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Empirical Mode Decomposition based Adaptive Filtering for Orthogonal Frequency Division Multiplexing Channel Estimation

E. Hari Krishna[a], K. Sivani[b], K. Ashoka Reddy*[c]

[a] Electronics and CommunicationEngineering Department, University College of Engineering, Kakatiya University, Kothagudem, Telangana, India
[b] Electronics and Instrumentation Engineering Department, Kakatiya Institute of Technology & Science, Warangal, Telangana, India
[c] Electronics and Communication Engineering Department, Kakatiya Institute of Technology & Science, Warangal, Telangana, India

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ABSTRACT

This paper presents an empirical mode decomposition (EMD) based adaptive filter (AF) for channel estimation in OFDM system. In this method, length of channel impulse response (CIR) is first approximated using Akaike information criterion (AIC). Then, CIR is estimated using adaptive filter with EMD decomposed IMF of the received OFDM symbol. The correlation and kurtosis measures are used to select the useful IMF component from among available IMFs. Conventional AF uses random initial weight vector. The novelty of the proposed method is that it uses decimated version of one of the decomposed IMFs of received OFDM symbol as initial weight vector. This makes the proposed EMD based AF method converge to minimum mean square error (MMSE) in less number of iterations resulting in almost 50% saving of computations. The simulation studies in terms of bit error rate (BER) and mean square error (MSE) calculations established the efficacy of proposed method; and comparative studies under different modulation schemes and fading conditions revealed improved performance.

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1. INTRODUCTION

In present day scenario there has been a vast demand for high data rate wireless communication system and that demand is increasing continuously. On similar lines, the research is also progressing. One of the key technologies which started its birth in 3G communication and continuing its existence with modifications to till latest 5G wireless standards is orthogonal frequency division multiplexing (OFDM). The principal advantage OFDM is that it provides high resistance to inter symbol interference (ISI) caused by the high data rate systems over a non-linear frequency selective channel [1-3]. OFDM uses the basic PSK, QAM constellations, the modelling and simulation of QAM is presented in [4]. Vast applications of OFDM includes wireless LAN, Wi-Fi and WiMAX standards with a provision of high speed multimedia transmission. A MIMO antenna system and its suitability for long term evolution (LTE) LAN is illustrated in [5] with good simulation study. At early days of OFDM wireless transmission system, the channel estimation was performed using pilot symbols with different interpolation techniques [6-8]. Different pilot structures were developed, but these methods transmit training symbols in addition to the original data symbols, which reduces the efficiency of the system. The least squares (LS) estimator and minimum mean square error (MMSE) estimators were developed in the literature for OFDM channel estimation (CE) [9]. For performance enhancement of LS or MMSE estimator, discrete Fourier transform (DFT) based method was established, which leads to reduction of out of band noise [10]. The decision directed CE method [11] will not use pilot symbols, once the initial CE has been completed. In this technique, if any error occurs in initial CE stage, the same will be propagated to later stages, leading to reduced performance and further degradation takes

*Corresponding Author's Email: *kareddy.iitm@gmail.com* (K. Ashoka Reddy)

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place if the variation of channel coefficients are faster compared to OFDM symbol period.

A simple method for CE [12] was developed by adding low power training signals to the data symbols, while ensuring that the system date rate is not reduced. In general, for fast varying channels, the wireless channel will disturb the orthogonality property of OFDM scheme among the subcarriers which leads to inter channel interference (ICI). Expectation maximization [EM] [13] is an iterative method which finds the maximum likelihood of the channel impulse response (CIR) coefficients. A discrete partial Fourier transform (DPFT) based CE method was developed with compressive sensing of input signal [14]. Cimini et al. [15] discussed the issues related to all the established CE methods and open their challenges. Iterative CE based on Wiener filtering [16] requires computationally complex calculations in addition to knowing the channel characteristics at receiver side. The convergence analysis of least mean square (LMS) and sample matrix inversion (SMI) with its optimization capabilities for smart antenna systems was presented in [17]. The methods like an adaptive filter based OFDM CE [18], a blind CE using low order constellation [19], and low rank approximation OFDM for CE [20] made attempts to make the CE process more accurate. Comparative measure such as bit error rate (BER) was made as standard for evaluation of digital communication systems over different multipath fading channels [21]. In this work, a signal processing method using empirical mode decomposition (EMD) [22] based adaptive filtering (AF) for OFDM channel estimation is presented.

2. WIRELESS TRANSCIEVER MODEL USING OFDM

Here, in this work the modulation schemes such as BPSK, QPSK, 16 QAM, 64 QAM and 256 QAM were considered as per IEEE 802.11 ac™ standards [23]. As shown in Figure 1, wireless transceiver using OFDM modulates the input binary sequence $b_T(n)$ onto PSK/QAM mapper $[F(k)]$ and then performs IFFT on parallel converted data.

$$f(n)=\sum_{k=0}^{N-1}F(k)e^{j2\pi nk/N},n=0,1,2,.....\ N-1 \tag{1}$$

N is the number of sub carriers. Before transmission onto wireless medium, the cyclic prefix (CP) is added to ensure zero ISI $\left[f_{cp}(n)\right]$ and then it is converted to analog domain.

The received signal at OFDM receiver can be written as:

$$y_R(n)=f_{cp}(n)\otimes h_{CIR}(n,k)+g(n) \tag{2}$$

$\otimes$ symbol indicates the convolution; $g(n)$ is the additive white Gaussian noise (AWGN) with zero mean and unit variance; $h_{CIR}(n)$ is the wireless multipath fading time varying CIR to be estimated and it is modeled as:

$$h_{CIR}(n,k)=\sum_i \alpha_i(n)w(n-k_i) \tag{3}$$

k_i is the delay incurred during the i^{th} path component, $\alpha_i(n)$ corresponding attenuation and $w(n)$ impulse response coefficient in the same i^{th} path. After removing the CP, the processed OFDM symbol is passed through FFT block as given below.

$$Y_R(k)=F_{cp}(k)H_{CIR}(k)+G(k) \tag{4}$$

where, $Y_R(k), F_{cp}(k), H_{CIR}(k)$ and $G(k)$ are N-point FFT of received OFDM symbol ($y_R(n)$), transmitted OFDM symbol ($f_{cp}(n)$), the channel CIR ($h_{CIR}(n)$) and Gaussian noise ($g(n)$).

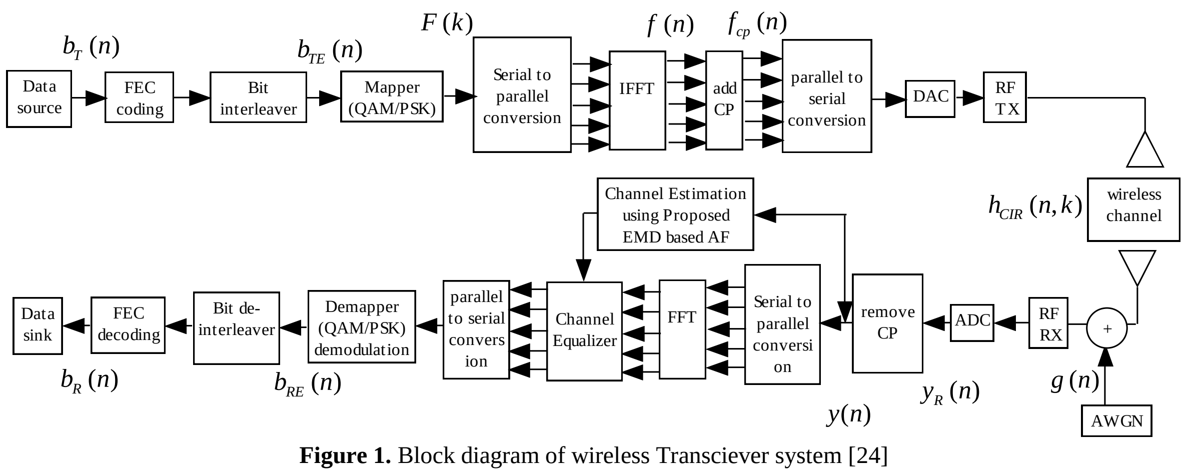

Figure 1. Block diagram of wireless Transciever system [24]

To recover the original transmitted binary sequence, the time varying CIR is to be estimated properly with use of some novel signal processing method.

3. EMD BASED ADAPTIVE FILTER FOR ESTIMATION OF CIR

3. 1. Empirical Mode Decomposition A simple and efficient EMD method proposed by N. E. Huang is an adaptive time-frequency analysis method [22].

It decomposes a given signal *f(n)* into a set of AM–FM components, called intrinsic mode functions (IMFs). The resulting L modes $I_l(n)$ and a residual term are expressed as:

$$f(n) = \sum_{l=1}^{L} I_l(n) + r(n) \tag{5}$$

The various steps of EMD algorithm are summarized in the flowchart shown in Figure 2.

3. 2. Adaptive Filtering AF uses a feedback mechanism to self-adjust the impulse response coefficients by means of an optimizing algorithm [25]. The Least Mean Square (LMS) algorithm, first developed by Widrow and Hoff, is widely used due to its computational simplicity. The LMS algorithm is described by the following iteration equations:

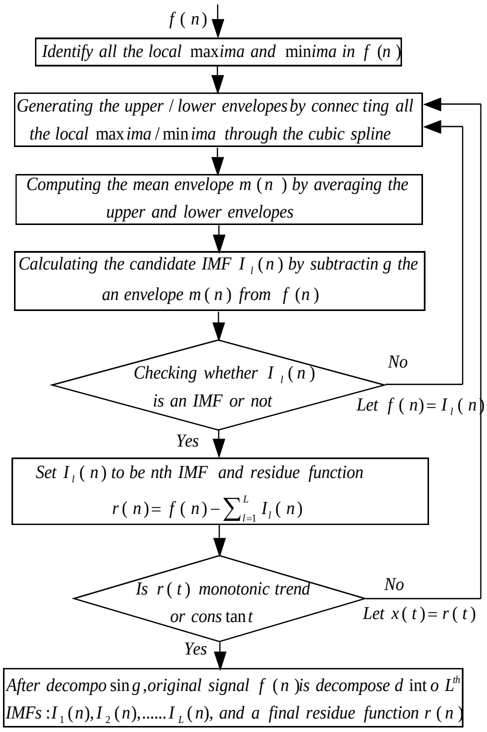

Figure 2. Flowchart indicating processing steps of EMD

$$y(n) = \sum_{i=0}^{N-1} W_i(n) X(n-i) = W^T(n) X(n) \tag{6}$$

$$y(n) = \sum_{i=0}^{N-1} W_i(n) X(n-i) \tag{7}$$

$$e(n) = d(n) - y(n) \tag{8}$$

$$W(n+1) = W(n) + \mu\, e(n) X(n) \tag{9}$$

where *y(n)* is the output of AF, $W(n)=[W_0(n), W_1(n, \ldots\ldots W_{N-1}(n)]^T$ the weight coefficient vector of AF, $X(n)=[X(n), X(n-1), \ldots\ldots X(n-N+1)]^T$ the input vector, n the time index, M the order of filter, *d(n)* the desired output, *e(n)* the error signal, and μ the step-size; superscript T denotes Hermitian transposition.

3. 3. EMD based Adaptive Filtering for CE A signal processing method with less number of computations is always desirable in real time applications. In this direction, a novel empirical mode decomposition (EMD) based adaptive filtering (AF) is developed here for OFDM channel estimation (CE). Different multipath fading channels are considered. In general, conventional AF uses random initial weight vector, whereas the proposed EMD based AF uses the initial weight vector derived from selected decimated decomposed intrinsic mode function (IMF) of received OFDM symbol, which forms the basis for the novelty of the proposed method. Because of attractive properties of EMD, i.e. the basis function of iterative decomposition process derived from the received OFDM symbol, the process of adaptation and consequently the estimation of CIR becomes simple.

The proposed EMD based adaptive filtering is shown in Figure 3. The received OFDM symbol $y(n)$ (i.e. after removal of CP) is given as input to two blocks, one is length estimator using Akaike information criterion (AIC) and another is EMD block. AIC is a way of selecting the model from different set of models [26, 27]. The chosen model is the one that minimizes the Kullback-Leibler distance between the model and the truth. It is based on information theory, but a heuristic way to think about it is as a criterion that seeks a model that has a good fit to the truth but few parameters. It is defined in maximum likelihood sense as:

$$AIC(M) = 2K - 2\ln\left(\ell\left(\hat{\theta}/y\right)\right) \tag{10}$$

where K is the number of free parameters in the model. $\ln\left(\ell\left(\hat{\theta}/y\right)\right)$ is the log likelihood function.

$$AIC(M) = 2K + \ln(RSS) \tag{11}$$

RSS is residual sum of squares [22]. This minimization is in least square sense. AIC is calculated for different values of M, the M for which AIC is minimum is taken as channel length.

The EMD block decomposes the received OFDM symbol into different (AM-FM) L number of intrinsic mode functions (IMF); the number of IMFs depends on the maxima and minima of the resulting signal. The beauty of the EMD algorithm is that it derives the basis function required for decomposition from the signal itself.

$$y(n)=\sum_{l=1}^{L} I_l(n)+r(n) \tag{12}$$

To select important IMF from among the available IMFs, the Pearson correlation coefficient is calculated between received OFDM symbol and all individual IMFs and kurtosis is calculated for individual IMFs;

$$ku=\frac{E(x-\mu)^4}{\sigma^4}-3 \tag{13}$$

where μ is the mean of x, σ is the standard deviation of x. Kurtosis is considered for estimation of randomness in the individual IMF's. If some perioidic component is present in the IMFs, then the Kurtosis value will be closer to zero, otherwise the vaue will be higher. The fact here is that, at OFDM transmitter side the individual bits are multipled with periodic subcarriers, which motivated us to use kurtosis in selection of IMFs.

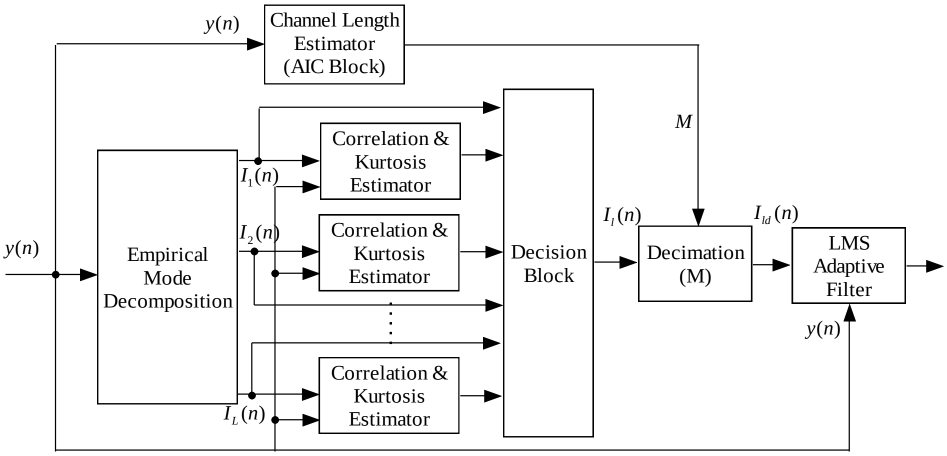

Figure 3. Block diagram of proposed EMD based adaptive filtering

Based on this high degree of correlation and best possible kurtosis values, one of the IMFs is selected. Selected IMF $I_l(n)$ is decimated to a level which is equal to the length of the CIR as estimated by the AIC.

$$I_{ld}(n)=I_l(nM)=\sum_{k=-\infty}^{\infty} h_{aaf}(k)\, I_l(n-k) \tag{14}$$

Here, $h_{aaf}(k)$ is anti-aliasing low pass filter; Now this decimated IMF i.e., $I_{ld}(n)$ serves as initial impulse response for the AF. This makes the proposed method different from the conventional AF, which uses random initial weight vector. Finally, the proposed AF optimizes the error performance surface in terms of minimizing the MSE. The converged weight vector of this AF, after good number of iterations, will be the best estimate of CIR.

Conventional AF uses random initial weight vector. The novelty of the proposed method lies in the fact that it uses decimated version of one of the decomposed IMFs of received OFDM symbol as initial weight vector. The selection of useful IMF component is based on correlation and kurtosis measures. Hence, it is expected that the proposed EMD based AF method converges to minimum mean square error (MMSE) in less number of iterations.

4. RESULTS AND DISCUSSION

The channel impulse response (CIR) estimation will be performed from the received OFDM symbol. In fact, the wireless medium with non-linear time varying characteristics modifies the transmitted symbol in a random fashion under severe fading conditions. The received OFDM symbol represents the variations in CIR which is to be estimated by using a suitable signal processing algorithm. The EMD, in fact, decomposes the signal into a set of AM-FM components called intrinsic mode functions (IMFs). These IMFs represent the varying frequency components present in the unknown signal. This motivated us to use EMD to extract the inherent components present in the received OFDM symbol for use in the proposed EMD based AF for CE.

To evaluate the performance of the proposed EMD based adaptive filtering, the following simulation parameters with Rayleigh and Rician fading channel are considered given below in Table 1.

The received symbol is shown in Figure 4. Received OFDM symbol passes through EMD block, and their corresponding IMF components are shown in Figure 5. Pearson correlation between decomposed IMF with that of received OFDM symbol and kurtosis of decomposed IMF is evaluated and tabulated as shown in Table 2. The first IMF component ($I_1(n)$) is having higher correlation than other IMFs. Kurtosis value is used when two IMF's have closer correlation value, then the IMF with lower value of kurtosis is considered for final selection. In addition to the above process, the received OFDM after being passed through AIC block, resulted in the length of CIR estimated as 36. Now, the $I_1(n)$ is decimated to the length of 36, as evaluated by AIC.

Length of IMF is 256, and the length of CIR estimated as per AIC is 36. Now the selected IMF component is resampled by a factor (9/64). The decimated impulse response is shown in Figure 6, assumed CIR for the above simulation is shown in Figure 7, and the estimated CIR after adaptive filtering is shown in Figure 8, which will be used for equalization.

TABLE 1. Simulation parameters considered for validation of proposed work

Simulation Parameters	Considered values
Carrier Frequency	5 GHz
System bandwidth	80 MHz
Sub carrier spacing	6.83 kHz
Modulation	BPSK, QPSK, 16 QAM, 64 QAM and 256 QAM
N-point IFFT	256 point IFFT
Length of Cyclic Prefix	16 samples
Doppler Frequency	100 Hz, 500 Hz and 1000Hz

TABLE 2. Calculated correlation and Kurtosis values

	Pearson Correlation	Kurtosis
$I_1(n)$	0.7760	1.9511
$I_2(n)$	0.3188	3.2426
$I_3(n)$	0.2833	4.3859
$I_4(n)$	0.1871	4.9890
$I_5(n)$	0.0586	5.7068
$I_6(n)$	0.0149	3.4342
r(n)	0.0119	7.8227

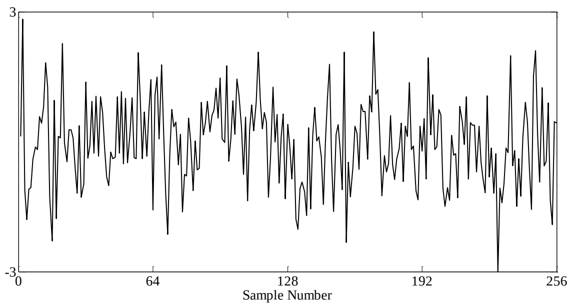

Figure 4. Received OFDM symbol of the transnsmitted symbol shown in Figure 4

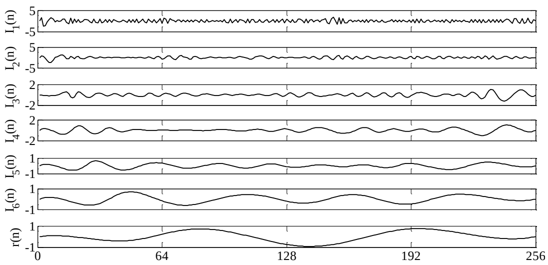

Figure 5. Decomposed IMF components of Received OFDM symbol

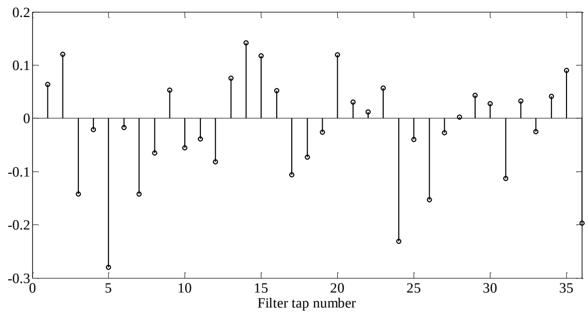

Figure 6. Initial impulse response of adaptive filer before adaptation process

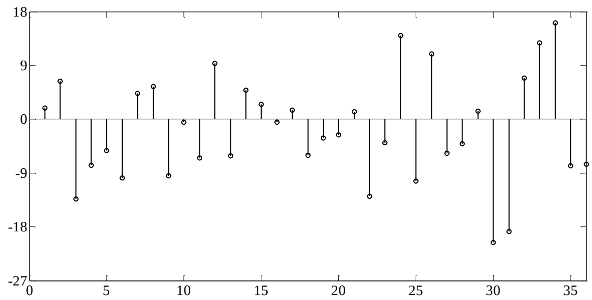

Figure 7. Assumed CIR of wireless channel

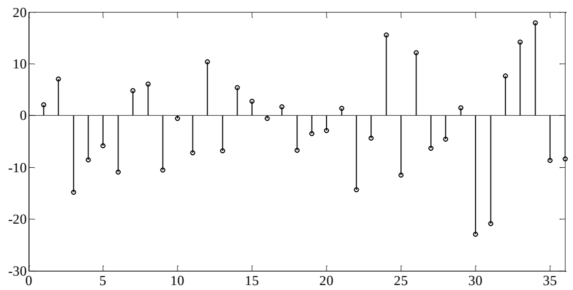

Figure 8. Final Estimated CIR of wireless channel

It can be clearly seen from the figure that the estimated CIR is closely following the trend of assumed CIR. For the sake of comparison, the convergence analysis of proposed AF is compared with conventional AF.

It can be clearly seen from Figure 9 that the proposed EMD based AF takes less number of iterations for a typical channel conditions. The improved convergence analysis is certainly due to the good initial weight vector for impulse response provided by the EMD process. Nearly only half number of iterations are required here for proposed EMD based AF as compared to normal AF.

Then, same adaptation convergence analysis is evaluated for different cases of channel using conventional adaptive filtering and is shown in Figure 10.

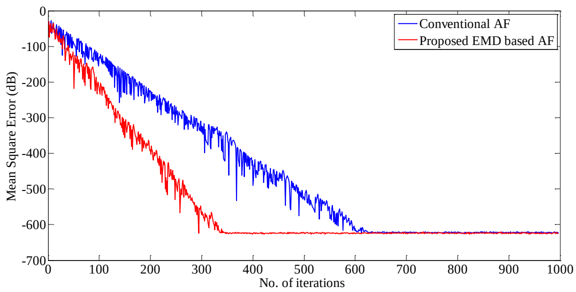

Figure 9. Convergance analysis for channel estimation: Conventional LMS AF and proposed EMD based AF for one typical case

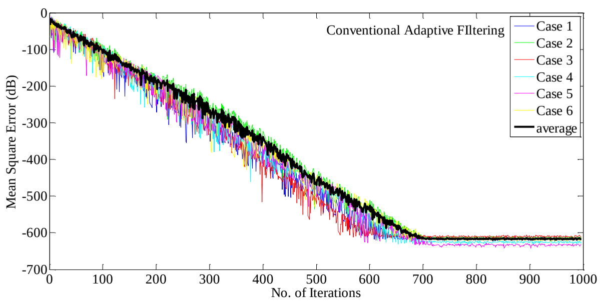

Figure 10. Convergance analysis for channel estimation: Comparison of conventional AF for 10 different cases of channel

In the same plot, average of all the cases is also shown, indicating around 700 iterations to converge. The same is repeated using proposed EMD based AF for all cases as shown in Figure 11. It can be clearly observed that the proposed EMD based AF takes almost half number of iterations as that of conventional AF to converge. For the sake of clarity, average of all cases using conventional AF and the proposed EMD based AF are shown in Figure 12. It has been noticed that the proposed EMD based AF is taking 325±25 iterations, whereas the normal AF is taking 610±25 number of iterations to reach MMSE point.

Most of the channel estimation methods are of the form of modified versions of least squares estimation (LSE) and minimum mean square error (MMSE). Hence, as the first step, the proposed EMD based adaptive filtering is compared with different forms of LMS algorithms in addition to well-known SVD based method for CE. In general, conventional adaptive filter is computationally simple compared to recursive least squares (RLS) algorithm. In literature, there are different variants of LMS algorithm [18, 28] with change in step size variations to improve the convergence analysis, which resulted in increased computations but better than RLS. The proposed work, resulted in improved convergence analysis as shown in Figure 13, without incorporating step size variations.

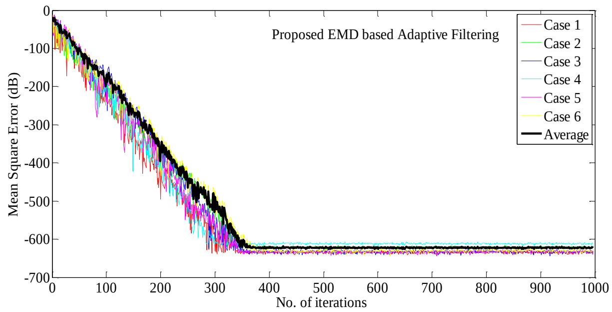

Figure 11. Convergance analysis for channel estimation: Comparison of proposed EMD based AF for 10 different cases of channel

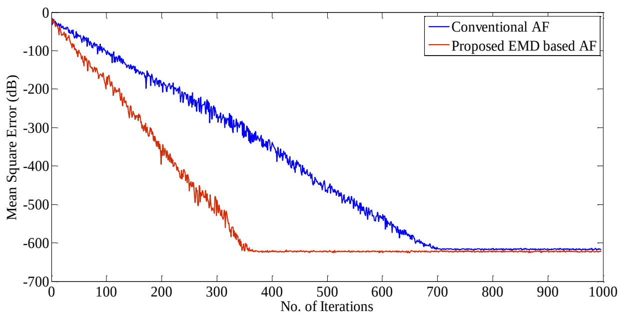

Figure 12. Convergance analysis for channel estimation: Comparison of conventional AF with proposed EMD based AF for average of 10 different cases of channel

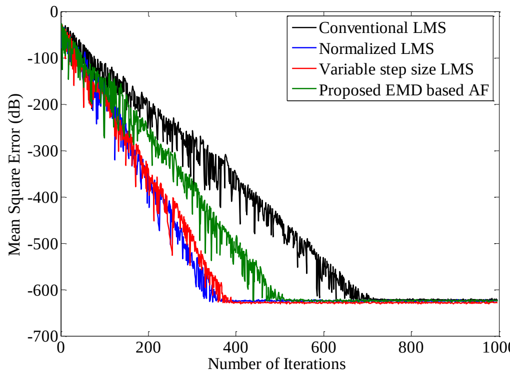

Figure 13. Convergence analysis of proposed EMD based AF with variants of LMS algorithms

The variants of LMS algorithms showed improved convergence at the cost of computations. Whereas in the proposed work improved convergence analysis is achieved with reduced computations.

This improvement is certainly due to the use of EMD generated initial weight vector for adaptive filter. The bit error rate (BER) analysis is performed for different modulation schemes BPSK, QPSK, 64-QAM and 256-QAM. The results are portrayed in Figure 14 through Figure 17. From Figure 14, under BPSK modulation it can be observed that for low values of SNR, the BER are closer but for higher values of SNR there is a clear separation. Overall there is an improvement of 3 to 5 dB in proposed EMD based AF as compared to conventional AF for BPSK constellation. Figure 15, for QPSK, the scenario is different that for low values of SNR there is a distinction, but for high values of SNR, the BER observations are close. For Figures 16 and 17 the performance improvement is unique for all values of SNR. Simulations have shown an average improvement of 3 dB in BER performance for proposed EMD based AF as compared to conventional AF. It can also be seen from these figures that the proposed EMD based AF has shown clear improvement in performance compared to the other methods for all modulation schemes as per IEEE 802.11 ac™ standards [26].

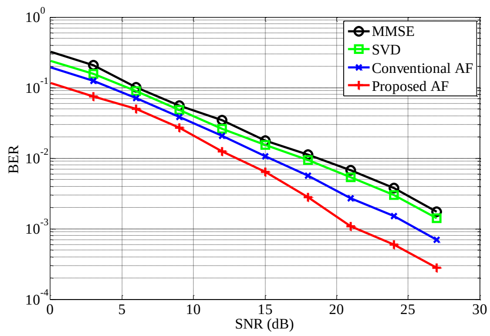

Figure 14. BER plot of OFDM transceiver using BPSK modulation Scheme

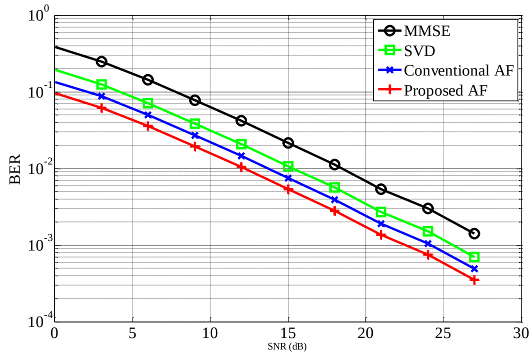

Figure 15. BER plot of OFDM transceiver using QPSK modulation Scheme

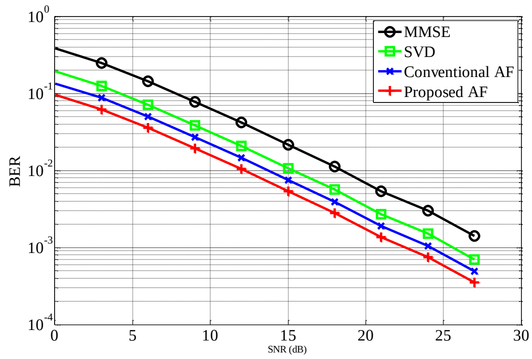

Figure 16. BER plot of OFDM transceiver using 64 QAM modulation Scheme

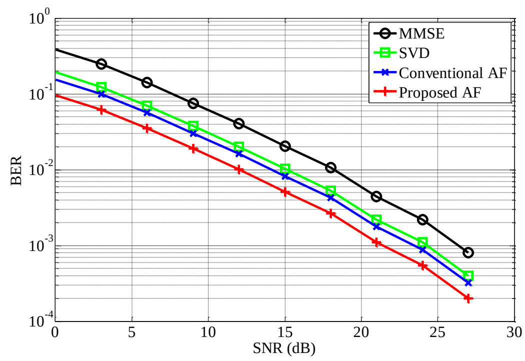

Figure 17. BER plot of OFDM transceiver using 256 QAM modulation Scheme

Similarly, the mean square error (MSE) in CE is evaluated and portrayed in Figure 18. There is a clear improvement in the values of MSE, which again can be devoted the use of EMD derived initial weight vector to the AF. The BER and MSE analysis establishes the efficacy of the proposed EMD based AF method.

In addition, to further evaluate performance of the proposed EMD based AF method, different channels such as selective fading, flat fading, slow and fast fading channel are considered. SNR improvement achievable in different methods BPSK, QPSK, 64 QAM and 256 QAM at a BER of 10^{-2} for the proposed method compared to conventional AF method are depicted in Table 3.

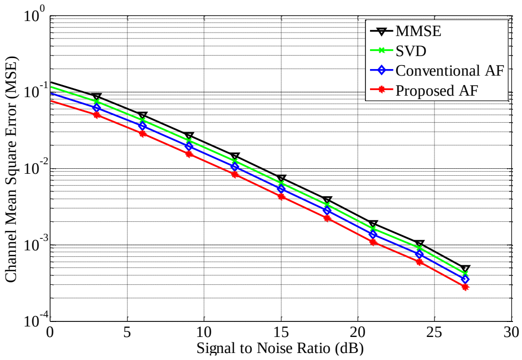

Figure 18. Channel MSE Comparison

TABLE 3. SNR improvement values of different methods at a BER of 10^{-2} for the proposed method as compared to Conventional AF method

Modulation/Fading	Flat Fading: Rayleigh fading	Flat Fading: Rician fading	Frequency Selective Fading	Slow fading	Fast fading
BPSK	3 dB	2dB	2 dB	3 dB	2 dB
QPSK	5 dB	4 dB	4 dB	6 dB	5 dB
64 QAM	7 dB	5 dB	6 dB	4 dB	3 dB
256 QAM	4 dB	3 dB	2 dB	4 dB	3 dB

5. CONCLUSION

The estimation of channel impulse response (CIR) under multipath fading wireless OFDM transceiver is essential requirement for error free reception. In this direction, a novel empirical mode decomposition (EMD) based adaptive filtering (AF) was presented in this paper for OFDM CE under Rayleigh and Rician fading channels. In general, conventional AF uses random initial weight vector. The novelty of the proposed method is that it uses a decimated selective intrinsic mode function (IMF) of received OFDM symbol as the initial weight vector. This made the process of adaptation and consequently the estimation of CIR simple. Improved convergence analysis was achieved with reduced computations. The Bit error rate (BER) and mean square error (MSE) simulation studies established the efficacy of proposed method; and comparative studies under different modulation schemes and fading conditions revealed improved performance. The proposed method has shown an average improvement of 3-5 dB over conventional AF method and 6-8 dB over SVD based method.

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Empirical Mode Decomposition based Adaptive Filtering for Orthogonal Frequency Division Multiplexing Channel Estimation

E. Hari Krishna[a], K. Sivani[b], K. Ashoka Reddy[c]

[a] *Electronics and CommunicationEngineering Department, University College of Engineering, Kakatiya University, Kothagudem, Telangana, India*
[b] *Electronics and Instrumentation Engineering Department, Kakatiya Institute of Technology & Science, Warangal, Telangana, India*
[c] *Electronics and Communication Engineering Department, Kakatiya Institute of Technology & Science, Warangal, Telangana, India*

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چکیده

این مقاله یک فیلتر انطباق مبتنی بر تجزیه حالت تجربی (EMD) را برای تخمین کانال در سیستم OFDM ارائه می دهد. در این روش، طول پاسخ ضربان کانال (CIR) ابتدا با استفاده از معیار اطلاعات Akaike (AIC) تقریب زده می‌شود. سپس CIR با استفاده از فیلتر انطباق با EMD تجزیه شده از IMF از نماد OFDM دریافت شده تخمین زده می‌شود. برای ارزیابی مولفه‌های IMF از میان IMFهای موجود استفاده از اقدامات همبستگی و kurtosis استفاده می شود. AF متعارف از بردار وزن اولیه تصادفی استفاده می کند. نوآوری روش پیشنهادی این است که از نسخه خراب شده یکی از IMFهای تجزیه شده از نماد OFDM دریافت شده به عنوان بردار وزن اولیه استفاده می‌کند. این باعث می شود روش AF مبتنی بر EMD با حداقل تعداد خطای مربع (MMSE) در تعداد کمی از تکرارها منجر به صرفه جویی در حدود ٪۵۰ زمان محاسبه شود. مطالعات شبیه‌سازی با استفاده از محاسبات خطای بیت (BER) و میانگین مربعات خطا (MSE)، اثربخشی روش پیشنهاد شده را تأیید کرد و مطالعات تطبیقی تحت برنامه های مختلف مدولاسیون و شرایط محو شوندگی عملکرد را بهبود بخشید.

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