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Compressive sensing-based channel estimation for high mobile systems with delay Doppler effects

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ABSTRACT

In this paper, channel overhead is reduced by exploiting channel sparsity for multiple input multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) system. Where, compressive sensing (CS) based dictionary design algorithms has been adopted as a channel estimation technique in high mobile systems with minimal number of pilots, such as high-speed train (HST) systems. A novel framework design of the dictionary-based CS was proposed considering both delay and Doppler effects in order to correctly recover the channel response. The channel under consideration is a 2 by 2 space-time block code (STBC) MIMO channel. Simulation tests according to the international telecommunication union (ITU) channel model demonstrated the suitability of the proposed dictionary for estimating the channel impulse response (CIR) of a liner time varying (LTV) channel with a mobility approaches 675 Km/h related to a Doppler frequency of 1500 Hz and 2.4 GHz carrier frequency. Two CS recovery algorithms were applied; orthogonal matching pursuit (OMP) and basis pursuit (BP), where by about 7 dB gain in signal to noise ratio (SNR) was achieved with mobility of 675 Km/h using OMP as compared to BP at a bit error rate (BER) of 10^{-3} with 128 OFDM subcarriers.

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1. INTRODUCTION

In wireless communications, there is an increased demand for high data rate transmissions with effective spectrum utilization [1], [2]. Multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM) has been considered in communication systems to fulfil these requirements [3], [4]. At the other hand, the accurate estimation of channel impulse response (CIR) is crucial in order to remove the effect of the channel at the receiver end. However, there are many estimation algorithms applied to estimate liner time varying (LTV) channel response. They are almost fail to track the channels with high Doppler environments such as high-speed train (HST) systems [5].

After the first introduction of compressive sensing (CS) in 2006 [6], it found its way into wireless communication channel estimation purpose known as compressive estimation [7]–[11]. However, CIR of the wireless channel is determined by a small number of strong paths, therefore, the wireless channel is sparse in nature. At the other hand, the working principle of CS is to recover a sparse signal with limited number of measurements; hence, compressive sensing can be used to recover the required CIR [12], [13]. Since the idea behind spares wireless channels and signal sparsity appears, many publications in the field of compressive sensing and signal processing community were introduced. A doubly selective channel estimation technique using CS was introduced in [14], [15]. The proposed methodology exploits the most effecting parameters; delay and Doppler, where the pilot's number used for estimation is reduced by about half of the total number of pilots required for least square (LS) method.

An advanced compressive estimation method was introduced in [16] for doubly dispersive channel estimation within a multicarrier OFDM system, where simulations using geometry based channel simulators outperforms the classical CS methods in terms of complexity. A recursive tracking of doubly selective channel based sequential delay-Doppler sparsity was exploited by [17] to improve estimation performance. The technique suggests the use of a modified version of orthogonal matching pursuit (OMP), where it demonstrates a substantial performance gain over conventional CS estimation in terms of computational complexity.

Ren *et al.* [18], CS approach was adopted for channel estimation in high mobility OFDM systems, where it used to utilize the inherent channel sparsity of the time-selectivity channel caused by high mobility in order to recover the CIR. A pilot pattern design within the OFDM symbol was considered with 120 pilots out of 512 subcarriers at a speed of 600 Km/h with a carrier frequency of 2.5 GHz. In [19], a single input multiple output single input multiple output orthogonal frequency division multiplexing (SIMO-OFDM) typical HST system was investigated to eliminate the inter carrier interference (ICI) of time variant channels, where CS is adopted with position based interference detection to recover the CIR by designing a pilot pattern. Out of 512 subcarriers, 40 pilots are used to recover the CIR correctly with 500 Km/h vehicle speed and carrier frequency of 2.35 GHz.

Both time domain preambles and frequency domain pilots are adopted in [20] to recover the selective channel response. First, the training in time domain is exploited. Seconed, pilot locations are optimized using genetic algorithm, where it employed to build the structured CS and estimating the channel at 240 Km/h with different number of transmit antennas.

A performance analysis of OMP based CS for channel estimation in mobile OFDM systems was proposed in [21]. The tests shows that the bit error rate (BER) performance degraded as the mobility increased. By using 90 pilots out of 512 subcarriers over a small-scale fading channel, the maximum speed provided was 140 Km/h at a BER performance of 7.8×10^{-4} and signal to noise power ratio (SNR) of 20 dB, where both assumed bandwidth and carrier frequency are 2.8 MHz and 5.8 MHz respectively.

A performance comparison of LS, basis pursuit (BP) and OMP based channel estimation was introduced by [22]. The tests consider a single input single output orthogonal frequency division multiplexing (SISO-OFDM) system with 128 OFDM subcarriers transmitted over a 3 tap Rayleigh channel. The tests do not consider a Doppler shift. With 25 pilots out of 128 subcarriers, the BER performance of BP algorithm outperforms both OMP and LS algorithms, where, the BER performance of LS, OMP, and BP are 0.0435, 0.0130, and 0.0022 at 30 dB respectively.

Abboud and Sabbar [23], a BER performance comparision of LS and BP algorithms was introduced with a dictionary design based channel delay variation for CS estimation. The tests show that the designed dictionary-based CS is suitable to recover the channel information with low to moderate Doppler effects. The main contributions of this paper are:

- A novel CS dictionary is designed based LTV channels' delay and Doppler effects analysis to estimate its coefficients.
- The suggested dictionary desgin is adopted to recover the CIR with different conditions of subcarrier length or Doppler shifts, which approves its applicability to estimate the CIR for high mobility systems. Where, the CIR is estimated with a mobility exceeds 675 Km/h at a BER approaching 10^{-4}.
- The spectral efficiency is improved by about 25%, while the estimation performance is improved by either increasing the Doppler shift and/or the OFDM subcarriers with a fixed ratio of pilot number.
- By adopting the designed dictionary-based CS, the BER performance of BP and OMP is improved, where the required SNR to obtain an acceptable error rate is reduced.

The rest of this paper is organized as: the proposed system model with required LTV channel analysis is presented in section 2 with CS methodology of the proposed dictionary. In section 3, simulation tests and assessment of results are proposed. Finally, in section 4, the final concluding remarks with suggestions of future work are proposed.

2. SYSTEM MODEL AND CS BASED LTV CHANNEL ESTIMATION METHODOLOGY

The MIMO-OFDM system of Figure 1 is considered with a stream of bits $X[k]$, (data $d[k]$ and pilots $p[k]$) are mapped using binary phase shift keying (BPSK) mapper and space-time block code (STBC) encoded using 2 by 2 Alamouti STBC encoder. To simplify analysis, the system is modeled as a 2 by 2 MIMO channel. Where, the transmitter has N_t parallel transmission paths. For each path, the frequency domain STBC encoded OFDM block $X[k]$of N subcarriers is transformed into a time domain block $x[n]$ by applying inverse fast fourier transform (IFFT) process, which followed by cyclic prefix (CP) insertion of length L_{cp} in order to prevent adjacent interference.

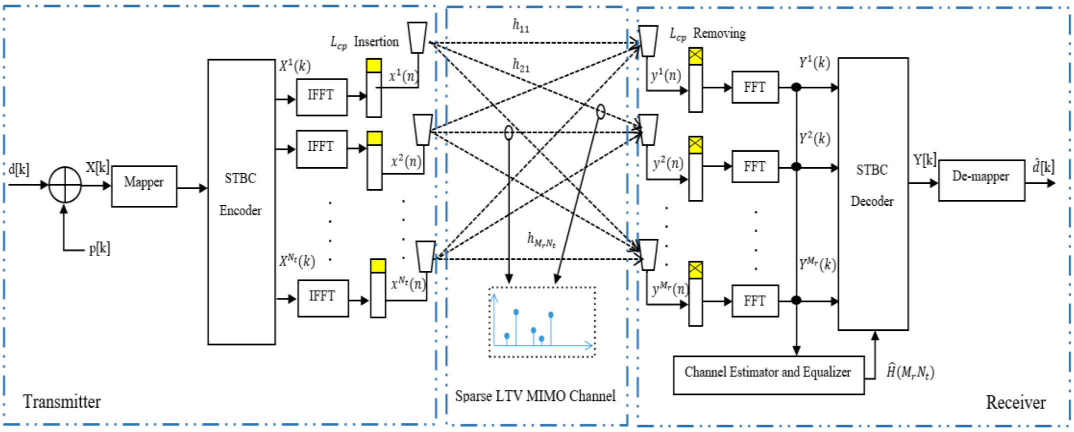


Figure 1. MIMO-OFDM system model

After cp insertion, the resultant OFDM blocks will be transmitted through multiple antenna system a cross a LTV MIMO channel which is modeled by both L paths of delay and Doppler effects τ_i and f_d respectively with attenuation a_i.

$$h(t) = \sum_{i=0}^{L-1} a_i \, e^{-j2\pi f_c \tau_i} \, e^{j2\pi f_d t} \tag{1}$$

At the receiver side, the tow effecting parameters (τ_i and f_d) of the LTV channel of (1) should be taken into consideration in order to recover time variant coefficients of the LTV channel. By applying CS technique to estimate the CIR using the classical linear measurement model $y = \phi x = \phi\psi\theta$, where; y is a measurement vector of size $N \times 1$, ψ is of size $M \times M$, and θ represents k-sparse vector of $M \times 1$ to be predicted using the functional measurement matrix $\phi\psi$. The sensing matrix ϕ is of size $N \times M$ should be designed carfuly. therefore, each noting of y vector represents the tumbling of vector x on a sensing matrix ϕ row [24].

In order to estimate the channel vector $h_{Mr,Nt} \in C^{N\times 1}$ from y_{Mr} received measurements, a CS problem should be formulated, where y_{Mr} is expressed.

$$y_{Mr} = A h_{Mr,Nt} + w_{Mr,Nt} \tag{2}$$

Where: $w_{Mr,Nt}$ is the additive white gaussian noise (AWGN) noise of N^{th} transmit antenna and M^{th} receive antenna of zero mean and fixed variance $N(0, \sigma_n^2)$, and A represents the designed sensing matrix. Referring to (1), CS dictionary atoms are designed considering both delay and Doppler channel profiles. The equispaced pilot subcarriers $p[k]$ are inserted within the data subcarriers $d[k]$ of the OFDM symbol, and the time domain channel matrix can be represented with both delay C_ℓ and Doppler F_j.

$$h(t) = \sum_{i=0}^{L-1} \sum_{\ell=j=0}^{N-1} a_i \; C_\ell \; F_j \tag{3}$$

The delay profiles C_ℓ of (3) is represented in (4) with $N \times N$ circulant matrix of the i^{th} path delay, and its atoms represented with a taped delay profile Δt of (5) along the OFDM symbol.

$$C_\ell = \begin{bmatrix} e^{-j2\pi\Delta t,1} & \cdots & e^{-j2\pi\Delta t,N} \\ \vdots & \ddots & \vdots \\ e^{-j2\pi\Delta t,2} & \cdots & e^{-j2\pi\Delta t,1} \end{bmatrix} \tag{4}$$

$$\Delta t = \left[0, i \times \frac{\alpha}{N}, \alpha\right] \text{ , } where \; i = 1, 2, 3, \dots, N \tag{5}$$

Where, α represents the minimum spacing between channel taps, which equals to $(G_i \times T_s - \frac{G_i \times T_s}{N})$, and G_i represents the guard interval, which assumed to be the cyclic prefix length applied to each OFDM symbol in order to overcome the ICI problem, and T_s represents the OFDM sampling time.

At the other hand, the Doppler profile F_j of (3) is represented in (6) with a diagonal matrix of the j^{th} Doppler shifts. The Doppler shift f_d is assumed to be normalized across OFDM symbols which calculated using (7).

$$F_j = \begin{bmatrix} e^{j2\pi f_{dnorm}} & \cdots & 0 \\ \vdots & e^{j2\pi(N-1)f_{dnorm}} & \vdots \\ 0 & \cdots & e^{j2\pi N f_{dnorm}} \end{bmatrix} \tag{6}$$

$$f_{dnorm} = \frac{f_d}{B_N}, B_N = \frac{B.W}{N} \tag{7}$$

Where B_N represents the subcarrier spacing between OFDM symbols.

At the receiver side, the symbols after reception are passed to N point fast fourier transform (FFT) process and retransformed to frequency domain. Mathematically, the Fourier transform of a circulant matrix results a diagonal matrix and vice versa [25]. Hence, the frequency domain channel matrix can be expressed.

$$H(f) = \sum_{i=0}^{L-1} \sum_{L=j=0}^{N-1} a_i \; C_L \; F_J \tag{8}$$

From the above analysis, the dictionary $D_{N\times N}$ is represented by atoms related to both channel delay and Doppler, where each OFDM subcarrier experience all delay and Doppler effects.

$$D_{N\times N} = \begin{bmatrix} e^{j2\pi f_{dnorm}} & \cdots & e^{j2\pi N f_{dnorm}} \\ \vdots & \ddots & \vdots \\ e^{j2\pi 2 f_{dnorm}} & \cdots & e^{j2\pi f_{dnorm}} \end{bmatrix} \times \begin{bmatrix} e^{-j2\pi\Delta t(1)} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e^{-j2\pi\Delta t(N)} \end{bmatrix} \tag{9}$$

However, N_p rows are chosen from D matrix which related to pilot locations in order to construct the sensing matrix A. The selected rows are multiplied by the pilot data of $N_p \times N$ matrix using dot product multiplication. Where, N_p represents the number of training pilots, P_j represents the pilot symbol which used for estimation assuming equally likely symbols, and $j = 1,2,3, \ldots., N_p$.

$$A_{N_p\times N} = D_{N_p\times N} \cdot \begin{bmatrix} e^{-j\pi\, P_{1,1}} & \cdots & e^{-j\pi\, P_{1,N}} \\ \vdots & \ddots & \vdots \\ e^{-j\pi\, P_{N_p,1}} & \cdots & e^{-j\pi\, P_{N_p,N}} \end{bmatrix}_{N_p\times N} \tag{10}$$

In order to prevent ICI and save bandwidth, an optimal number of pilot subcarriers should be assumed for estimation. The classical channel estimation methods can only be employed under the assumption that $N_p \geq L_{cp}$ [7], while, by adopt CS technique to estimate channel coefficients, an functional channel estimation can be acquired with a littel number of pilots using a smart construction of sensing matrix. A primary target is to recover the k-sparse channel coeffecints while utilizing bandwidth using a limited number of pilots with almost no performance degradation such that $N_p \leq L_{cp}$.

Once the channel significant taps estimated, the reminder CIR is constructed at all channel taps using:

$$\widehat{H} = D \times \theta \tag{11}$$

When estimating the CIR $\widehat{H}(M_r, N_t)$ at each channel path, the multiple received signal copies $Y^j[k]$ are combined by STBC combiner system with the estimated CIR. It is important to mention that maximum likelihood (ML) detection is used in order to estimate the transmitted symbols. After signal combining which resulting with a single data stream $Y[k]$, the frequency domain signal is passed to the detection process in order to recover the original data.

3. SIMULATIONS AND RESULTS

The 2×2 STBC MIMO-OFDM system of Figure 1 was simulated and performance test was carried over international telecommunication union (A-ITU) time varying channel of Table1 in the form of BER versus SNR. In simulations, SNR is defined by the corresponding $\frac{E_b}{N_0}$ in dB. Two CS algorithms; BP and OMP, was evaluated with different Doppler frequencies in order to compare their performances with conventional LS. The OFDM system parameters considered in simulations are shown in Table 2. For the purpose of evaluating the effectiveness of the suggested dictionary in recovering CIR with limited number of pilots, 16 pilots are considered in simulations out of different subcarriers.

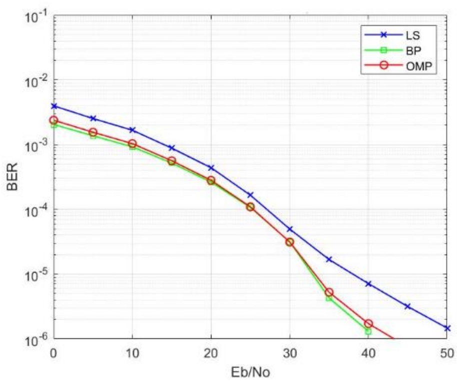
In the proposed simulations, Figure 2(a) and Figure 2(b) are presented to evaluate the design success of the suggested dictionary in recovering the CIR with a variations of Doppler shifts considering 64 subcarriers. Using BP based CS channel estimation, the BER performance approaches 10^{-6} as compared to 7×10^{-6} using LS method at 40 dB with f_{dmax} = 0 Hz. In order to evaluate the dictionary applicability to recover the CIR in the existence of high Doppler effects. When Doppler frequency increased above 0 Hz, the BER performance degraded and LS method could not track channel variations. Regarding the performance tests of OMP and BP in moderate Doppler effects, the performance of OMP algorithm outperforms BP tests at low SNR values, where for f_{dmax} = 500 Hz. Regarding Figure 3(a) and Figure 3(b) tests considering the same parameter simulations, OMP outperforms BP performance by about 9 dB at a BER of 10^{-3}, and by about 5 dB when f_{dmax} increased to 1000 Hz and 1500 Hz at the same error rate respectively. This improvement can be explained by the relation of (7), where, as the Doppler shifts increased, the normalized Doppler value f_{dnorm} is increased, and the sensitivity of the proposed dictionary for the real Doppler values increased, which enhance the estimation performance. After proving the success of the work of the proposed dictionary with different Doppler values, Figure 4 and Figure 5 are presented to evaluate the applicability of the suggested dictionary to retrieve the CIR with various OFDM subcarriers. And since the main target of this work is to estimate channel parameters with high Doppler shifts and minimal number of pilots, both tests consider 16 pilots and a Doppler shift of 1000 Hz, and 1500 Hz.

Table 1. Vehicular A-ITU channel model [26]

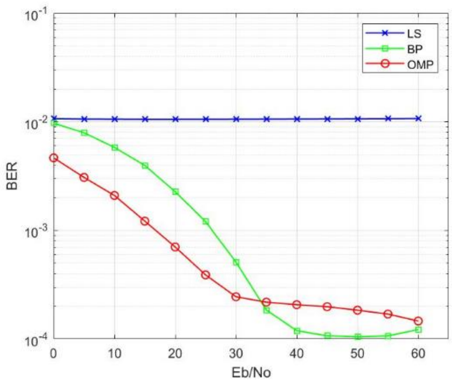
Taps no.	Relative delay (ns)	Average power (dB)
1	0	0
2	310	-1.5
3	710	-9.0
4	1090	-10.0
5	1730	-15.0
6	2510	-20.0

Table 2. Simulation parameters

Parameter	Value
Modulation	BPSK
Sampling time T_s sec.	10^{-6}
Bandwidth $B.W$ Hz	20×10^{-6}
OFDM subcarriers N	64, 128, 256
Number of pilots N_p	16
Cyclic prefix length $L_{cp} = G_i$	16, 32, 64
Transmit and receive antennas N_t, M_r	2, 2
Carrier frequency f_c Hz	2.4×10^{9}
Maximum Doppler shift f_{dmax} Hz	0 – 1500
Mobile velocity v Km/h	$(f_d \times c)/f_c$
Speed of light c m/sec.	3×10^{8}

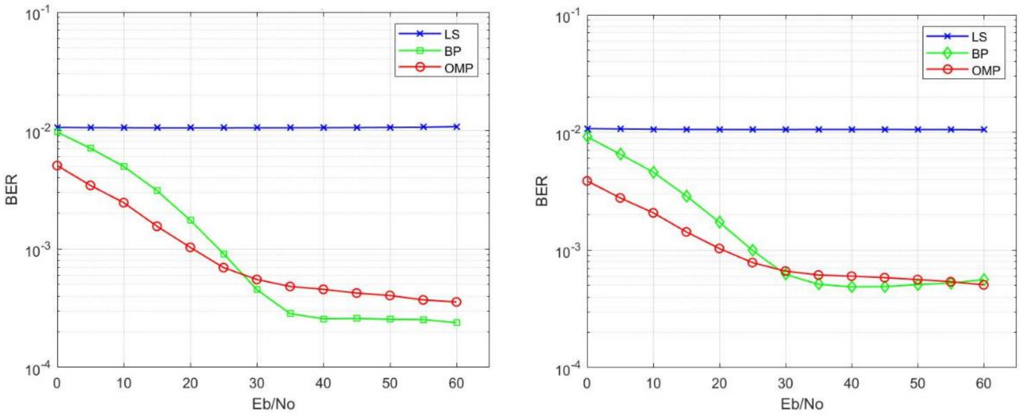


(a)



(b)

Figure 2. BER Performance of different estimation methods for MIMO-OFDM system with $N_p = 16$, $N = 64$, zero and 500 Hz: (a) $f_{dmax} = 0\ Hz$ and (b) $f_{dmax} = 500$ Hz

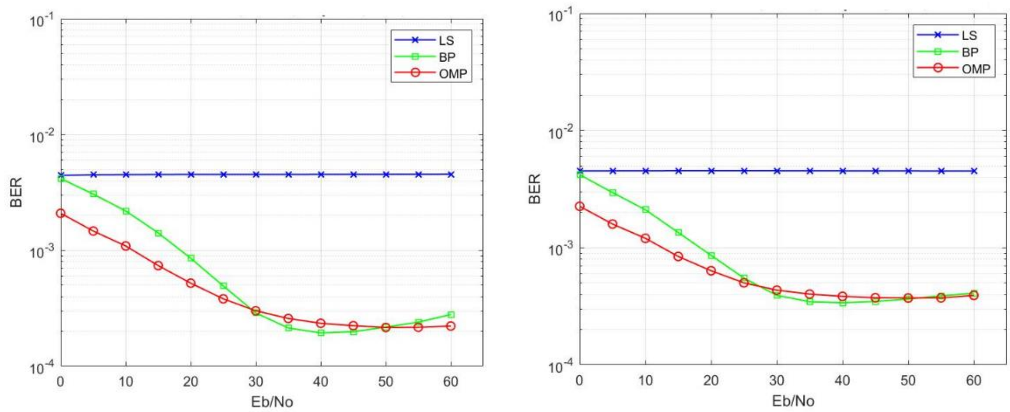


(a) (b)

Figure 3. BER Performance different estimation methods for MIMO-OFDM system with $N_p = 16$, $N = 64$, zero and high f_{dmax}: (a) $f_{dmax} = 1000$ Hz and (b) $f_{dmax} = 1500$ Hz

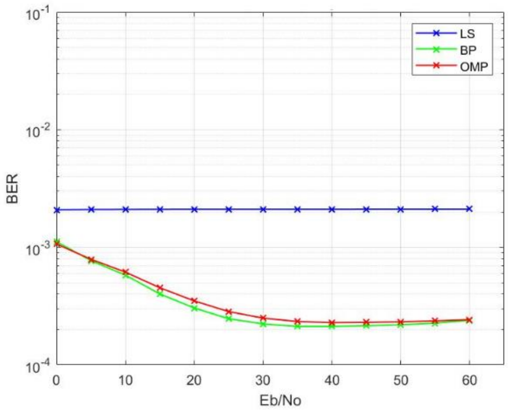
Figure 4(a) and Figure 4(b) consider 128 subcarrieres, which showed the BER performance of LS, BP, and OMP with respect to 1000 Hz and 1500 Hz Doppler frequencies. The tests show that as N increased from 64 subcarrier to 128 subcarrier, the BER performance of BP and OMP is improved by about 6 dB and 9 dB respectively at $f_{dmax} = 1000\ Hz$ and by about 6 dB and 8 dB at $f_{dmax} = 1500\ Hz$ for the same error rate respectively with 128 subcarriers. Considering 256 subcarriers tests of Figure 5(a) and Figure 5(b), the test results show that by increasing the subcarrier number to 256 subcarriers, the BER performance of both BP and OMP is improved to be almost identical at low SNR values, where they need only 0 dB to obtain a BER of 10^{-3}. The reason behind the performance improvement when the subcarrier number increased is also related to (7). Where, as OFDM subcarrier number increased, the spacing between OFDM subcarriers decreased, which effects the Doppler distribution. With a higher normalized Doppler frequency f_{dnorm}, the proposed dictionary becom more sensitive to the real Doppler values, which enhance the estimation performance.

As a final assessment of results, either by increasing of OFDM subcarriers from 64 to 256 or Doppler shifts up to 1500 Hz, the BER performance is improved, where the sensitivity of the proposed dictionary for real Doppler values is increased. At the other hand, bandwidth efficiency is improved by using a minimum number of pilots which adopted for estimation. This indicates the suitability of the proposed dictionary in recovering the CIR at high mobility conditions while saving bandwidth by using a minimum number of pilots.

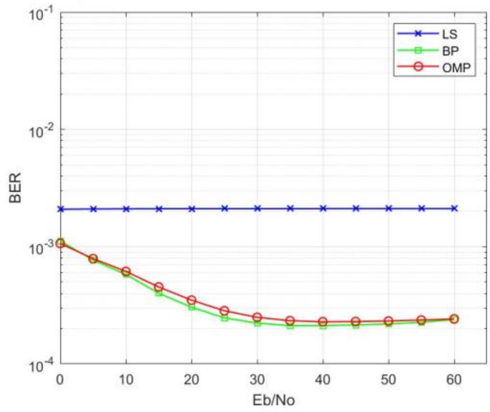


(a) (b)

Figure 4. BER Performance different estimation methods for MIMO-OFDM system with $N_p = 16$, N $= 128$, and high f_{dmax}: (a) $f_{dmax} = 1000$ Hz and (b) $f_{dmax} = 1500$ Hz



(a)



(b)

Figure 5. BER Performance different estimation methods for MIMO-OFDM system with $N_p = 16$, $N = 256$, and high f_{dmax}: (a) $f_{dmax} = 1000$ Hz and (b) $f_{dmax} = 1500$ Hz

4. CONCLUSIONS AND FUTURE WORK

In the proposed work, a noval frame work design of CS dictionary is introduced in order to recover the channel response. The design considers both delay and doppler effects of LTV channel. As a result of applying CS based the proposed dictionary to estimate CIR, the response was recovered correctly for MIMO-OFDM systems with only 16 pilots out of 64, 128, and 256 subcarrirs even when the mobile system moves with high-speed approaches 675 Km/h such as in HST systems. This result indicates that the analysis of the delay and Doppler effects on the doubly selective channel with the proposed dictionary design is working probably. At the other hand, the combination of MIMO-OFDM system improves channel capacity as well as BER using STBC. Hence, by applying MIMO-OFDM combination jointly with the proposed CS dictionary, bandwidth efficiency can be increased and CIR can be successfully recovered even for deep faded time variant channels.

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