Performance Analysis of OFDM Scheme with Channel Estimation and Doppler Shift Effects

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***Abstract*— Future wireless communication systems will require robust technologies such as orthogonal frequency division multiplexing (OFDM) with multi-input multi-output (MIMO) to overcome the challenges of data communication over frequency-selective fading channels. This paper presents a simplified single-in single-out (SISO) transmission scheme for OFDM systems using low complexity zero-forcing (ZF) detection algorithm. The paper studies and evaluates the impact of the Doppler frequency shift caused by the relative movement between the transmitting and receiving antennas on the OFDM-SISO system. Moreover, the paper investigates how the channel estimation using Pilot assessment and interpolation techniques impacts the performance of bit error rate (BER) and studies the mean square error (MSE) of the estimated channel on the OFDM system. Additionally, the effect of varying the pilots' interval on system performance has been studied. Also, this work provides a comparative study of two different interpolation techniques that can be used for the channel estimation; linear interpolation and interpolation based on fast Fourier transform (FFT). The main results show that the Doppler frequency shift significantly and not linearly affects the BER performance of the system, especially at higher frequencies. On the contrary, the channel estimation performance does not change since the MSE of the estimated channel almost remains the same for different Doppler frequencies. Furthermore, the findings show that changing the Pilots' interval will not significantly affect channel estimation since the MSE variation is small. However, data transmission rates will be strongly affected. Finally, the results reveal that the FFT-based interpolation technique outperforms the linear interpolation for estimating the wireless communication channel.**

***Index Terms*— OFDM, channel estimation, Doppler effect, signal detection, wireless communication.**

I. INTRODUCTION

THE Orthogonal frequency division multiplexing (OFDM) is a widely adopted transmission technique for the current state-of-the-art wireless communication standards such as IEEE 802.11 and 3GPP LTE families due to its ease of implementation and robustness against multipath fading [1]. In the OFDM transmission technique, the signal is divided into many narrow-band, low-rate, frequency non-selective sub-channels whereby multiple symbols are transmitted in parallel resulting in high-speed transmission rate, mobility, and network resource utilization [2]. Each sub-channel signal can also send information for different users, which results in a simple multiple access scheme known as orthogonal frequency division multiple access (OFDMA).

Recently, an adaptive peak cancellation method was used to reduce one problem with the OFDM system, which is the peak-to-average power ratio (PAPR). This reduction has been made while keeping in-band distortion power and the out-of-band power leakage below the pre-determined level [1].

The Doppler shift impairs the orthogonality of the OFDM sub-carriers waveform as a result of changes in frequency due to relative motion between the transmitting and receiving antennas [3]. In order to alleviate the impact of Doppler shift for bit error rate loss, several studies have been reported in the literature that devised estimation and compensation algorithms for minimizing the Doppler shift effect and improving error performance rate [4]-[8].

A. Literature Review

Tao et al. [4] presented a cross ambiguity function algorithm for fast estimation of time delay, Doppler shift, and Doppler rate due to higher ambiguity function and zoom-FFT. The algorithm achieves an accurate estimate of the time delay, Doppler shift, and Doppler rate of moving target at lower computational complexity.

A joint-estimation algorithm for Doppler shift and Doppler rate based on pilot symbols for low SNR has been discussed [5]. The algorithm achieves low complexity and estimation performance close to Cramer-Rao Lower Bound suitable for practical systems.

The problem of the Doppler frequency shift estimation algorithm for the OFDM-based transform domain communication system can be addressed by employing the Doppler shift estimation algorithm using cross-correlation to estimate the relative Doppler shift [6], [7]. The estimation algorithm is exploited for reducing the effect of the Doppler shift on the BER performance.

Recently, a time-domain block filtering technique has been applied to a pulse of Doppler-shifted linear frequency modulated (LFM) signals, and its improvement discussed in [8]. The side lobe filtering technique on stationary targets is extended to moving target using LFM waveforms [9]–[11].

A new approach to measure Doppler shift in indoor corridors by utilizing the CSI acquisition system using Wi-Fi has been introduced in the literature [7]. The FFT of CSI is not conjugate symmetric since the CSI data are guided by theoretical derivation in different corridor scenarios and obtained the Doppler shift of relative motions. This method is applicable to crowd counting and human activity recognition based on Wi-Fi.

In underwater communication, the acoustic channel is selective in time and frequency, and thus the signal is difficult to be detected. The Doppler shift needs to be estimated and compensated. A new method to estimate the Doppler shift, detect and synchronize the signal in a single-input multiple-output (SIMO) has been presented as an extension to the single-input single-output (SISO) model [12].

Furthermore, OFDM index modulation (OFDM-IM) has been proposed in recent literature as a multi-carrier transmission scheme that modulates symbol bits onto sub-carriers as well as active sub-carrier indices by constellation mapping [13]. The study analyzed the error performance scenario for the proposed system and derived analytical expressions for error performance gain based on maximum likelihood (ML) detection.

B. Motivation and contributions

In OFDM systems, the frequency and time resources are split into a uniform sub-carriers with stringent frequency and time alignment needed to achieve orthogonality. Despite its advantages for a range of industrial applications, OFDM suffers from drawbacks such as high side lobes in frequency and detection complexity.

To mitigate the impact of detection complexity, this study considers the ZF technique that exhibits a low complexity detection in SISO compared to the optimum maximum-likelihood (ML) detection scheme. The low complexity detection technique makes the proposed OFDM algorithm a highly attractive scheme for high data rate wireless communications over time-varying frequency-selective radio channels.

The OFDM system can be applied to various applications such as satellite communications and fiber optics. Hence, this performance study will add a valuable understanding of how this system will perform with different applications. The main contributions of this paper are:

- Study and evaluate the impact of Doppler frequency shift caused by the relative movement between the Tx and Rx on the ODFM-SISO system;
- Investigate how the channel estimation using Pilots assessment and interpolation techniques will affect the BER and MSE of the OFDM system;
- Discuss what will happen to the system performance when we change the Pilots' intervals;
- Finally, provide a comparative study of two different interpolation techniques can be used for the channel estimation.

II. SYSTEM MODEL

Fig. (1) depicts a block diagram representing the process via which data from the Tx to the Rx goes through in this work that employs OFDM over the multipath wireless channel.

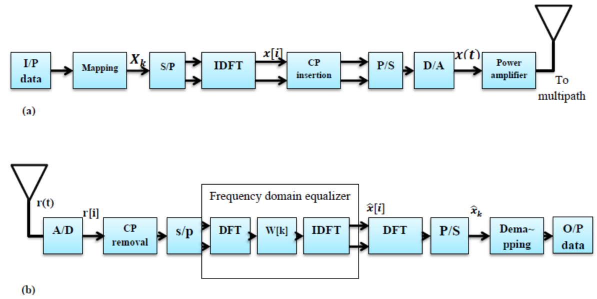

Fig. 1. The Tx and Rx of the wireless OFDM system.

OFDM is a transmission technique that improves the spectral efficiency and combats the effects of multipath conditions. The orthogonality allows simultaneous transmissions on multiple sub-carriers in a limited frequency space without interference from one another. This is a significant advantage of the OFDM, and with this technique, we can improve the bandwidth use. Modulation of all sub-carriers is done separately. Then the modulated sub-carriers go through an IFFT to generate the OFDM signal. The IFFT converts the signal from the frequency domain to the time domain by successively multiplying it by a range of sinusoids. When this is completed, the system adds a cyclic prefix. The cyclic prefix is a repetition of the last data symbols in a block. The purpose of the cyclic prefix is to mitigate the ISI and fading effects. The cyclic prefix is discarded at the receiver because it is the only purpose is to mitigate the referred last two effects.

In this section, the signal model consists of a SISO scheme represented by the following equation

$$y = xh + n, \quad (1)$$

where y is a matrix that represents the received signal, x is a matrix of the transmitted data samples, h is the wireless channel frequency response, and n is the white Gaussian noise in the frequency domain.

A. Signal Detection

The detection of the signal is based on the Zero-Forcing (ZF) technique. ZF is a simple and effective approach for retrieving multiple transmitted data streams at the receiver, and it is based on neglecting the channel's noise effect to detect the transmitted signal from the channel. From (1), by applying the ZF technique, we have the following equation

$$\hat{x} = \frac{y}{h}, \quad (2)$$

where $\hat{x}$ is the matrix of the detected signal. Note that at a low noise level, the detected signal is close to the transmitted signal.

B. Channel Estimation

In order to recover the transmitted information correctly, the effect of the channel on the transmitted information must be estimated. There are many techniques utilized for channel estimation. This study focuses on estimating the channel frequency response h, as h_p using different pilots assisted channel estimation schemes. Suppose a data stream x is to be transmitted, after assisting pilots with known values at known locations, this signal x_p will be transmitted and then exposed to the noise in the transmission channel. y_p is the received noisy copy from x_p. Then, y_p can be expressed as

$$y_p = x_p h_p + n_p. \quad (3)$$

By applying ZF detection to obtain the channel transfer function at the location of the assisted pilots, the estimated channel at the locations of the pilots can be written as

$$h_p = \frac{y_p}{x_p}. \quad (4)$$

The response of the channel at the data sub-carriers is subsequently determined by interpolation. The interpolators used for the estimation are linear, second-order, cubic, FFT-based, or time-domain interpolators derived from both the statistical and deterministic point of view. Two interpolation techniques have been used in this work; a linear interpolation and an interpolation based on fast Fourier transform (FFT-based interpolation).

III. RESULTS AND DISCUSSIONS

This section discusses the error performance analysis of the OFDM system. Monte Carlo simulation has been conducted using MATLAB 2018 version A. The parameters used are presented in Table (I). Three practical channel models are investigated and bench-marked against perfect and estimated channels. In this work, a perfect channel model is a channel model with a known impulse response, which is based on the Rayleigh fading channel model. On the other hand, the estimated channel model is based on pilot training and interpolation techniques. The pilot symbols have varied at different pilot intervals (i.e., T_s = 5, 10, 20, and 30 μs) in the OFDM block.

Figures (2) to (5) depict the impact of varying the Doppler frequency on the BER for multipath fading channel models, namely Extended Pedestrian A (EPA), Extended Vehicular A (EVA), and Extended Typical Urban (ETU) in comparison with One Path channel model at different signal-to-noise ratio (SNR) values. Generally, the figures show that the BER for an ideal channel is lowest as compared to EPA, EVA, and ETU as expected. Comparatively, at 14 dB, the distinctions are tabulated below in Table (II). It is evident from the Table that at $f_d = 300\,Hz$, one-path channel outperforms all the investigated channel models in this work. Additionally, at $f_d = 50\,Hz$, the BER for $EPA = 3 \times 10^{-3}$, $EVA = 10^{-2}$, and for $ETU = 2 \times 10^{-2}$. As expected of the three models, the EPA channel model has the best BER performance against the Doppler frequency shift. This is because the EPA channel model has less dominant multipath components that are more coherent to the line-of-sight signal in terms of delay and power. Furthermore, the ETU channel model has the worst performance below and beyond 14 dB. It can be noted that the Doppler frequency impacts the BER of various channels differently in multipath fading channels in communication systems. This issue is critical in the radio planning and optimization of current and future mobile networks.

TABLE I. PARAMETERS USED IN OFDM SYSTEM SIMULATION

Parameter	Value
Number of sub-carriers	1024
Cyclic prefix length	64
Fast Fourier transform size	1024
Signal to noise ratio in dB	0-20
Number of generated bits	16384000
Input sample period	1 μs

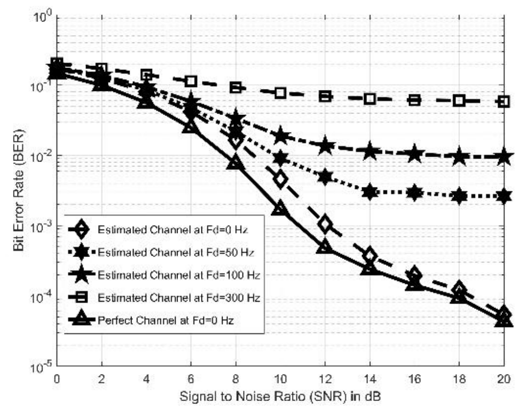

Fig. 2. Impact of varying the Doppler frequency on BER for EPA channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

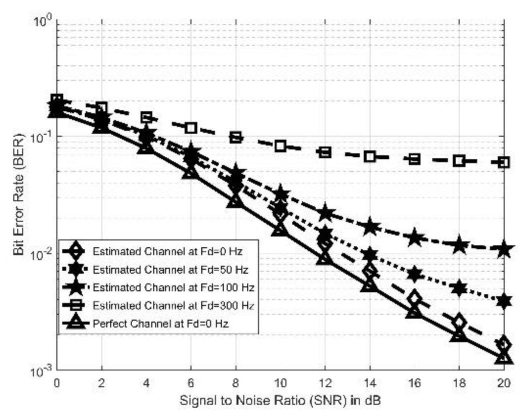

Fig. 3. Impact of varying the Doppler frequency on BER for EVA channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

Figures (6) to (9) present the impact of varying the Doppler frequency on the MSE between the perfect and estimated multipath fading channels used in this work plotted as a function of the SNR. To evaluate the performance metrics of the BER and MSE, we investigate the exact parameters of interest used in Table (II). Generally, the figures show that the MSE is approximately the same for all the channel models used. However, as the Doppler frequency increase, the MSE values rapidly increases. Comparatively, at 14 dB, the distinctions are tabulated below in Table (III). Additionally, at $f_d = 50\,Hz$, the MSE for $EPA = 3 \times 10^{-5}$, $EVA = 3 \times$

10^{-5}, and for $ETU = 4 \times 10^{-5}$As expected of the three models, ETU is the worst channel model. In the main, varying the Doppler frequency on the multipath fading channel that employs OFDM impacts the MSE of various channels differently. Comparatively, BER is a better performance metric as compared to MSE when determining the channel dynamics as a function of SNR considering the Doppler phenomenon. However, MSE between the estimated and the perfect channels gives us an insight into how the channel estimation is affected by varying channel (or channel estimation) parameters such as Doppler frequency, Pilots' Interval, or Interpolation techniques employed for channel estimation.

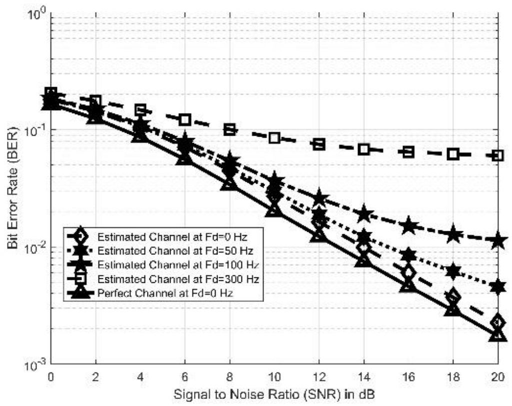

Fig. 4. Impact of varying the Doppler frequency on BER for ETU channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

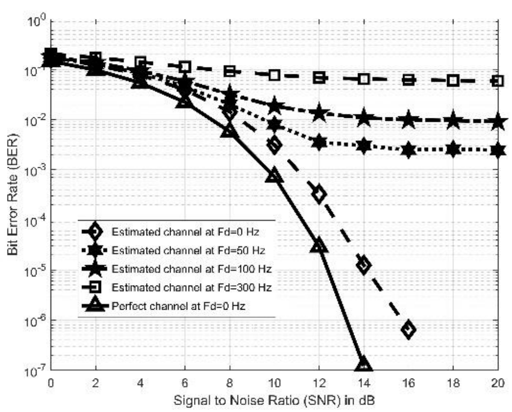

Fig. 5. Impact of varying the Doppler frequency on BER for one-path channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

Figures (10) and (11) present the performance analysis of fixing the Doppler frequency on BER & MSE for EPA, EVA, ETU, and one-path channel delay profiles at different Doppler frequencies, i.e., $f_d = 0$, 50, 100, and 300 Hz. Generally, there is no variability in the MSE in all channel models investigated such that at all, the SNR values the MSE for EPA, EVA, ETU, and one-path models are approximately the same. At the same time, the MSE reduces as the SNR value increases, reflecting what is expected. However, the BER shows variability from SNR = 2 to 20 dB, as depicted in Fig. (10). Noticeably, EPA and one-path channels show similar performance analysis trends and distinct from that of EVA and ETU models, which also display their similar performance analysis trends. When all models are compared at the same Doppler frequency of 50 Hz as highlighted in GREEN in Table. (IV) . Furthermore, when the models are evaluated at 14 dB SNR for $f_d = 0$, 100, and 300 Hz, BER is a better metric as compared to MSE because the MSE does not vary much to impact channel estimation as compared to that of BER.

TABLE III. BER FOR EPA, EVA, ETU, AND ONE PATH AT 14 DB

Doppler Frequency (Hz)	**BER**			
	One Path	**EPA**	**EVA**	**ETU**
0 (Perfect)	10^{-7}	2×10^{-4}	5×10^{-3}	7×10^{-3}
0 (Estimated)	10^{-5}	4×10^{-4}	7×10^{-3}	9×10^{-3}
50	4×10^{-3}	3×10^{-3}	10^{-2}	2×10^{-2}
100	10^{-2}	10^{-2}	3×10^{-2}	4×10^{-2}
300	7×10^{-2}	6×10^{-2}	9×10^{-2}	8×10^{-2}

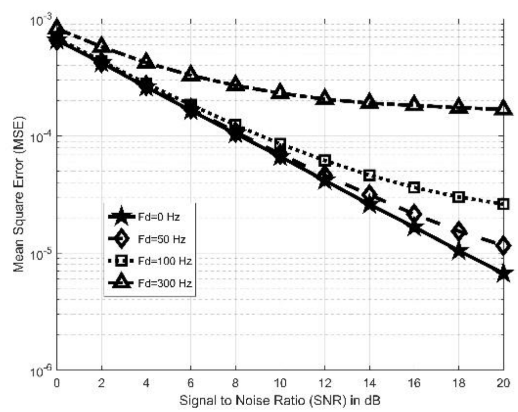

Fig. 6. Impact of varying the Doppler frequency on MSE for EPA channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

TABLE III MSE FOR EPA, EVA, ETU, AND ONE PATH AT 14 DB.

Doppler Frequency (Hz)	**MSE**			
	One Path	**EPA**	**EVA**	**ETU**
0	2×10^{-5}	2×10^{-5}	3×10^{-5}	3×10^{-5}
50	3×10^{-5}	3×10^{-5}	4×10^{-5}	5×10^{-5}
100	5×10^{-5}	5×10^{-5}	6×10^{-5}	6×10^{-5}
300	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}

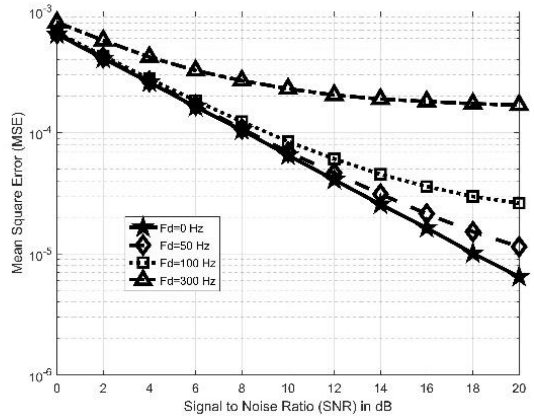

Fig. 7. Impact of varying the Doppler frequency on MSE for EVA channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

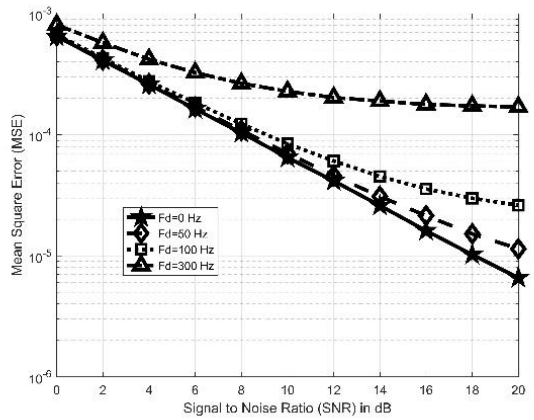

Fig. 8. Impact of varying the Doppler frequency on MSE for ETU channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

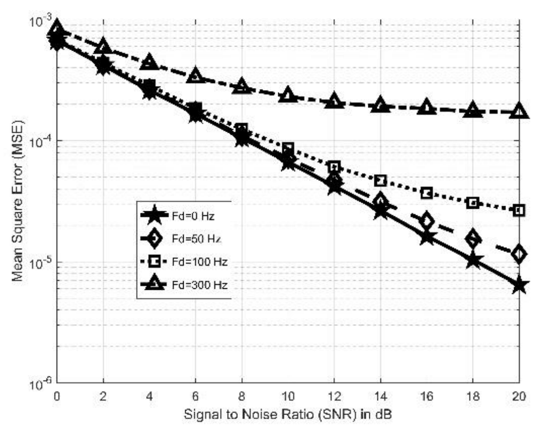

Fig. 9. Impact of varying the Doppler frequency on BER for one-path channel model at $f_d = 0, 50, 100,$ and $300\ Hz$.

Figures (12) and (13) depict the performance analysis of varying pilots on BER and MSE for channel estimation. The results show that varying pilots' interval does not alter the MSE for the estimated channel at any given SNR value. However, the MSE reduces as the SNR values increase. On the other hand, even though the BER plot clearly shows a distinction between the perfect and estimated channels at nearly all SNR values, varying the pilots does significantly affect the performance of the estimated channel but has a significant impact on the data rates of the system.

Figures (14) and (15) show the impact of using FFT and Linear interpolation on channel estimation performance for BER and MSE as a function of SNR in Fig. (14) and (15), respectively. It is evident that overall the FFT based interpolation outperforms the linear one as expected. The difference is conspicuous in MSE where for instance, at SNR value of 14 dB, there is a difference of about 2×10^{-5} MSE between FFT and Linear based interpolation. Whereas for BER, the discrepancy between FFT and Linear based interpolation is about 4×10^{-3}. From the results presented in this work, it can be seen that the optimum performance in terms of higher data rates and better BER performance of the OFDM-SISO system is having a Pilot interval of 30 and FFT-based interpolation for the channel estimation. Additionally, results show that it is better for the system to work with SNR value starts from 14 dB.

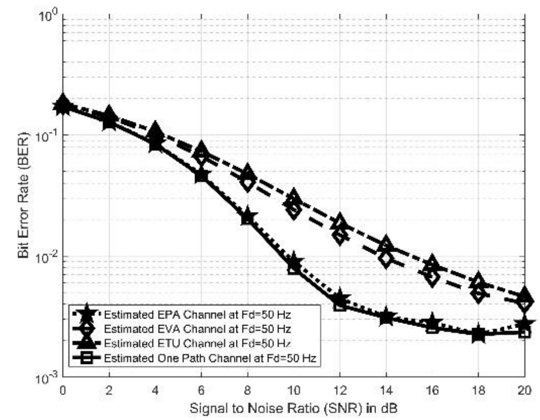

Fig. 10. Impact of Fixing the Doppler Frequency on BER for Multipath Fading Channel Delay Profiles at $f_d = 50\ Hz$.

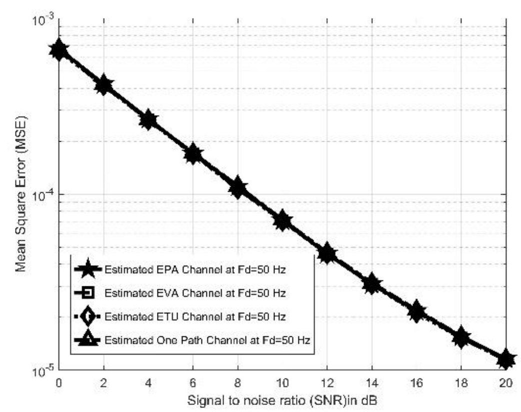

Fig. 11. Impact of Fixing the Doppler Frequency on MSE for Multipath Fading Channel Delay Profiles at $f_d = 50\ Hz$.

IV. CONCLUSIONS

In this paper, an OFDM for SISO wireless channel has been investigated. OFDM was employed due to its ability to mitigate the inter-symbol interference caused by channel frequency selectivity. Its use of simple frequency domain equalizers at the receiver for efficient detection, which is more realistic. Coherent detection of transmitted signals in wireless communication systems necessitates the need for accurate estimation of channel state information at the receiver. The results show that the channel estimation performance does not have a notable effect because of the Doppler frequency shift, while the BER is significantly affected. Also, in estimating the wireless channel using Pilots assessment and interpolation technique, the optimum performance can be achieved using relatively large Pilots' intervals and FFT-based interpolation approach. This work will be extended to cover the massive MIMO-OFDM wireless system and improve the system performance by turbo coding and Kalman filtering.

TABLE IV. BER AND MSE FOR EPA, EVA, ETU, AND ONE PATH AT 14 DB

Doppler Frequency (Hz)	One Path		EPA		EVA		ETU	
	BER	MSE	BER	MSE	BER	MSE	BER	MSE
0 (Perfect)	10^{-7}	2×10^{-5}	2×10^{-4}	2×10^{-5}	5×10^{-3}	3×10^{-5}	7×10^{-3}	3×10^{-5}
0 (Estimated)	10^{-5}		4×10^{-4}		7×10^{-3}		9×10^{-3}	
50	4×10^{-3}	3×10^{-5}	3×10^{-3}	3×10^{-5}	10^{-2}	4×10^{-5}	2×10^{-2}	5×10^{-5}
100	10^{-2}	5×10^{-5}	10^{-2}	5×10^{-5}	3×10^{-2}	6×10^{-5}	4×10^{-2}	6×10^{-5}
300	7×10^{-2}	2×10^{-4}	6×10^{-2}	2×10^{-4}	9×10^{-2}	2×10^{-4}	8×10^{-2}	2×10^{-4}

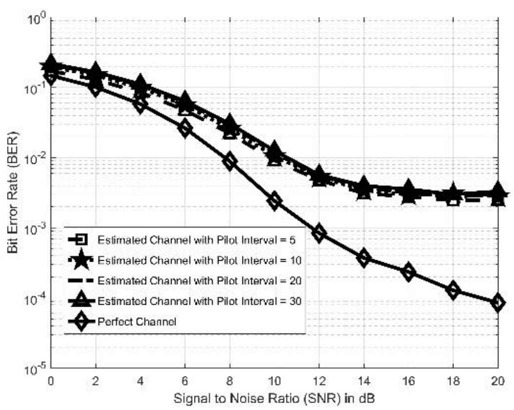

Fig. 12. Impact of Varying Pilots' interval of the channel estimation on the BER performance at $f_d = 50\ Hz$.

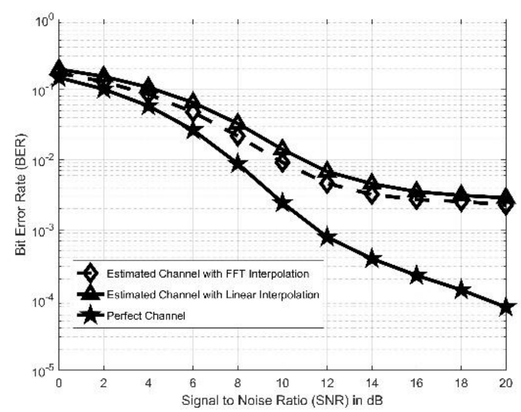

Fig. 14. Impact of varying interpolation techniques of the channel estimation on the BER performance at $f_d = 50\ Hz$.

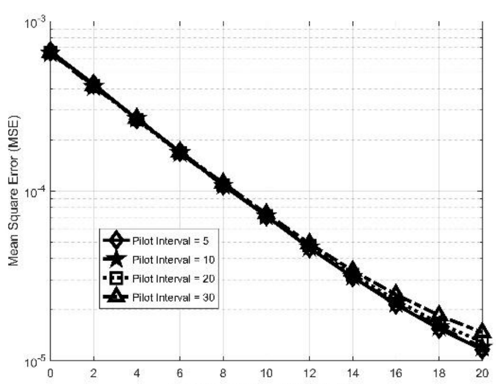

Fig. 13. Impact of Varying Pilots' interval of the channel estimation on the MSE performance at $f_d = 50\ Hz$.

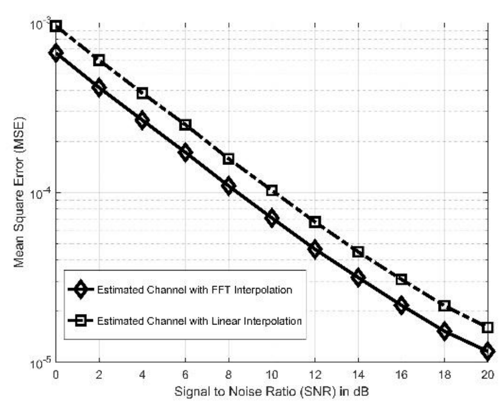

Fig. 15. Impact of varying interpolation techniques of the channel estimation on the BER performance at $f_d = 50\ Hz$.

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