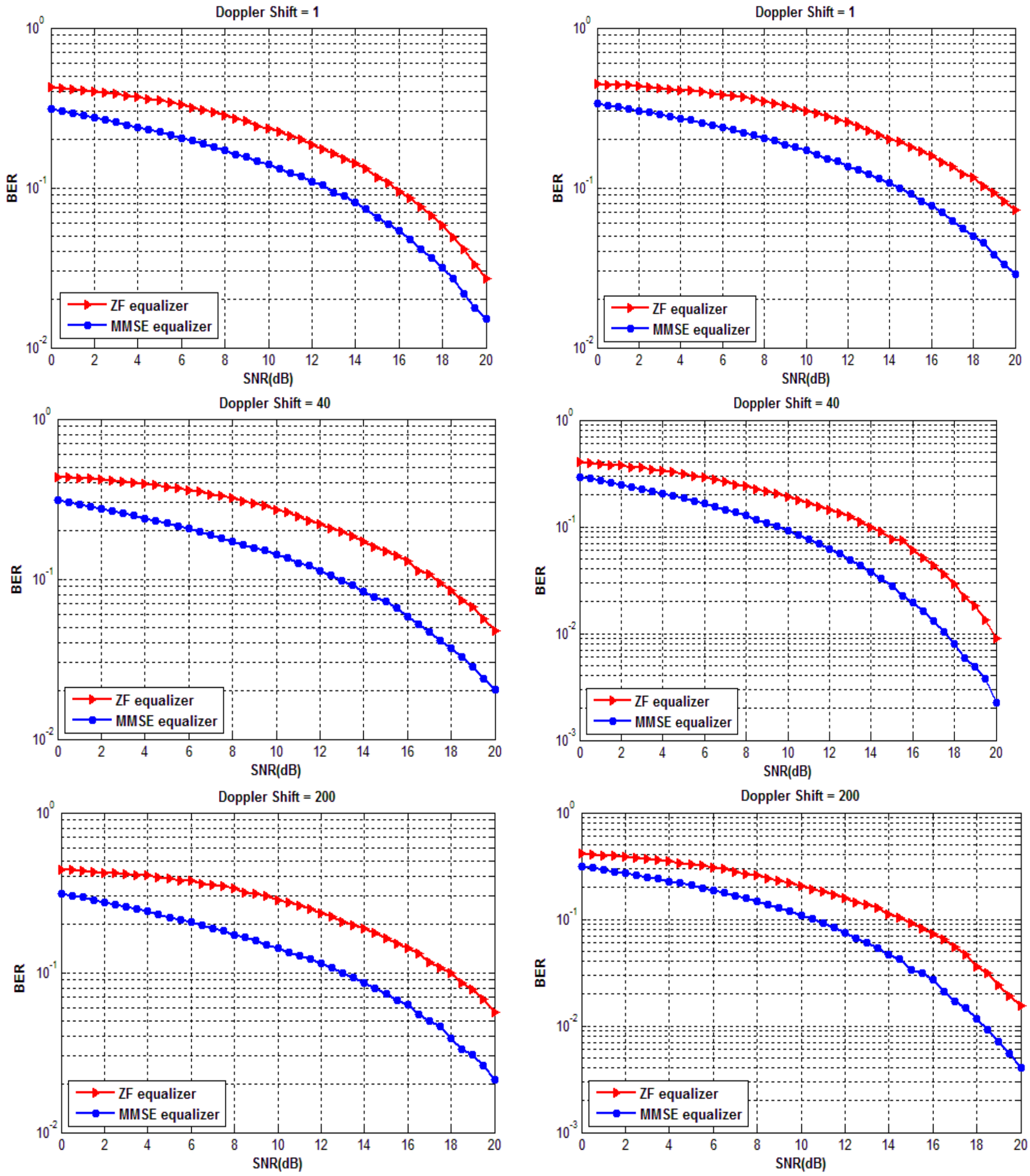


**Fig. 4**. BER performance for the MMSE and ZF equalizer using 16-QAM. (a), (c), and (e) are the 2-tap channel representation whereas (b),(d), and (f) are the 6-tap channel representation.

Similarly, **Fig. 4** shows the effect of the static and dynamic environment on the BER in relation to the SNR. Nevertheless, we discover that when the modulation index increase (i.e., 16 QAM), the values of the BER become larger compared to the values that previously achieved in Figures 3. Moreover, the BER has values of larger than 20 dB for the SNR for all the tested conditions including the number of taps and the maximum Doppler shift.

## 7. Conclusion

An attractive alternative to the conventional OFDM is the single-carrier technique based on the frequency domain equalization. The objective of this paper is to study the vehicular communication system using orthogonal single carriers. Similar to the OFDM, the FFT/IFFT transform is applied to the propagated signal with a modification in the places. The proposed model incorporate the digital receivers to convert the input data signal into the frequency domain. Then, the channel distortion can be identified in the frequency domain instead of the time domain.

The aim of this model is to implement the ZF and MMSE equalizers to the received signal and compare their performance in order to reduce the intersymbol interference and achieve low PAPR. The simulation results are applied to the multipath vehicular channel in a vehicle-to-roadside environment using two different values for the channel taps. Additionally, this model simulates the static and dynamic cases for the channel through allocating various maximum Doppler shift using QPSK, and 16-QAM modulations. Simulation results have shown that the MMSE equalizer outperforms the ZF equalizer.

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