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Channel Estimation and Prediction of Inter Carrier Interference Cancellation for Adaptive OFDM

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Abstract: Channel estimation and prediction algorithms are developed and evaluated for use in broadband adaptive OFDM has recently been used widely in wireless communication systems. OFDM is very effective in combating inter-symbol interference and can achieve high data rate in frequency selective channel. For OFDM communication systems, the frequency offsets in mobile radio channels distort the orthogonality between subcarriers resulting in Inter Carrier Interference (ICI). ICI causes power leakage among subcarriers thus degrading the system performance. A well-known problem of OFDM is its sensitivity to frequency offset between the transmitted and received carrier frequencies. There are two deleterious effects caused by frequency offset one is the reduction of signal amplitude in the output of the filters matched to each of the carriers and the second is introduction of ICI from the other carriers. We present and evaluate a state-space realization of such an adaptation law, with computational complexity of the order of the square of the number of parallel tracked pilot subcarriers. In an adaptive OFDM system, prediction of the channel power a few milliseconds ahead will also be required. Frequency-domain channel estimates can be transformed to the time domain, and used as regressors in channel predictors based on linear regression. We also make a preliminary evaluation of the direct use of complex channel prediction in the frequency domain for channel power prediction.

Keywords: Orthogonal frequency Division Multiplexing (OFDM); Inter Carrier Interference(ICI); Carrier to Interference Power Ratio; Self Cancellation(SC);Carrier Frequency Offset (CFO).

1. INTRODUCTION

Adaptive transmission can radically improve the spectral efficiency when multiple users have independently fading links. The users may then share the available bandwidth, and resources are allocated to terminals who need them best and/or can utilize them best via link adaptation. This paper focuses on the downlink of an adaptive OFDM system that employs Frequency Division Duplex (FDD). OFDM is emerging as the preferred modulation scheme in modern high data rate wireless communication systems. OFDM has been adopted in the European digital audio and video broadcast radio system and is being investigated for broadband indoor wireless communications. Standards such as HIPERLAN2 (High Performance Local Area Network) and IEEE 802.11a and IEEE 802.11b have emerged to support IP-based services. Such systems are based on OFDM and are designed to operate in the 5 GHz band. OFDM is a special case of multi-carrier modulation.

Multi-carrier modulation is the concept of splitting a signal into a number of signals, modulating each of these new signals to several frequency channels, and combining the data received on the multiple channels at the receiver. In OFDM, the multiple frequency channels, known as sub-carriers, are orthogonal to each other. One of the principal advantages of OFDM is its utility for transmission at very nearly optimum performance in unequalized channels and in multipath channels.

In this paper, the effects of ICI have been analyzed and three solutions to combat ICI have been presented. The first method is a self-cancellation scheme[1], in which redundant data is transmitted onto adjacent sub-carriers such that the ICI between adjacent sub-carriers cancels out at the receiver. The present paper outlines research aimed at meeting the above requirements. We start from a combined pilot-aided and decision directed channel estimator in the form of a Kalman state estimator. It provides minimal mean square estimation errors (MMSE estimates) at the pilot locations. The main computational complexity of this Kalman algorithm resides in the required update of a Riccati difference equation. That update may be avoided by using the recently developed General Constant Gain (GCG) class of adaptation laws [4], which are well suited to the present problem. They provide performance close to hat of the Kalman algorithm, but with much lower computational complexity. The works presented in this paper concentrate on a quantitative ICI power analysis of the ICI cancellation scheme, which has not been studied previously. The average carrier-tointerference power ratio (CIR) is used as the ICI level indicator, and a theoretical CIR expression is derived for the proposed scheme.

II. SYSTEM MODEL

The Fig. 1 describes a simple idealized OFDM system model suitable for a time-invariant AWGN channel.

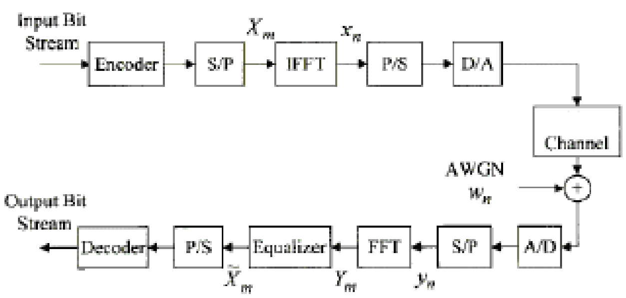

Fig. 1.Idealized OFDM System

In an OFDM system, at the transmitter part, a high data-rate input bit stream b[n] is converted into N parallel bit streams each with symbol period Ts through a serial-toparallel buffer. When the parallel symbol streams are generated, each stream would be modulated and carried over at different center frequencies. The sub-carriers are spaced by 1/NTs in frequency, thus they are orthogonal over the interval Model (0, Ts). Then, the N symbols are mapped to bins of an Inverse Fast Fourier Transform (IFFT). These IFFT [10] bins correspond to the orthogonal sub-carriers in the OFDM symbol. Therefore, the OFDM symbol can be expressed as

$$X(n) = \frac{1}{N}\sum_{m=0}^{N-1} X_m{}^{j\frac{2\pi nm}{N}} \qquad (1)$$

where the Xm are the base band symbols on each sub carrier. Then, the X (i) points are converted into a time domain sequence x(i) via an IFFT operation and a parallel to serial conversion. The digital-to-analog (D/A) converter then creates an analog time-domain signal which is transmitted through the channel. At the receiver, the signal is converted back to a discrete N point sequence y(n) , corresponding to each subcarrier. This discrete signal is demodulated using an N-point Fast Fourier Transform (FFT) operation at the receiver. The demodulated symbol stream is given by

$$Y(m) = \sum_{n=0}^{N-1} y(n)e^{\frac{-j2\pi nm}{N}} + W(m)k \qquad (2)$$

where w (m) corresponds to the FFT of the samples of w (n), which is the time invariant Additive White Gaussian Noise (AWGN) introduced in the channel Then, the signal is down converted and transformed into a digital sequence after it passes an Analog-to-Digital Converter (ADC). The following step is to pass the remaining TD samples through a parallel-to-serial converter and to compute N-point FFT.

The resulting Yi complex points are the complex baseband representation of the N modulated sub carriers. As the broadband channel has been decomposed into N parallel sub channels, each sub channel needs an equalizer (usually a 1-tap equalizer) in order to compensate the gain and phase introduced by the channel at the sub channel�fs frequency. These blocks are called Frequency Domain Equalizers (FEQ).Therefore the groups of bits that has been placed on the subcarriers at the transmitter are recovered at the receiver as well as the high data-rate sequence.

III. ICI SELF CANCELLATION SCHEME

A. Self-Cancellation

ICI self-cancellation is a scheme that was introduced by Yuping Zhao and Sven-Gustav Haggman[1] in to combat and suppress ICI in OFDM. The main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self- cancellation.

1) Cancellation Method

In self cancellation scheme the main idea is to modulate the input data symbol on to a group of sub carriers with predefined self coefficients such that the generated ICI signals within the group cancel each other. The data pair (X ,-X) is modulated on to two adjacent subcarriers (*l*,*l* +1). The ICI signals generated by the subcarrier l will be cancelled out significantly by the ICI generated by the subcarrier l +1.The signal data redundancy makes it possible to improve the system performance at the receiver side. In considering a further reduction of ICI, the ICI cancellation demodulation scheme is used. In this scheme, signal at the (k +1) subcarrier is multiplied by "-1" and then added to the one at the k subcarrier.

Then, the resulting data sequence is used for making symbol decision.

2). ICI Cancelling Modulation

The ICI self-cancellation scheme requires that the transmitted signals be constrained such that X(1) = -X(0), X(3) = -X(2),......., X(N -1) = -X(N -2) using this assignment of transmitted symbols allows the received signal on subcarriers k and k +1 to be written as

$$Y'(k) = \sum_{l=0,2,4,6}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \quad (3)$$

$$Y'(k+1) = \sum_{l=0,2,4,6}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_{k+1} \quad (4)$$

and the ICI coefficient S' reffered as

$$S'(l-k) = S(l-k) - S(l+1-k) \quad (5)$$

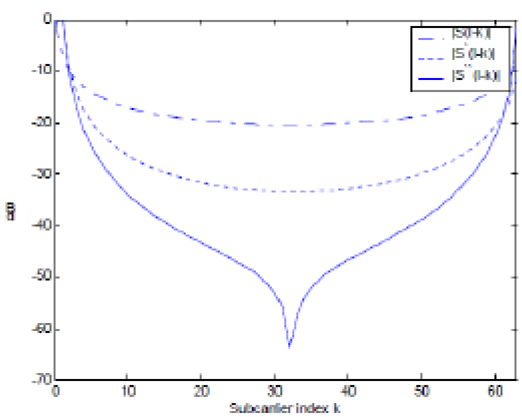

Fig 2: Comparison of |S(l-k)|, |S`(l-k)|, and |S``(l-k)| for N = 64 and ε = 0.4

Fig. 2 shows a comparison between |S'(l-k)| and |S(l-k)| on a logarithmic scale. It is seen that |S'(l-k)| << |S(l-k)| for most of the l-k values. Hence, the ICI components are much

smaller than they are in |S(l-k)|. Also, the total number of interference signals is halved since only the even subcarriers are involved in the summation.

3). ICI Canceling Demodulation

ICI modulation introduces redundancy in the received signal since each pair of subcarriers transmit only one data symbol. This redundancy can be exploited to improve the system power performance, while it surely decreases the bandwidth efficiency. To take advantage of this redundancy, received signal at the (k + 1) th subcarrier, where k is even, is subtracted from the k th subcarrier.

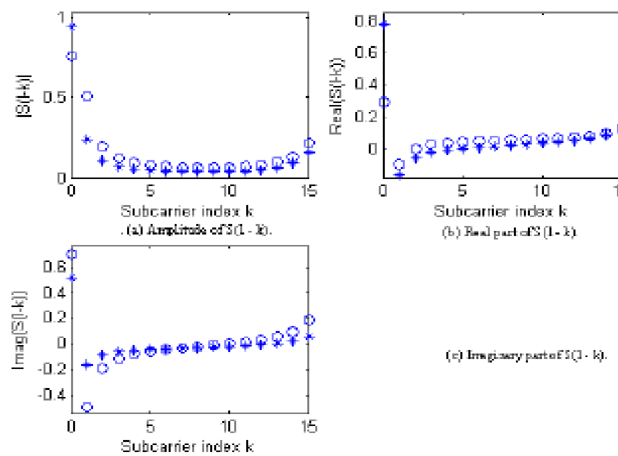

Fig. 3 An example of S(l - k) for N = 16; l = 0. (a) Amplitude of S(l - k). (b) Real part of S(l - k). (c) Imaginary part of S(l - k).

This is expressed mathematically as

$$Y''(k) = Y'(k) - Y'(k+1) =$$

$$\sum_{l=0}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_k + 1 \quad (6)$$

Subsequently, the ICI coefficients for this received signal becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \quad (7)$$

When compared to the two previous ICI coefficients S(1-k) for the standard OFDM system and S(1-k) for the ICI canceling modulation, S "(1- k) has the smallest ICI coefficients, for the majority of l-k values, followed by S(1-k) and S(1-k) .The combined modulation and demodulation method is called the ICI self-cancellation scheme. The reduction of the ICI signal levels in the ICI selfcancellation scheme leads to a higher CIR. The theoretical CIR can be derived as

$$CIR = \frac{|-S(-1) + 2S(0) - S(1)|^2}{\sum_{l=2,4,6}^{N-1} |-S(l-1) + 2S(l) - S(l+1)|^2} \quad (8)$$

As mentioned above, the redundancy in this scheme reduces the bandwidth efficiency by half. This could be compensated by transmitting signals of larger alphabet size. Using the theoretical results for the improvement of the CIR should increase the power efficiency in the system and gives better results for the BER. Hence, there is a tradeoff between bandwidth and power tradeoff in the ICI self-cancellation scheme.

ICI self-cancellation scheme can be combined with error correction coding. Such a system is robust to both AWGN and ICI, however, the bandwidth efficiency is reduced. The proposed scheme provides significant CIR improvement, which has been studied theoretically and by simulations. The scheme also works well in a multipath radio channel with Doppler frequency spread. Under the condition of the same bandwidth efficiency and larger frequency offsets, the proposed OFDM system using the ICI self-cancellation scheme performs much better than standard OFDM systems. In addition, since no channel equalization is needed for reducing ICI, the element without increasing system complexity.

The comparison of the theoretical CIR curve of the ICI self-cancellation scheme, calculated by, and the CIR of a standard OFDM system is calculated. As expected, the CIR is greatly improved using the ICI selfcancellation scheme. The improvement can be greater than 15 dB for $0 < \varepsilon < 0.5$.

IV. MAXIMUM LIKELIHOOD ESTIMATION

The second method for frequency offset correction in OFDM systems was suggested by Moose. In this approach, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver. This technique involves the replication of an OFDM symbol before transmission and comparison of the phases of each of the subcarriers between the successive symbols. When an OFDM symbol of sequence length N is replicated, the receiver receives, in the absence of noise, the 2N point sequence {r(n)} is given by

S ''(1- k) (9)

where {x(k)} are the 2k +1 complex modulation values used to modulate 2k +1 subcarriers, H(K) is the channel transfer function for k^{th} carrier and ε is the normalized frequency offset of the channel.

A. Offset Estimation

The first set of N symbols is demodulated using an N -point FFT to yield the sequence R1(k), and the second set is demodulated using another N -point FFT to yield the sequence R2(k). The frequency offset is the phase difference between R1(k) and R2(k), that is

$$R_2(k) = R_1(k)e^{j2\pi\varepsilon} \quad (10)$$

adding the AWGN yields

$$Y_1(k) = R_1(k) + W_1(k) \quad (11)$$

$$Y_2(k) = R_1(k)e^{j2\pi\epsilon} + W_2(k) \quad (12)$$

Where k = 0,1,....,N -1

This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and was computed using the received data. The maximum likelihood estimate of the normalized frequency offset is given by:

$$\hat{\varepsilon} = \frac{1}{2\pi}\tan^{-1}\left[\frac{\sum_{k=-K}^{K} \operatorname{Im} Y_2(k)Y_1^*(k)}{\sum_{k=-K}^{K} \operatorname{Re} Y_2(k)Y_1^*(k)}\right] \quad (13)$$

Once the frequency offset is known, the ICI distortion in the data symbols is reduced by multiplying the received symbols with a complex conjugate of the frequency shift and applying the FFT,

$$X(n) = FFT\{Y(n)e^{\frac{-j2\pi n\epsilon}{N}}\} \quad (14)$$

V.EXTENDED KALMAN FILTERING

A. Problem Formulation

A state-space model of the discrete Kalman filter is defined as

$$z(n) = a(n)d(n) + v(n) \quad (15)$$

In this model, the observation z(n) has a linear relationship with the desired value d(n). By using the discrete Kalman filter, d(n) can be recursively estimated based on the observation of z(n) and the updated estimation in each recursion is optimum in the minimum mean square sense.

The received symbols are

$$Y(n) = X(n)e^{\frac{j2\pi n'\epsilon(n)}{N}} + W(n) \quad (16)$$

It is obvious that the observation y(n) is in a nonlinear relationship with the desired value ε_n. At the receiver

$$Y(n) = f(\in(n)) + W(n) \quad (17)$$

Where

$$f(\in(n)) = X(n)e^{\frac{j2\pi n'\in(n)}{N}} \quad (18)$$

In order to estimate ε efficiently in computation, we build an approximate linear relationship using the first-order Taylor's expansion, the Kalman Filter is an estimator for what is called the "linear quadratic problem", which focuses on estimating the instantaneous "state" of a linear dynamic system perturbed by white noise. Statistically, this estimator is optimal with respect to any quadratic function of estimation errors. In practice, this Kalman Filter is one of the greater discoveries in the history of statistical estimation theory and possibly the greatest discovery in the twentieth century. It has enabled mankind to do many things that could not have been done without it, and it has become as indispensable as silicon in the makeup of many electronic systems.

In a more dynamic approach, controlling of complex dynamic systems such as continuous manufacturing processes, aircraft, ships or spacecraft, are the most immediate applications of Kalman filter. In order to control a dynamic system, one needs to know what it is doing first. For these applications, it is not always possible or desirable to measure every variable that you want to control, and the Kalman filter provides a means for inferring the missing information from indirect (and noisy) measurements. Some amazing things that the Kalman filter can do is predicting the likely future courses of dynamic systems that people are not likely to control, such as the flow of rivers during flood, the trajectories of celestial bodies or the prices of traded commodities.

It aids mankind in solving problems, however, it does not solve any problem all by itself. This is however not a physical tool, but a mathematical one, which is made from mathematical models. In short, essentially tools for the mind. They help mental work become more efficient, just like mechanical tools, which make physical work less tedious. Additionally, it is important to understand its use and function before one can apply it effectively.

This is a complete characterization of the current state of knowledge of the dynamic system, including the influence of all past measurements. The reason behind why it is much more than an estimator is because it propagates the entire probability distribution of the variables it is tasked to estimate. These probability distributions are also useful for statistical analyses and the predictive design of sensor systems.

B. ICI Cancellation

There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

1). Offset Estimation Scheme

To estimate the quantity $\varepsilon(n)$ using an EKF in each OFDM frame, the state equation is built as

$$\varepsilon(n) = \varepsilon(n-1) \quad (19)$$

i.e., in this case we are estimating an unknown constant ε. This constant is distorted by a non-stationary process x(n), an observation of which is the preamble symbols preceding the data symbols in the frame. The observation equation is

$$Y(n) = X(n)e^{\frac{j2\pi n'\in(n)}{N}} + W(n) \quad (20)$$

where y(n) denotes the received preamble symbols distorted in the channel, w(n) the AWGN, and x(n) the IFFT of the preambles X(k) that are transmitted, which are known at the receiver. Assume there are N_p preambles preceding the data symbols in each frame are used as a training sequence and the variance σ of the AWGN w(n) is stationary. The computation procedure is described as follows.

1. Initialize the estimate and corresponding state error P(0).

2. Compute the H(n), the derivative of y(n) with respect to $\varepsilon(n)$ at , the estimate obtained in the previous iteration.

3. Compute the time-varying Kalman gain K(n) using the error variance P(n- 1), H(n), and σ^2.

4. Compute the estimate $y^\wedge(n)$ using x(n) and) $\varepsilon^\wedge(n-1)$, i.e. based on the observations up to time n-1, compute the error between the true observation y(n) and y^(n).

5. Update the estimate $\varepsilon^\wedge(n)$ by adding the K(n)-weighted error between the observation y(n) and y^(n) to the previous estimation $\varepsilon^\wedge(n-1)$.

6. Compute the state error P(n) with the Kalman gain K(n), H(n), and the previous error P(n-1).

7. If n is less than N_p, increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation $\varepsilon^\wedge(n)$ from the ideal value $\varepsilon(n)$ are computed in each step and are used for adjustment of estimation in the next step.

The pseudo code of computation is summarized as Initialize P(n), $\varepsilon^\wedge(0)$. For n=1,2□c.Np compute,

$$H(n) = \frac{\partial y(x)}{\partial x} \tag{21}$$

$$= \frac{j2\pi n'}{N} e^{\frac{j2\pi n'\epsilon(n-1)}{N}} X(n) \tag{22}$$

$$K(n) = P(n-1)H^*(n)[P(n-1)+\sigma^2]^{-1} \tag{23}$$

$$\varepsilon^\wedge(n) = \varepsilon^\wedge(n-1) + \mathrm{Re}\{K(n)[y(n) - x(n)e^{\frac{j2\pi n'\epsilon(n-1)}{N}}\} \tag{24}$$

$$P(n) = [1 - K(n)H(n)]P(n-1) \tag{25}$$

2). Offset Correction Scheme

The ICI distortion in the data symbols x(n) that follow the training sequence can then be mitigated by multiplying the received data symbols y(n) with a complex conjugate of the estimated frequency offset and applying FFT, i.e.

$$X^\wedge(n) = FFT\{Y(n)e^{\frac{j2\pi n'\epsilon}{N}}\} \tag{26}$$

As the estimation of the frequency offset by the EKF scheme is pretty efficient and accurate, it is expected that the performance will be mainly influenced by the variation of the AWGN.

VI. SIMULATED RESULT ANALYSIS

A. Performance

In order to compare the three different cancellation schemes, BER curves were used to evaluate the performance of each scheme. For the simulations in this paper, MATLAB was employed with its Communications Toolbox for all data runs. The OFDM transceiver system was implemented as specified by Fig. 1. Frequency offset was introduced as the phase rotation. Modulation schemes of binary phase shift keying (BPSK) and Quadrature amplitude modulation (QAM) were chosen as they are used in many standards such as 802.11a.Simulations for cases of normalized frequency offsets equal to 0.05, 0.15, and 0.30.

B. BER Performance

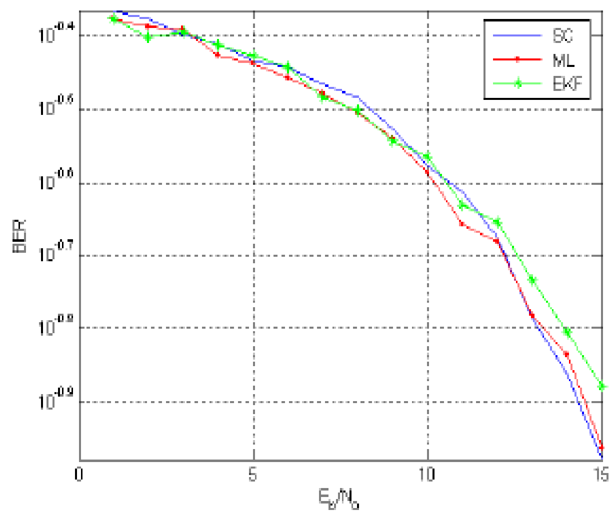

Fig. 4. BER Performance with ICI Cancellation, ε=0.15 for 4-BPSK

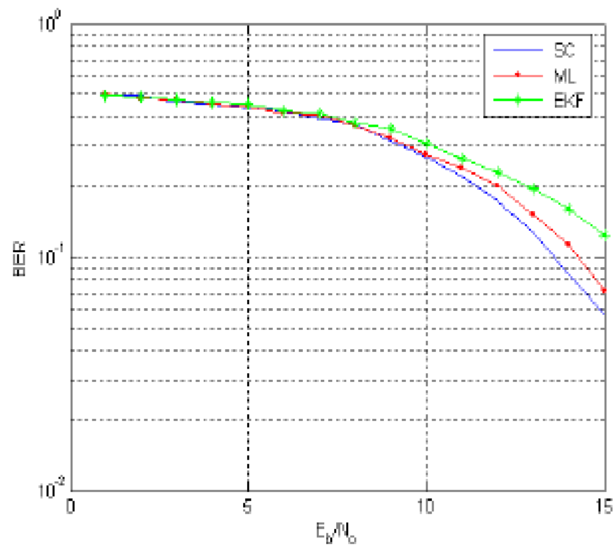

Fig. 5: BER Performance with ICI Cancellation, ε=0.30 for 16-BPSK.

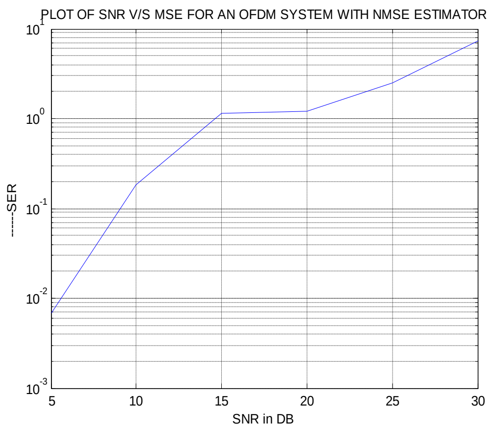

Fig. 6: SER Performance with NMSE Estimation

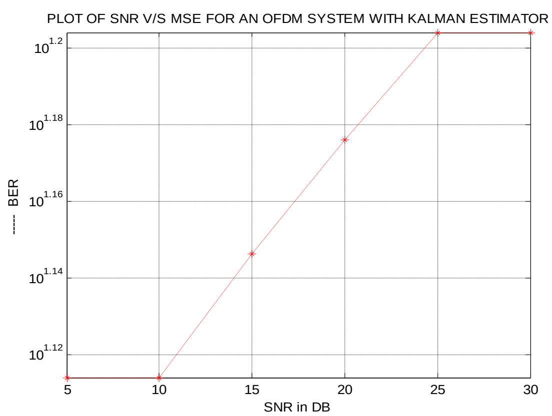

Fig. 7: BER Performance On OFDMA System with Kalman Estimator.

VII.CONCLUSION

In this paper, the performance of OFDM systems in the presence of frequency offset between the transmitter and the receiver has been studied in terms of the Carrier-to- Interference ratio (CIR) and the bit error rate (BER) performance. Inter-carrier interference (ICI) which results from the frequency offset degrades the performance of the OFDM system. The purpose of this document was to give some insight into the power of the OFDM transmission scheme. It has discussed not only the transmission scheme itself, but also some of the problems that are presented in mobile communications as well as the techniques to correct them. Digital Communications is a rapidly growing industry and Orthogonal Frequency Division Multiplexing is on the forefront of this technology. OFDM will prove to revolutionize mobile communications by allowing it to be more reliable and robust while maintaining the high data rate that digital communications demands.

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