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Evaluation of Channel Estimation Algorithms in MIMO-OFDM Systems with Considering the Carrier Frequency Offset

Navid daryasafar and Babak ehyaee

Abstract— **The aim of this survey is to investigate channel estimation algorithms with carrier frequency offset in MIMO-OFDM systems. According to this, with investigating the channel estimation method, we will design optimum training courses for these systems and will introduce related comparative methods based on LMS and EM algorithms. On the other hand, the LS and MMSE channel estimation methods are introduced for MIMO-OFDM systems that on this basis pilots were inserted among subcarriers in transmitter with distances emerged of sampling theory then Least Square (LS) method was chosen for initial channel estimation in pilots at receiver. These algorithms use simple reversible and present a suitable estimation of channel. The efficiency of these algorithms can be investigated with simulation and the results of estimation will come to a comparison.**

Index Terms— **Multi-Input Multi-Output Systems, Channel Estimation, Synchronization, LMS algorithm, EM Algorithm and Minimum Mean-square Error (MMSE)**

I. Introduction

OFDM is a modulation technique, which is used in frequency selective fading channels, divides a high data rate into a number of lower data rate streams over subcarriers transmitted simultaneously through channel. Each sub stream experiences flat fading narrowband channel (Proakis, 2001).

Subcarriers are orthogonal in time domain, which save bandwidth in frequency domain, resulted in ICI cancelation. Additionally, CP (Nee and Prasad, 2000) as a guard interval with a length, longer than delay spread, that is a copy of last N_g samples, in front of each symbol, avoids ISI (Nee and Prasad, 2000), therefore OFDM technique is a method to remove the effects of frequency selective fading channels and to enhance the bandwidth efficiency up to 50% comparing with FDM technique.

OFDM system is combined with multiple antennas in both sides of link, resulted in MIMO-OFDM system and higher channel capacity (Telatar, 1999).

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MIMO-OFDM systems are one of the systems which have become the basis of many communication researches nowadays. A system is with several high speed inputs and outputs in sending information or suitable diversity between transmitter and receiver; however the estimation of the channel in this connection is complex. In order to reveal the coherent of received signals, digital communication systems must have an exact estimation of the situation of exchange channel between transmitter and receiver. Since increasing the number of transmitter and receiver antennas causes an increase in the number of unknowns (coefficients of the channel between both antennas of transmitter and receiver) the estimation of channels in multi-antenna systems is a lot more challenging than in one-antenna ones [1].

A multi carrier orthogonal modulation system, using the immediate Fourier diversion technique creates interest range and changes the switch frequency to several flat sub channels; but lack of source and target and outbreak of delay by the channel decreases the function of this system. In other words, this kind of system has a high sensitivity toward time and frequency delays.

Demodulation of OFDM signals requires time synchronization and frequency offset estimation. Time synchronization involves finding the optimum time instant of the start of the OFDM frame. Use of a cyclic prefix provides some tolerance in estimation of the symbol timing. OFDM on the other hand is extremely sensitive to frequency offsets and can tolerate offsets only to within a small fraction of the subcarrier spacing.

The objective of this study is improving channel estimation accuracy in MIMO-OFDM system because channel state information is required for signal detection at receiver and its accuracy affects the overall performance of system and it is essential to improve the channel estimation for more reliable communications. MIMO-OFDM system was chosen in this study because it has been widely used today due to its high data rate, channel capacity and its adequate performance in frequency selective fading channels. For this purpose a 2×2 system was designed and pilot aided channel estimation with interpolation, is made iterative to enhance BER performance.

Approach: First of all, pilots were inserted among subcarriers in transmitter with distances emerged of sampling theory then Least Square (LS) method was chosen for initial channel estimation in pilots at receiver, using applicable proposed receiver, which has simple and usable structure, then channel state information was estimated by linear interpolator in information subcarriers, which uses two adjacent channel estimation in pilots to compute channel in another subcarriers and LMS iterative algorithm, including a feedback of output is added to system. This algorithm uses the channel estimation of last iteration in current estimation.

The recent digital transmission systems impose the application of channel equalizers with low complexity and low Bit Error Rate (BER). Adaptive equalizers are unavoidable to satisfy these requirements. A channel equalizer is an important component of a communication system and is used to mitigate the ISI introduced by the channel. The equalizer depends upon the channel characteristics. In a wireless channel, due to multipath fading, the channel characteristics change with time. Thus it may be necessary for the channel equalizer to track the time varying channel in order to provide reasonable performance (Kavitha and Sharma, 2007).

An adaptive equalizer is essentially a linear adaptive filter used to model the inverse transfer function of the channel. Two well-known adaptive algorithms are the (LMS) algorithm and the (RLS) algorithm. Although the RLS algorithm has better convergence speed than the LMS algorithm, its complexity for hardware implementation can be very high. Actually, the LMS algorithm is widely adopted in hardware implementation because of its simplicity and robustness (Chen et al, 2003). The LMS algorithm executes quickly but converges slowly, and its complexity grows linearly with the number of weights.

On the other hand, There are some estimators in two limit modes of (NDA, DA) and one middle mode of (CA), separated from what is used as scale for estimation, related to the amount of receiver knowledge of assumed density function. The DA ML estimator does not exploit all the information available about the channel because it makes use of the data free observation samples only. To improve the channel estimate quality, the channel can be estimated on the basis of the whole received burst, including both the training sequence and the data. However, when the transmitted sequence is unknown and encoded, the likelihood function exploiting the code is much more difficult to compute.

The EM algorithm enables iteratively solving this problem. The EM algorithm has been exploited previously to estimate the channel, but it has usually been used to estimate the channel taps only.

Further, in the second chapter the MIMO OFDM systems are introduced. In the third chapter, estimating methods of coefficients of channel, in the fourth chapter synchronizing methods are introduced. In the fifth chapter the Channel's coefficients estimation algorithms in MIMO-OFDM systems will be described and finally, the simulation results will indicate the performance of suggested algorithms.

II. INTRODUCTION OF MIMO OFDM SYSTEMS

In a traditional wireless communication system, provided that the bandwidth is constant, there is no possibility of increasing the sending rate of information. In this kind of situation, only diversity methods can be used to improve the quality of revealing. In designing communication systems, bandwidth, information sending rate and software-hardware complexities are the important parameters. To expand the new generation of communication systems, methods such as MIMO, OFDM and integrating them together as MIMO-OFDM, are suggested.

The high intrinsic resistance of OFDM against the ISI event and its suitable function against fading destructive event, besides the high rate of information sending of MIMO, creates a very efficient complex in accession toward the fourth generation of wireless communication's demands. Like OFDM systems, the MIMO-OFDM systems have a great deal of sensitivity toward synchronization errors. Again, according to the increase in number of unknowns, estimating the channel in these systems are more complex than estimating channel in one antenna systems [2]. Diagram block of one kind of MIMO-OFDM systems, is shown in the Fig. 1.

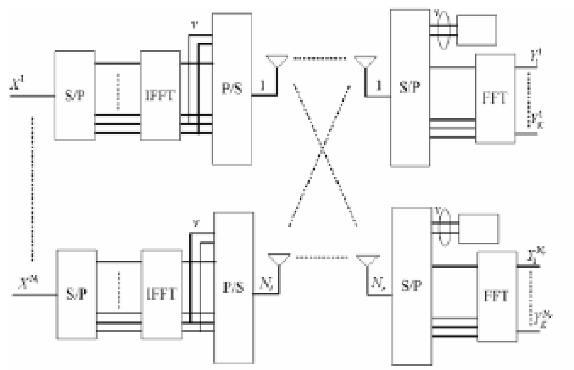

Fig. 1. Displaying a MIMO-OFDM system

According to the Fig. 1, the information in each antenna is sent after IDFT actions and addition of (CP) cyclic prefix. Each receiver antenna receives sum of noises and signals sent by the transmitter's antenna. In each receiver antenna the revealing is done after removing CP and DFT actions.

III. CHANNEL ESTIMATION METHODS IN MIMO OFDM SYSTEMS

The major considered estimating channel methods are as follows:

A. *Using educational sequence methods*

By putting samples in the sent symbol which are known by the receiver, we can reach the channel's domain which is multiplied by sum symbol and shift results. Now by using the channels reached coefficients, we can reveal the rest of symbol samples which are the desired inputs and the receiver is unaware of them [3].

B. *Blind methods*

In this method which has no need of educational samples, using the covariance matrix, the receiver estimates the coefficients of channel and reveals the sent inputs by using them [4].

C. *Half blind methods*

In this method the between up between properties of the two previous methods are used [5].

IV. SYNCHRONIZATION METHODS

According to the surveys which have done until now, the first article with title synchronization in MIMO-OFDM systems has been published by Mody and Stuber in 2001.[6,7].In those articles, Mody and Stuber generalized synchronization algorithm, proposed by Schmidl , Cox[8],for OFDM systems with one sender antenna and one receiver antenna to MIMO-OFDM. Zelst and Schenk in source[9] with considering all the necessary changes in synchronization algorithm, channel estimation,…,have generalized the OFDM based standard of IEEE-802.11a to MIMO .

The most important intrinsic restriction of the OFDM technique is its high sensitivity toward synchronizing errors. The first creator factor is called the asynchronousity of carrier frequency offset (CFO). This causes the loss of orthogonality between subcarriers and outbreak of interference between carriers. Another factor of asynchronousity is inequality of sending and receiving rate of samples precisely, which is introduced as sampling frequency delay. The proposed synchronizing algorithms for OFDM based systems are categorized to the following two main groups [10]:

A. *Before FFT algorithms*

The above-mentioned algorithms are divided to two groups of input based algorithms and non input based algorithms as follows:

Non input based algorithms: this group of algorithms estimates the synchronization parameters using the special structure of OFDM symbols. This group is also called cyclic prefix based methods [11] and [12].

Input based algorithms: this group of algorithms uses the educational symbols sent in information frames to estimate synchronization parameters [13], [14], [15] and [16].

B. *After FFT algorithms*

The algorithms of this group are also categorized in two groups of pilot based algorithms and direct decision algorithms. In comparing the two algorithms, before FFT algorithms are faster than after FFT algorithms, but after FFT algorithms have a higher throughput spectral.

V. CHANNEL'S COEFFICIENTS ESTIMATION ALGORITHMS AND THE PRESENTED CARRIER FREQUENCY OFFSET

A MIMO-OFDM system is supposed, with N transmitter antennas and M receiver antennas and K sub carrier which has the following diagram block.

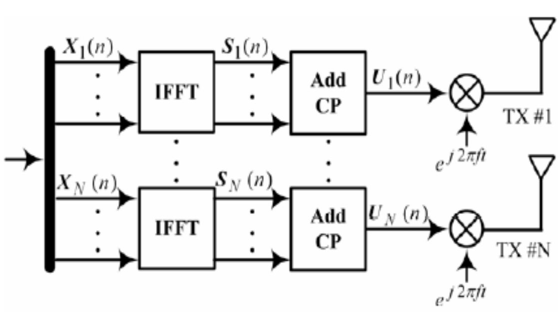

Fig. 2. Diagram block of MIMO-OFDM system's transmitter

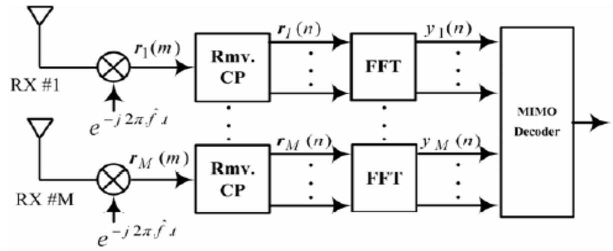

Fig. 3. Diagram block of MIMO-OFDM system's receiver

For a 2*2 MIMO-OFDM channel, the impact response under the channel between ith transmitter antenna and jth receiver is represented by $h_{i,j}$ [17]:

$$H\ (K) = \sum_{L=0}^{L-1} h_L\, e^{-j\frac{2\pi}{N}KL}\ k = 0, \dots, N-1 \qquad (1\,)$$

Signal model is as follows:

$$s^{cp}(n) = \frac{1}{N}\sum_{K=0}^{N-1} X(k)e^{j\frac{2\pi}{N}k(n-Ncp)}\ ;$$

$$n = 0, \dots, N + Ncp - 1 \qquad (2)$$

Then vector r rate in the presence of carrier frequency offset is:

$$r^{cp}(n) = e^{j2\pi\Delta fn} \times s^{cp}(n) * h(n) + V(n);\ n = 0, \dots, N_s - 1 \qquad (3)$$

With eliminating cp and doing a series of operations ,we have:

$$r(n) = e^{j2\pi\Delta f(n+Ncp)} \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(K) \sum_{L=0}^{L-1} h_L\, e^{-j\frac{2\pi}{N}kL} e^{j\frac{2\pi}{N}kn} + V(n) \qquad (4)$$

Where V (n) is White Gaussian Noise with an average of 0 . The output of the receiver is as follows:

$$y(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r(n) e^{-j\frac{2\pi}{N}kn}\ ; k = 0, \dots, N-1 \qquad (5)$$

Result

$$y(n) = e^{j2\pi\Delta fNcp} \sum_{i=0}^{N-1} x(i)\, H(i) \delta_{i,k} + V(k) \qquad (6)$$

And

$$\delta_{i,k} = \frac{1}{N}\sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}n(CFO+i-k)} = sinc\ (CFO + i - k)e^{j\pi(CFO+i-k)};\ i, k = 0\ , \dots, N-1 \qquad (7)$$

Finally Channel's coefficients estimation in MIMO-OFDM system is as follows:

$$if\colon \tilde{k} \in pilot_{2L} \to \underline{\hat{h}_1}_{2L\times 1} = A^{-1}(\tilde{k}) y_1(\tilde{k})\,, \underline{\hat{h}_2}_{2L\times 1} = A^{-1}(\tilde{k}) y_2(\tilde{k}) \qquad (8)$$

Where

h1=[h11;h21] ,h2=[h12;h22] (9)

And WL is a matrix N × L consisting of all $e^{-j\frac{2\pi}{N}K_L L}$.

A. LS Channel Estimation

The combination of orthogonal frequency division multiplexing (OFDM) with space-time coding has received much attention recently to combat multipath delay spread and increase system capacity. Channel parameters are needed in order to coherently decode the transmitted signal. Least square (LS) channel estimation for MIMO-OFDM systems has been addressed in. But if the multipaths are not sample-spaced, the well known leakage problem for DFT based channel estimation induces an irreducible error floor for estimation error. To reduce this error floor, more taps have to be used, which not only increases computational complexity but also makes estimation problem more ill-conditioned and thus enhances noise. As an alternative, channel estimation algorithm based on parametric model has been proposed in and extended to MIMO-OFDM.

Channel information is required at receiver for signal detection. However, There are different methods of channel estimation such as pilot aided (Li, 2002) and blind (Gao and Nallanathan, 2007) approaches, the first method is chosen as a channel estimation method in this study due to its less complexity. According to sampling theory (Oppenheim and Schafer, 1999), Pilots are inserted equal-spaced among subcarriers in frequency domain at transmitter, which are known at receiver and will be extracted to estimate channel at pilot subcarriers and interpolation is implemented for channel estimation in another subcarriers. In the analysis, channel is estimated with LS (Coleri *et al*., 2002) method at pilots, then linear interpolation is used to complete the estimation (Coleri *et al*., 2002; Hsieh and Wei, 1998).

Receiver designing: At the receiver, nr × nt sets of extracted received pilot tones are used for channel estimation, which LS method is chosen due to its simplicity. The standard formula for this approach at mth symbol is computed as:

$$H_{LS}(m) = ((x^p(m))^H x^p(m))^{-1}(x^p(m))^H Y^p(m) \quad (10)$$

where, XP(m) and YP(m) respectively show the transmitted and received pilots.

The LS estimate of the channel can be obtained as:

$$H_{LS} = \arg\{\min\{(Y - XH_{LS})^H (Y - XH_{LS})\}\} \quad (11)$$

Set

$$\frac{\partial\{(Y - XH_{LS})^H (Y - XH_{LS})\}}{\partial H_{LS}} \quad (12)$$

Consequently

$$\widehat{H_{LS}} = \frac{Y}{X} = \mathrm{H} + \frac{N}{X} \quad (13)$$

ignore the impact of noise, then

$$\widehat{H_{LS}} = \{H(0)H(1)\dots H(K-1)\}^T \quad (14)$$

Although, LS estimation algorithm is very simple, its performance is sensitive to the noise. The veracity of the estimation is reduced at the low SNR.

B. MMSE Channel Estimation

The MMSE estimate of the channel can be obtained as:

$$\widehat{H_{MMSE}} = F\widehat{h_{MMSE}} = F R_{KY} R_{YY}^{-1} Y \quad (15)$$

Where

$$R_{KY} = E[hY^H] = R_{KK} F^H X^H \quad (16)$$

$$R_{YY} = E[YY^H] = XFR_{KK}F^H X^H + \sigma_n^2 I_N \quad (17)$$

Then

$$\widehat{H_{MMSE}} = FR_{KK}F^H X^H (XFR_{KK}F^H X^H + \sigma_n^2 I_N)^{-1} Y \quad (18)$$

Where $R_{KY} = E[hY^H]$ is the channel autocorrelation matrix, σ_n^2 is the variance of noise,F=[W_k^{nk}]is the DFT matrix with $W_k^{nk} = \frac{1}{\sqrt{K}} e^{-j2\pi\frac{nk}{K}}$.

The MMSE channel estimation has well performance but higher complexity. It requires the inversion of a K×K matrix, which implies a high complexity when K is large. Notice that it requires the channel statistical properties including the channel autocorrelation matrix and noise variance which is always unknown in the practice systems.

C. EM Channel Estimation

By studying the equation (6) again, we can observe that this relation has two unknown parameters of w and h(i). Since v is supposed the white Gaussian noise with a zero average, estimating the maximum similarities of w and h_i unknown parameters, equals estimating their minimum squares. Estimating the maximum similarities of w and h_i can be obtained from the following cost function [18]:

$$\min_{w.h_i}\left\{\sum_{i=1}^{M}\left|r_i - \Gamma(w)Ah_i\right|^2\right\}, \quad \Gamma(w) = diag\left(1, e^{jw}, \dots, e^{jw(k-1)}\right), \quad A(n) = \left[e^{jwN_8}, A_1(n), \dots, e^{jwN_8} \cdot A_N(n)\right]_{k\times N.L} \quad (19)$$

Step 1 (estimating the carrier frequency offset):
the question of estimating maximum similarity of carrier frequency offset can be presented as follows:

$$\hat{\omega} = \arg_w^{\max} \sum_{i=1}^{M} \log\int p(r_i|w,h_i)p(h_i)dh_i \quad (20)$$

The EM algorithm estimates carrier frequency offset in two following steps:

Step E: Expectation:

$$Q\left(w \setminus w^{(k)}\right) = E\left\{\left[\sum_{i=1}^{M}\log p\left(r_i|w,h_i\right)\right] r_i, w^{(k)}\right\} \quad (21)$$

Step M: Maximation:

$$w^{(k+1)} = \arg_W^{\max} Q\left(w \setminus w^{(k)}\right) \quad (22)$$

In above relations, w(k) show the estimated carrier frequency offset in the k^{th} repetition of EM.

At the end "Equation 8" after a series of calculations becomes like the following:

$$w^{(k+1)} = \arg_w^{\max}\left(\sum_{i=1}^{M}\sum_{p=0}^{k-1}\mathrm{Re}\left[r_i^*(\rho)V_i^{(k)}(\rho).e^{jwp}\right]\right) \quad (23)$$

With the assumption of $S_i^{(k)}(p)=r_i^*(p)v_i^{(k)}(p)$, relation number 9 is rewritten like the following:

$$w^{(k+1)} = \arg_w^{\max}\ \mathrm{Re}\left(\sum\nolimits_{i=1}^{M} R_i^{(k)}\right) \quad (24)$$

The above relation can be calculated using FFT. Thus the proposed method has a suitable calculation speed.

Step 2 (estimating the coefficients of fading channel): after the estimation of rate of carrier frequency offset, it's time to estimate the maximum similarities of coefficients of fading channel h_i (i =1,...,M). Thus the estimation of maximum similarities of channel's coefficients can be obtained from the following relation:

$$\hat{h}_i = (A^H A)^{-1} A^H \Gamma^H(\hat{\omega}).r_i, i=1,\ldots,M \quad (25)$$

D. LMS Channel Estimation

There are different iterative algorithms which are used to improve channel estimation and various methods are obtained as initial estimation. Also estimation in each iteration can be used as side information and feed back to system to achieve better result in next iteration.

The necessary steps carried out in LMS channel estimation are given below:

1- Initially the channel is estimated by using LSE technique, giving $\widehat{H}_{LS}[n]$.

2- After finding the coefficients, the estimation of the channel becomes

$$\widehat{H}_{LMS}[n] = \widehat{W}^H[n]\,\widehat{H}_{LS}[n] \quad (26)$$

Where

$$\widehat{H}_{LS}[n] = [\,\widehat{H}_{LS}[n]\widehat{H}_{LS}[n-1]\ldots\widehat{H}_{LS}[n-1+M]] \quad (27)$$

Where M is LMS filter length.

3- Error at iteration n is given by

$$E[N] = \widehat{H}_{LS}[n] - \widehat{H}_{LMS}[n] \quad (28)$$

4- Co-efficient are updated according to

$$\widehat{W}[n+1] = \widehat{W}[n] + \mu\widehat{H}_{LS}[n]E^*[n] \quad (29)$$

Where μ is the adjustable step-size parameter.

5- Error given by weight vector is

$$\epsilon[n] = W[n] - \widehat{W}[n] \quad (30)$$

Mean Square Error (MSE) given by the LMS algorithm is defined as:

$$D[n]=Tr[K(n)] \quad (31)$$

Where $K(N) = E[\epsilon(n)\ \epsilon^*(n)]$

E[.] shows the expectation operator.

For real-time wireless communication, the value of the step-size parameter is taken very small.

For slow co-efficient updating with better performance $\mu = 0$ is used but for less computational time $\mu = 1$ is used, giving $\widehat{H}_{LMS}[n+1] = \widehat{H}_{LMS}[n]$

As illustrated in Fig. 4, LMS algorithm is applied to receiver and the channel which was estimated in each iteration is used for next iteration, additionally the output signal is fed to source signal for next channel estimation. Another important factor in channel estimation through this method is μ which influences on estimation and should be precisely chosen [19].

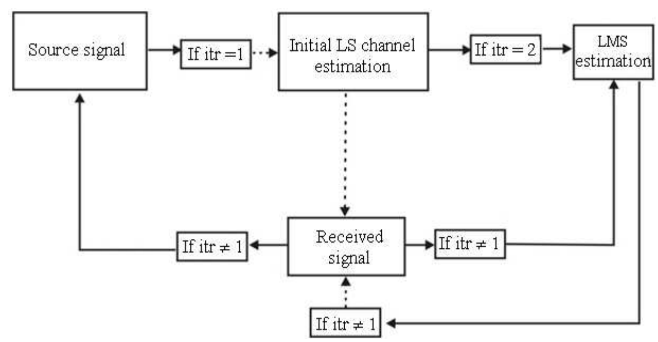

Fig. 4. Implementing LMS algorithm in receiver

In this method the coefficients of the vector H_n are obtained applying LMS recurrence as following:

$$\hat{H}_n=\hat{H}_{n-1}-\mu\times e\times X^* \quad (32)$$

Where
n = The iteration state
e = The signal error
μ = A coefficient between 0-1

VI. SIMULATION RESULTS

In this section, a MIMO-OFDM system with 2 transmitter antennas and 2 or 1 receiver ones is used for the simulation. The assumed system has a QPSK or BPSK modulation. The total number of subcarriers, N, is 64 or 32 and L is the tap of channel.

A. Simulation results for LS and MMSE algorithms

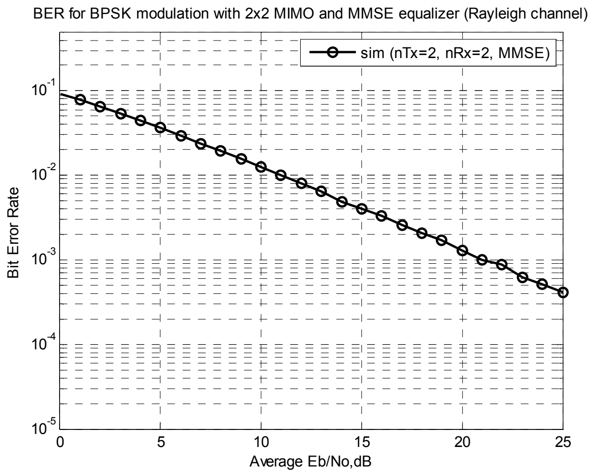

Fig. 5. BER for BPSK modulation with 2x2 MIMO and MMSE equalizer (Rayleigh channel)

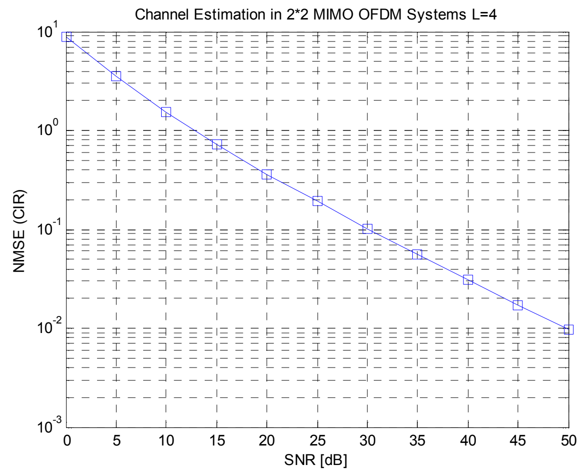

Fig . 8. Channel estimation in 2*2 MIMO-OFDM systems L=4 without synchronization

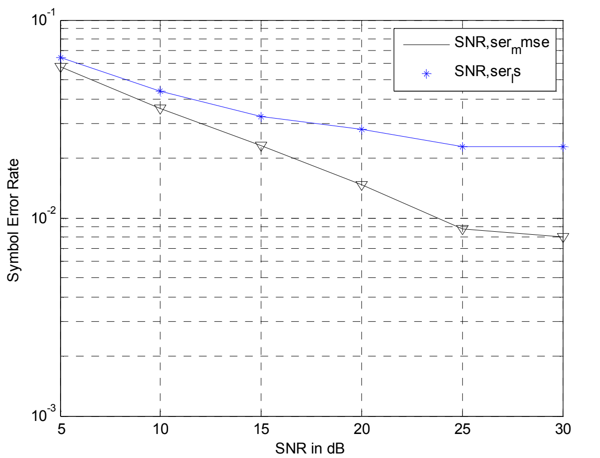

Fig. 6. Plot of SNR V/S SER for an OFDM system with MMSE/LS estimator based receivers

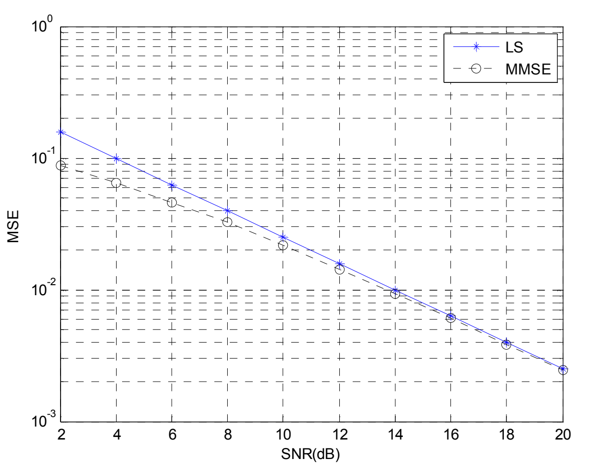

Fig. 7. Channel estimation in 2*2 MIMO-OFDM systems L=4 with LS and MMSE methods

B. Simulation results for EM and LMS algorithms

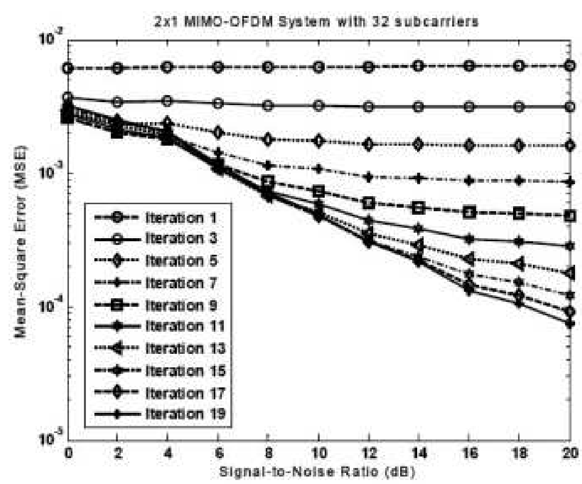

Fig . 9. Mean square error according to SNR for MIMO-OFDM system with 32 sub carriers, which uses 2 transmitter antennas and one receiver antenna with EM algorithm

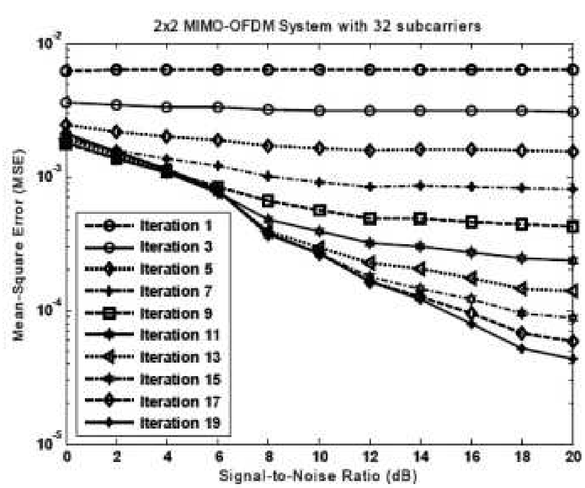

Fig. 10. Mean square error according to SNR for MIMO-OFDM system with 32 sub carriers, which uses 2 transmitter antennas and 2 receiver antennas with EM algorithm

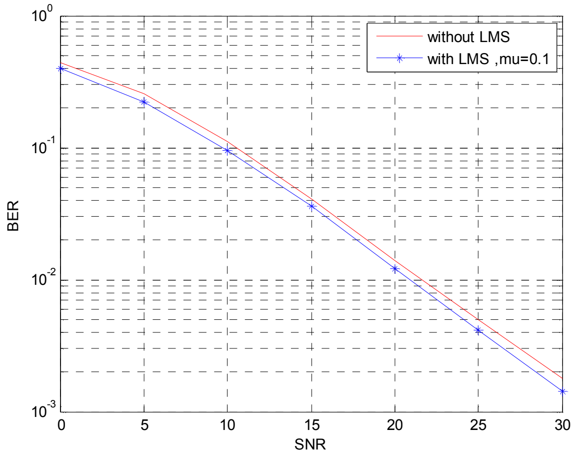

Fig. 11. Channel estimation in SISO-OFDM systems L=5 with synchronization and LMS algorithm μ=0. 1

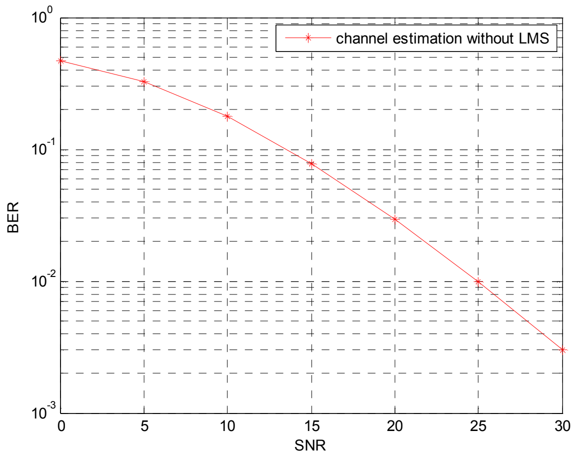

Fig. 12. Channel estimation in 2*2 MIMO-OFDM systems L=4 with synchronization

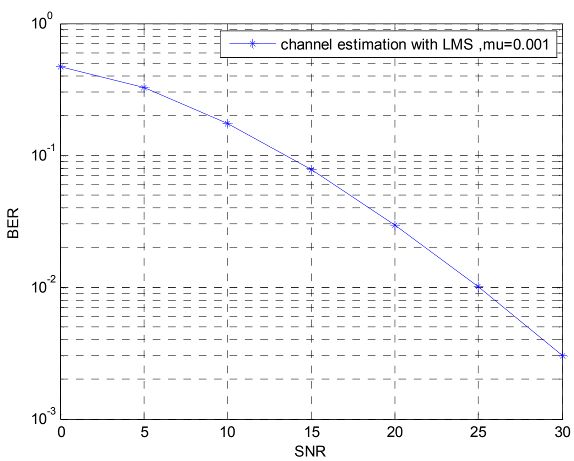

Fig. 13. Channel estimation in 2*2 MIMO-OFDM systems L=4 with synchronization and LMS algorithm μ=0.001

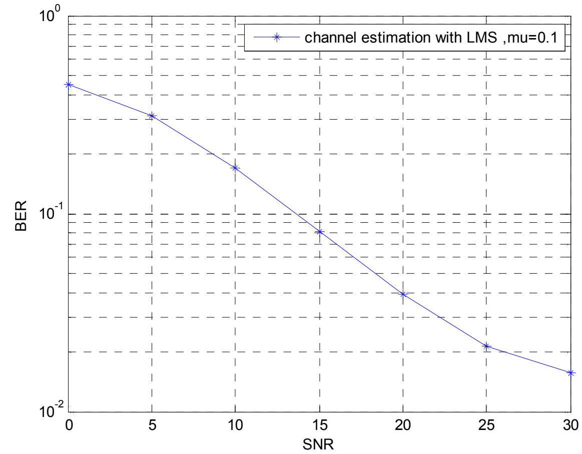

Fig. 14. Channel estimation in 2*2 MIMO-OFDM systems L=4 with synchronization and LMS algorithm μ=0. 1

VII. CONCLUSION

Estimation of channel coefficients and synchronization parameters are two main challenges in realization of MIMO-OFDM systems which are practical. In almost all published references till no, estimation of cannel coefficients is done with the assumption of total frequency synchronously of transmitter and receiver. The created frequency synchronously between transmitter and receiver, in practice, is always exposed to risk due to presence of factors such as Doppler phenomenon and phase noise. Therefore for exact estimation of fading channel status, it’s necessary to keep the created frequency synchronously between transmitter and receiver, uninterrupted.

The MMSE channel estimation has well performance but higher complexity than least-square(LS) channel estimation. The channel autocorrelation matrix and noise variance were estimated, which could be used in the MMSE estimator. The simulation results showed that the performance of MSE in the proposed method was close to the ideal MMSE estimator and better than the LS estimator. The SER performance was also improved effectively.

On the other hand, the presented EM algorithm estimates the carrier frequency offset and fading channel coefficients in two sequential steps, using the header sequence at the beginning of sent frames. The aforementioned algorithm is also extendable to different STC-OFDM systems. The LMS method is extremely dependant to parameter, μ. This method presents appropriate channel estimation through applying simple recurrence relations.

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