

A Novel BEM- Based Channel Estimation Algorithm for Time Variant Uplink OFDMA System

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ABSTRACT — IN this paper the effect of different channel estimation approaches in OFDMA uplink system which are based on Basis Expansion Model (BEM) and widely used to consider time varying channels are discussed. It has been shown in previous works that modeling error will be reduced by applying oversampled BEM with cost of increasing sensitivity to noise. This problem will be solved by combining oversampled BEM and MMSE channel estimator with cost of increasing computational complexity. In this paper a novel channel estimation approach is represented in which by combining oversampled BEM and low rank MMSE in frequency domain, almost the same performance as the full rank MMSE has been achieved while computational complexity reduces significantly.

INDEX TERMS —Channel estimation, Basis Expansion Model (BEM), MMSE, OFDMA, Time varying channel.

I. INTRODUCTION

In recent years, Orthogonal Frequency Division Multiplex Access (OFDMA) has been considered and proposed as one of the most important access schemes. The most advantage of exploiting OFDMA is avoiding Multiple Access Interference (MAI) due to orthogonal nature of subcarriers.

The mobile channel is usually described as a frequency selective fading channel. The frequency selective characteristic of the channel is due to the multipath propagation and the fading is mainly because of the terminal's moving. These channels can be mentioned as a time variant and frequency selective channel and OFDM can be efficiently applied as a transmission method in this case. Orthogonal Frequency Division Multiple Access (OFDMA) combines the OFDM and Frequency Division Multiple Access (FDMA). It can also control the data rate variation of each user by allocating different number of subcarriers to any user.

Channel estimation is crucial for those systems which use coherent detection. In multiple access systems such as OFDMA, channel estimation in uplink path is much interesting because of obtaining higher detection performance at the Base Station (BS).

A channel estimator should be able to provide a good estimation of both the frequency selectivity and the fading

degrees of the channels. Thus it is ideal to have the joint channel estimation in both the time domain and the frequency domain. In practice, pilot-aided channel estimation with acceptable overhead is widely used for this purpose. Density of pilots may be determined very well in conditions like fast fading channels and frequency selective fading channels in order to provide an estimator with desirable performance. In other words, there is a trade off between data throughput and channel estimation performance.

In time variant channels, channel parameters vary during one OFDM symbol due to the Doppler spreads and this leads to inter carrier interference (ICI). Doppler spread has the most effect on orthogonality between subcarriers especially in the case of mobile reception. Pilot based channel estimation methods can be used to reduce destroying effect of ICI. These methods have been preferred because of their ability to track fast changes of channel parameters within time duration.

According to [8, 13], channel modeling schemes can roughly be divided in to two main categories: Statistical Modeling and Basis Expansion Modeling (BEM). In statistical modeling each channel tap is considered as an uncorrelated stationary random process. This modeling scheme is suitable for channels with so many scattering objectives. In BEM scheme, telecom channel has been assumed as a deterministic model in which time varying channel is represented as a superposition of few complex exponential functions spanning the entire Doppler range. This model is widely used in case of cellular radio application in which multipath is caused by few but strong reflectors and path delays are functions of mobiles kinematics [8].

In this paper a novel channel estimation based on BEM has been represented. Proposed channel estimation also based on Minimum Mean Square Error (MMSE) in frequency domain.

This paper is organized as follow:

In section2, OFDMA uplink system is considered. An introduction to BEM is represented in section3. Pilot based MMSE channel estimator in frequency domain is investigated in section4. Numerical simulation and conclusion are presented in section 5 and section6, respectively.

II. OFDMA UPLINK SYSTEM

Transmitted signal from an arbitrary user in an OFDMA system with N subscriber and U user can be presented as below:

$$x_u(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} M_u(k) X(k) e^{j \frac{2\pi k n}{N}} ; -N_g \leq n \leq N-1 \quad (1)$$

Where $X(k)$ is inverse discrete Fourier transform (IDFT) of the complex data and

$$M_u(k) = \begin{cases} 1 & \text{if } k \text{ is used by user } u \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

is the masking variable identifying the subscribers used by user u and N_g is the length of Cyclic Prefix (CP).

The choice of CP length according to the channel delay spread, will relinquish any signal degradation due to inter-subcarrier interference (ISI) and multipath propagation by conversion of linear convolution to the cyclic convolution one.

As it has been said before, the major advantage of OFDMA is avoiding multi user interference (MUI) due to orthogonality between subcarriers. When OFDMA signal transfers via a communication channel this orthogonality may lose because of carrier frequency offset.

III. INTRODUCTION TO BASIS EXPANSION MODEL

As a matter of fact, BEM representation of a channel uses time invariant parameter to describe random characteristic of a time variant channel. Assume that $h(n, l)$ denote one tap of a multipath mobile channel then [8]:

$$h(n, l) = \sum_{q=1}^Q c_q(l) e^{j\phi_q} e^{j(2\pi/\lambda) \cos(2\pi l/Q) n} \quad (3)$$

Where c_q is the amplitude of the q th path, ϕ_q is a uniformly distributed random variable in $[0, 2\pi]$, λ is the wavelength which corresponds to the carrier frequency. $h(n, l)$ can be represented as a realization of a stochastic process, too. In this case

$$h(n, l) = \sum_{q=1}^Q \bar{h}_q(l) b_q(n) \quad (4)$$

where $\{\bar{h}_q(l)\}_{l=0}^{Q-1}$ are time invariant parameters and $\{b_q(n)\}_{n=0}^{Q-1}$ are bases to describe system characterization. So, $\bar{h}_q(l) = c_q(l) e^{j\phi_q}$ and $b_q(n) = \exp(j\omega_q n)$ where $\omega_q = (2\pi/\lambda) \cos(2\pi l/Q) n$.

Candidate basis functions include complex exponential (Fourier) functions, polynomials, and discrete prolate spheroidal sequences, etc.

Complex exponential BEM (CE-BEM)[2] exploits Fourier basis to give an approximate model of the time varying channel within a period of time. These Fourier Bases which are sampled in Doppler frequency domain give an accurate approximation of the Channel Impulse Response (CIR). Mathematically, CIR of any path can be represented as below

$$h(t, \tau) \cong \delta(t - \tau) \sum_{q=-Q}^Q a_q \exp(j2\pi f_q \tau) ; 0 \leq t \leq T \quad (5)$$

where f_q is the q -th sampled frequency in Doppler domain and a_q is the associated coefficient of it. The discrete time model of (5) with T_s sampling interval is given by

$$h(n, l) = h(t = nT_s, \tau = lT_s) \\ = \delta(n - l) \sum_{q=-Q}^Q a_q \exp(j2\pi T_s f_q) ; \quad (6)$$

$$N - 1 = \lfloor T/T_s \rfloor ; L - 1 = \lfloor \tau_{\max}/T_s \rfloor \\ 0 \leq n \leq N - 1, 0 \leq l \leq L - 1$$

In the above equation $\tau_{\max}$ is the actual delay spread in the time domain and L is delay spread in the discrete time model.

Let's

$$f_q = \frac{q}{gT} ; -\lceil g f_{\max} T \rceil \leq q \leq \lceil g f_{\max} T \rceil \quad (7)$$

In the above equation g represents frequency resolution in the Doppler domain if $g=1$ and then equation (8) will show the conventional BEM. If $g>1$ then (8) represents the oversampled version of BEM [2]

$$h(n, l) = \delta(n - l) \sum_{q=-Q}^Q a_q \exp\left(\frac{j2\pi q l}{gN}\right) \quad (8)$$

In [8] this representation is considered very well and it has been shown that if the number of Q , number of paths, increases BEM approximates random coefficient fading model very well. As a result, random coefficient models used to simulate mobile channels can be obtained from the basis expansion model with random parameters [8]. Obviously, like other models, this modeling can cause errors, too. In [14] it has been investigated that error between true channel and BEM is quite high in case of equality of BEM period and time window. Also, it has been shown that oversampling the Doppler spectrum may reduce this error with cost of increasing sensitivity to noise. It has been shown that using MMSE pilot based estimator can reduce this sensitivity [14,1].

By exploiting (8) and received OFDMA block of any user, for example user u , can be presented as (9) and $z(n)$ in this equation is a complex Additive White Gaussian Noise (AWGN) with variance σ_n^2 [2]:

$$r_u(n) = \sum_{l=0}^{L-1} \bar{h}_u(n, l) x_u(n - l) + z(n) \\ = \sum_{q=-Q}^Q \exp\left(\frac{j2\pi q l}{gN}\right) \sum_{l=0}^{L-1} a_u(l, q) x_u(n - l) + z(n) ; 0 \leq n \leq N - 1 \quad (9)$$

Substitute (1) in (9)

$$r_u(n) = \sum_{q=-Q}^Q \exp\left(\frac{j2\pi q l}{gN}\right) \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \left(\sum_{l=0}^{L-1} a_u(l, q) M_u(k) X(k) \exp\left(\frac{j2\pi k l}{N}\right) \right) \times \exp\left(\frac{j2\pi q l}{N}\right) + z(n) ; 0 \leq n \leq N - 1 \quad (10)$$

It is common to show above result in matrix form for more convenience [2]:

$$\begin{aligned}
\mathbf{r}_u &= \sqrt{N} \sum_{q=0}^Q \mathbf{D}_q \mathbf{F} \text{diag}[\mathbf{M}_u \mathbf{X}] \mathbf{F}^H(:, L) \mathbf{a}_{u,L} + \mathbf{z} ; \\
\mathbf{D}_q &= \text{diag}[1 \exp(\frac{j2\pi q}{gN}) \dots \exp(\frac{j2\pi(N-1)q}{gN})] \\
[\mathbf{F}]_{xy} &= \frac{1}{\sqrt{N}} \exp(\frac{j2\pi xy}{gN}) \\
\mathbf{M}_u &= \text{diag}[M_u(0) \ M_u(1) \ \dots \ M_u(N-1)] \\
\mathbf{X} &= [X(0) \ X(1) \ \dots \ X(N-1)]^T \\
\mathbf{a}_{u,L} &= [a_u(0,q) \ a_u(1,q) \ \dots \ a_u(L-1,q)]^T
\end{aligned} \tag{11}$$

In above equation $\mathbf{F}$ is IFFT matrix, $\mathbf{F}^H$ is FFT matrix and $\mathbf{F}^H(:, L)$ is the matrix formed from columns 1 to L of $\mathbf{F}^H$.

According to (11) OFDMA blocks which are received at BS can be obtained as follow:

$$\mathbf{r} = \sum_{u=1}^U \mathbf{r}_u = \sqrt{N} \sum_{u=1}^U \sum_{q=0}^Q \mathbf{D}_q \mathbf{F} \text{diag}[\mathbf{M}_u \mathbf{X}] \mathbf{F}^H(:, L) \mathbf{a}_{u,L} + \mathbf{z} \tag{12}$$

It is clear that transmitted symbols by user u will be represented in time domain by:

$$\begin{aligned}
\mathbf{x}_u &= \mathbf{F} \mathbf{M}_u \mathbf{X} \\
\mathbf{C}(\mathbf{x}_u) &= \mathbf{F} \text{diag}[\mathbf{M}_u \mathbf{X}] \mathbf{F}^H(:, L) \\
&= \begin{bmatrix} \mathbf{x}_u(0) & \mathbf{x}_u(N-1) & \dots & \mathbf{x}_u(N-L+1) \\ \mathbf{x}_u(1) & \mathbf{x}_u(0) & \dots & \mathbf{x}_u(N-L+2) \\ \dots & \dots & \dots & \dots \\ \mathbf{x}_u(N-1) & \mathbf{x}_u(N-2) & \dots & \mathbf{x}_u(N-L) \end{bmatrix}
\end{aligned} \tag{13}$$

As it can be seen from (13) $\mathbf{C}(\mathbf{x}_u)$ is a matrix with L columns formed by circularly shifting $\mathbf{x}_u$.

Equation (12) can be written as

$$\begin{aligned}
\mathbf{r} &= \sum_{u=1}^U \mathbf{F}_u \mathbf{a}_u + \mathbf{z} ; \\
\mathbf{F}_u &= \sqrt{N} [\mathbf{D}_{-Q} \mathbf{C}(\mathbf{x}_u) \ \dots \ \mathbf{D}_{+Q} \mathbf{C}(\mathbf{x}_u)] \\
\mathbf{a}_u &= \sqrt{N} [\mathbf{a}_{u,-Q}^T \ \dots \ \mathbf{a}_{u,+Q}^T]
\end{aligned} \tag{14}$$

And finally by exploiting follow equation, the received OFDMA blocks at BS can be shown as [2]

$$\begin{aligned}
\mathbf{r} &= \mathbf{F} \mathbf{a} + \mathbf{z}; \\
\mathbf{F} &= [\mathbf{F}_1 : \mathbf{F}_2 : \dots \ \mathbf{F}_U] \\
\mathbf{a} &= [\mathbf{a}_1 : \mathbf{a}_2 : \dots \ \mathbf{a}_U]
\end{aligned} \tag{15}$$

In receiver, after FFT demodulation, OFDMA blocks in frequency domain can be presented as

$$\begin{aligned}
\mathbf{y} &= \mathbf{F}^H \mathbf{r} = \mathbf{F}_F \mathbf{a} + \mathbf{z}_F; \\
\mathbf{F}_y &= [\mathbf{F}^H \mathbf{F}_1 : \mathbf{F}^H \mathbf{F}_2 : \dots \ \mathbf{F}^H \mathbf{F}_U]
\end{aligned} \tag{16}$$

where $\mathbf{z}_F$ is the noise in frequency domain.

As it can be seen from above equations, BEM coefficients vector, $\mathbf{a}$, must be estimated to obtain CIR coefficients.

IV. PILOT BASED MMSE CHANNEL ESTIMATOR IN FREQUENCY DOMAIN

Many of previous works consider BEM for channel estimation with help of pilot insertion in time clusters. For frequency domain communication such as OFDMA, these

approaches suffer from a large estimation errors [15,16,17,18].

It has been shown in [2] that Least Square (LS) channel estimator in frequency domain highly suffers from Inter Carrier Interference (ICI). It is clear that this happens because the LS estimator neglects the channel correlation among the subcarriers and processes them independently. Minimum Mean Square Error (MMSE) estimator has been investigated to perform better channel estimation with the help of known channel statistic and cost of increasing computational complexity.

In case of exploiting pilot subcarriers in frequency domain, (15) can be written as:

$$\mathbf{y} = \mathbf{F}_F \mathbf{a} + \mathbf{z}_F = \mathbf{P}_F \mathbf{a} + \mathbf{D}_F \mathbf{a} + \mathbf{z}_F \tag{17}$$

where $\mathbf{P}_F$ and $\mathbf{D}_F$ are pilot and data vectors, respectively.

All following considered channel estimation approaches will be applied for pilot vectors which are assumed to be scattered in frequency domain.

So, LS estimation of BEM coefficients can be obtained as follow:

$$\hat{\mathbf{a}}_{LS} = \mathbf{P}_F^{-1} \mathbf{y} \tag{18}$$

And associated MMSE estimation will be:

$$\begin{aligned}
\hat{\mathbf{a}}_{MMSE} &= \mathbf{R}_{HH} (\mathbf{R}_{HH} + \frac{\beta}{SNR} \mathbf{I})^{-1} \hat{\mathbf{a}}_{LS}; \\
\beta &= E[|\mathbf{P}_F|^2] E\left[\left|\frac{1}{\mathbf{P}_F}\right|^2\right],
\end{aligned} \tag{19}$$

where β is a constant value depending on the modulation type [5].

In [5,12] two methods are represented to reduce computational complexity. The main difference between these two approaches is the algorithm domain of their algorithms. In [5] it has been investigated that low rank MMSE channel estimation algorithm in frequency domain has better performance than low rank MMSE channel estimator in time domain especially in high SNR condition.

A. Novel BEM-Based MMSE Channel Estimator in Frequency Domain

As it can be seen from (19), BEM-based MMSE channel estimation consists of two separated calculation steps:

First, autocorrelation matrix of the channel, $\mathbf{R}_{HH}$, of the channel must be calculated and used in calculation of

$$\mathbf{R}_{HH} (\mathbf{R}_{HH} + \frac{\beta}{SNR} \mathbf{I})^{-1}$$

Second, according to (3) and (8), follow equation must be solved to obtain optimum BEM coefficients:

$$\begin{aligned}
&\min_{\mathbf{a}_q} \|\mathbf{c}_q - \mathbf{A} \mathbf{a}_q\|^2 ; \\
\mathbf{A} &= \begin{bmatrix} 1 & \dots & 1 \\ \exp(-\frac{j2\pi Q}{gN}) & \dots & \exp(\frac{j2\pi Q}{gN}) \\ \vdots & & \vdots \\ \exp(-\frac{j2\pi Q(N-1)}{gN}) & \dots & \exp(\frac{j2\pi Q(N-1)}{gN}) \end{bmatrix}
\end{aligned} \tag{20}$$

The solution of above minimization problem is given by:

$$\mathbf{a} = \mathbf{A}^T \mathbf{c} \quad (21)$$

Equation (19) is yield by combining of these two steps.

Our novel approach is obtained by focus on the first step.

From (3), it is easy to see that autocorrelation matrix of channel is a $Q \times Q$ matrix as follow:

$$\mathbf{R}_{HH} = \begin{bmatrix} r_f(0,0) & r_f(0,1) & \dots & r_f(0,Q-1) \\ r_f(1,0) & r_f(1,1) & \dots & r_f(1,Q-1) \\ \vdots & \vdots & \ddots & \vdots \\ r_f(Q-1,0) & r_f(Q-1,1) & \dots & r_f(Q-1,Q-1) \end{bmatrix} \quad (22)$$

where

$$r_f(k_1, k_2) = \sigma_h^2 J_0(2\pi f_{\max}(k_1 - k_2)T) \quad (23)$$

In (23), $r_f(k_1, k_2)$ is autocorrelation of Jake's Model of channel in frequency and where J_0 is the zero-th order Bessel function and σ_h^2 is channel variance.

The basic innovation of our proposed methods is to replace those elements of a relatively small value in $\mathbf{R}_{HH}$ with a value of zero, So that only those taps with a significant weight are used for channel estimation process. The number of non-zero taps determines the computational complexity of the estimator and may have a great impact on the approximation error if significant taps are ignored in the channel estimation process. Let's assume that only $2n+1$ taps have significant value due to $\max \{ r_f(i, j) \}$ in each row of autocorrelation matrix. So, (22) can be represented as follow [5] in case of $n=1$

$$\mathbf{R}_{HH}^{prop} = \begin{bmatrix} r_f(0,0) & r_f(0,1) & r_f(0,2) & 0 & \dots & \dots & \dots & 0 \\ r_f(1,0) & r_f(1,1) & r_f(1,2) & 0 & \dots & \dots & \dots & 0 \\ 0 & r_f(1,0) & r_f(1,1) & r_f(1,2) & 0 & \dots & \dots & 0 \\ 0 & 0 & r_f(1,0) & r_f(1,1) & r_f(1,2) & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \dots & \dots & \dots & 0 & r_f(Q-1,0) & r_f(Q-1,1) & r_f(Q-1,2) \\ 0 & \dots & \dots & \dots & 0 & r_f(Q-1,0) & r_f(Q-1,1) & r_f(Q-1,2) \end{bmatrix} \quad (24)$$

It is clear that by substituting (24) in (19), computational complexity will reduce effectively. It is a trade off between computational complexity and accuracy of channel estimation. As it will be depicted in next section, our proposed channel estimation has acceptable performance and less computational complexity in comparison with BEM-based conventional MMSE channel estimator.

V. SIMULATION RESULTS

In this section we consider our proposed BEM-based MMSE channel estimation in frequency domain.

In the simulation a 4-user 64-subcarrier uncoded OFDMA system uplink is considered. In Jake's model of channel $f_{\max}$ is taken equal to 250Hz and

$T_{\text{sampling}} = 10 \mu\text{sec}$. Number of pilot subcarriers are 8.

The modulation scheme is QPSK and in proposed BEM-based MMSE channel estimator, the number of considered taps is 29.

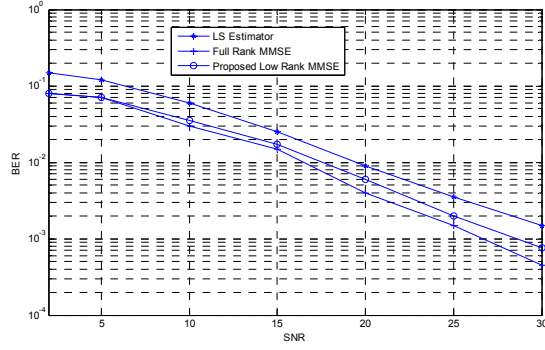


Figure 1. BER Performance Comparison for Uncoded System Employing LS, MMSE and Low Complexity MMSE Approaches with QPSK Modulation

In case of exploiting oversampled BEM, oversampling factor is 2.

The average of bit error rate performance for QPSK is shown in Figure 1. It can be seen from this figure that the performance of the proposed method is close to that of the full-rank MMSE estimator, while it outperforms the LS estimator by about 2.5 dB in average E_b/N_0 for a bit error rate of 10^{-2} .

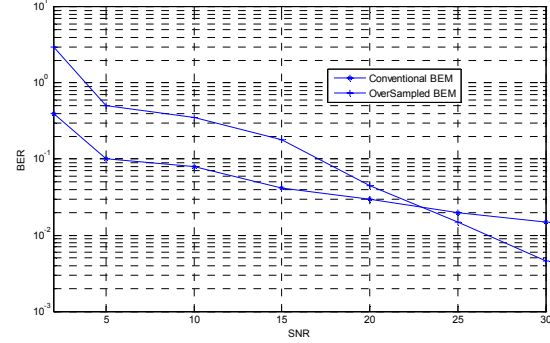


Figure 2. BER Performance Comparison of BEM and oversampled BEM with QPSK Modulation

Figure 2 has shown that oversampled BEM suffers from noise more than conventional BEM.

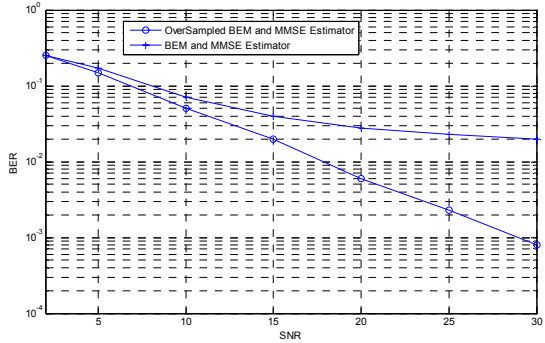


Figure 3. BER Performance Comparison of BEM and Oversampled BEM Applying MMSE Estimator with QPSK Modulation

To achieve better performance of channel estimation a combination of BEM and MMSE estimator has been used. The result which has been shown in figure3 represents better

performance of this combination but it can be seen that this combination does not have efficiency of MMSE estimator. The reason of efficiency reduction is modeling error due to BEM usage.

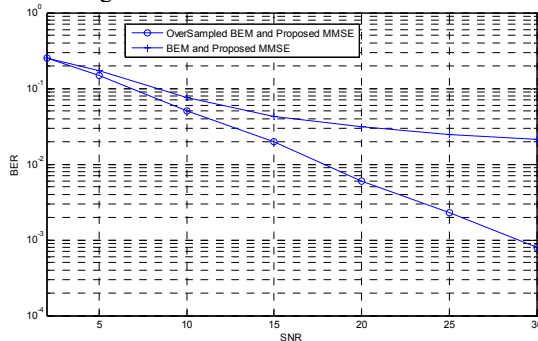


Figure 4. BER Performance Comparison of BEM and Oversampled BEM Applying Proposed MMSE Estimator with QPSK Modulation

Finally, we compare bit error rate performance of our proposed MMSE estimator in two cases of applying conventional and oversampled BEM. The simulation results have been shown in figure 4. This figure depicts that performance of our method is very close to full rank MMSE, mainly in case of applying oversampled BEM.

VI. CONCLUSION

In this paper, the effect of different channel estimation approaches in OFDMA uplink system has been studied. Basis Expansion Model (BEM) which is widely used to consider time varying channels is discussed very well. To achieve better performance of channel estimation, BEM is exploited simultaneously with one estimator in time or frequency. In fact OFDMA is categorized in frequency domain communication systems so we choose frequency domain channel estimator. There are two main categories of estimator in frequency domain: Least Square (LS) and Minimum Mean Square Error (MMSE). MMSE estimator is more accurate because it considers correlation between any two subcarriers. According to this we exploit MMSE channel estimator in frequency domain. Also, BEM is used in two different conditions: conventional and oversampled. It has been shown in previous works that modeling error will be reduced by applying oversampled BEM with cost of increasing sensitivity to noise. This problem will be solved by combining oversampled BEM and MMSE channel estimator with cost of increasing computational complexity. In this paper a novel channel estimation approach is represented as a method of combining oversampled BEM and low rank MMSE in frequency domain, almost the same performance as the full rank MMSE has been achieved while reducing computational complexity significantly.

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