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ICI Reduction using Extended Kalman Filter in OFDM System

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is emerging as preferred modulation scheme in modern high data rate wireless communication systems. A well known problem of OFDM system is sensitivity to frequency offset between the transmitted and received signals, which may be caused by Doppler shift in the channel or by the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality between sub carriers and the signal transmitted on each carrier are not independent of each other, leading to inter carrier interference (ICI)[1]-[4].

In this paper, the effects of ICI have been analyzed and two solutions to combat ICI have been presented. The first method is a self cancellation scheme, in which redundant data is transmitted onto adjacent subcarriers such that the ICI between adjacent sub carriers cancels out at the receiver. The other technique the Extended Kalman Filter (EKF) method statistically estimate the frequency offset and correct the offset using the estimated value at the receiver.

Keywords: Extended Kalman Filter (EKF), OFDM, ICI, AWGN, BER

1. INTRODUCTION

ICI self-cancellation is a scheme that was introduced by Yuping Zhao and Sven-Gustav Häggman in 2001 in [6][7] to combat and suppress ICI in OFDM systems. The increase of bit rates in digital mobile radio communication systems [17], the inter-symbol interference (ISI) and channel deep fading become big problems in conventional single carrier systems. A proposal to use Orthogonal Frequency Division Multiplexing (OFDM) in radio mobile environment has been analyzed [8].Since a long symbol interval is used, the system has strong ability to combat channel deep fading, and the ISI can be mitigated by means of guard intervals. In an OFDM system, the whole available bandwidth is divided into N small parts, and a block of N data symbols are modulated on N corresponding subcarriers which are orthogonal to each other. The spectra of the subcarriers are over lapping; therefore precise frequency recovering is needed. However, in the mobile radio environment [4], the relative movement between transmitter and receiver causes Doppler frequency shifts, in addition the carriers can never be perfectly synchronized. These random frequency errors in OFDM system distort orthogonality between subcarriers, as a result inter-carrier interference (ICI) occurs. Researchers have proposed various methods to combat the ICI in OFDM systems. The existing approaches that have been developed to reduce ICI can be categorized as frequency-domain equalization, time –windowing and the ICI self cancellation scheme. Literature show that in such systems, the bit error rate (BER) increases rapidly with increasing frequency offsets. This is a main restriction in OFDM systems [8]-[10].There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

2. EXTENDED KALMAN FILTERING TO OFDM SYSTEM

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

$$z(n) = a(n)\,d(n) + v(n) \tag{2.1}$$

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.

$$y(n) = x(n)\,e^{j\frac{2\pi n'\varepsilon(n)}{N}} + w(n) \tag{2.2}$$

It is obvious that the observation $y(n)$ is in a nonlinear relationship with the desired value $\varepsilon(n)$, i.e.

$$y(n) = f(\varepsilon(n)) + w(n) \tag{2.3}$$

$$\text{Where } f(\varepsilon(n)) = x(n)\,e^{j\frac{2\pi n'\varepsilon(n)}{N}} \tag{2.4}$$

In order to estimate $\varepsilon(n)$ efficiently in computation, we build an approximate linear relationship using the first-order Taylor's expansion:

$$y(n) \approx f(\hat{\varepsilon}(n-1)) + f'(\hat{\varepsilon}(n-1))[\varepsilon(n) - \hat{\varepsilon}(n-1)] + w(n) \tag{2.5}$$

Where $\hat{\varepsilon}(n-1)$ is the estimation of $\varepsilon(n-1)$

$$f'(\hat{\varepsilon}(n-1)) = \left.\frac{\partial f(\varepsilon(n))}{\partial \varepsilon(n)}\right|_{\varepsilon(n)=\hat{\varepsilon}(n-1)} = j\frac{2\pi n'}{N}x(n)e^{j\frac{2\pi n'\varepsilon(n-1)}{N}} \quad (2.6)$$

Define

$$\begin{aligned} z(n) &= y(n) - f(\hat{\varepsilon}(n-1)) \\ d(n) &= \varepsilon(n) - \hat{\varepsilon}(n-1) \end{aligned} \quad (2.7)$$

And the following relationship

$$z(n) = f'(\varepsilon(n-1))d(n) + w(n) \quad (2.8)$$

Which has the same form as equation 2.1, i.e., $z(n)$ is linearly related to $d(n)$. Hence the normalized frequency offset $\varepsilon(n)$ can be estimated in a recursive procedure similar to the discrete Kalman filter. As linear approximation is involved in the derivation, the filter is called the extended Kalman filter (EKF). The derivation of the EKF is omitted in this report for the sake of brevity. The EKF provides a trajectory of estimation for $\varepsilon(n)$ .The error in each update decreases and the estimate becomes closer to the ideal value during iterations. It is noted that the actual error in each recursion between $\varepsilon(n)$ and $\hat{\varepsilon}(n)$ does not strictly obey equation 2.8. However it has been proved that EKF is a very useful method of obtaining good estimates of the system state. Hence it has motivated us to explore the performance of EKF in ICI cancellation in an OFDM system.

In the following estimation using the EKF, it is assumed that the channel is slowly time varying so that the time-variant channel impulse response can be approximated to be quasi-static transmission of one OFDM frame. Hence the frequency offset is considered to be constant during a frame. The preamble preceding each frame can thus be utilized as a training sequence for estimation of the frequency offset imposed on the symbols in this frame. Furthermore, in the estimation, channel is assumed to be flat-fading and ideal channel estimation is available at the receiver. Therefore in the derivation and simulation,one-tap equalization is temporarily suppressed.

3. ICI CANCELLATION

There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme. The main reason for ICI is the normalized frequency offset. So first we have to estimate using EKF algorithm and then we have to correct using offset model.

3.1 Offset Estimation Scheme:

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

$$\varepsilon(n) = \varepsilon(n-1) \quad (3.1)$$

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 in the observation equation (2.2). where $y(n)$ denotes the received preamble symbols distorted in the channel, $w(n)$ is 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 variance σ^2 of the AWGN $w(n)$ is stationary. The computation procedure is described as follows.

1. Initialize the estimate $\hat{\varepsilon}(0)$ and corresponding state error $p(0)$.
2. Compute the $H(n)$, the derivative of $y(n)$ with respect to $\widehat{\varepsilon}(n)$ at $\hat{\varepsilon}(n-1)$. The estimate obtained in 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 $\hat{y}(0)$ using $x(n)$ and $\hat{\varepsilon}(n-1)$ i.e. based on the observations up to time n-1, compute the error between the true observation $y(n)$ and $\hat{y}(n)$
5. Update the estimate $\hat{\varepsilon}(n)$ by adding $k(n)$ weighted error between the observation $y(n)$ and $\hat{y}(n)$ to previous estimation $\hat{\varepsilon}(n-1)$
6. Compute the state error $p(n)$ with the Kalman gain $k(n)$, $H(n)$ and the previous error $p(n-1)$
7. If $n < N$ increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation $\hat{\varepsilon}(n)$ from the ideal value $\varepsilon(n)$ are computed in each step and are used for adjustment of estimation in next step. Through the recursive iteration procedure described above, an estimate of the frequency offset ε can be obtained.

The pseudo (code for EKF) of computation is summarized as follows:

Initialize state error $p(n)$, estimate $\hat{\varepsilon}(0)$

For $n = 1,2,....N_p$ Compute

$$H(n) = \left.\frac{\partial y(x)}{\partial x}\right|_{x=\hat{\varepsilon}(n)} = \frac{j2\pi n'}{N}e^{\frac{j2\pi n'\hat{\varepsilon}(n-1)}{N}}x(n) \quad (3.2)$$

Kalman gain

$$k(n)=p(n-1)H^*(n)[p(n-1)+\sigma^2]^{-1} \qquad (3.3)$$

Update the estimate

$$\hat{\varepsilon}(n)=\hat{\varepsilon}(n-1)+\mathrm{Re}\left\{k(n)\left[y(n)-x(n)e^{\frac{j2\pi n'\hat{\varepsilon}(n-1)}{N}}\right]\right\} \qquad (3.4)$$

State error

$$p(n)=[1-k(n)H(n)]p(n-1) \qquad (3.5)$$

3.2 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.

$$\hat{x}(n)=FFT\left\{y(n)e^{-j\frac{2\pi n'\hat{\varepsilon}}{N}}\right\} \qquad (3.6)$$

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[17]-[22].

4. SIMULATION RESULTS

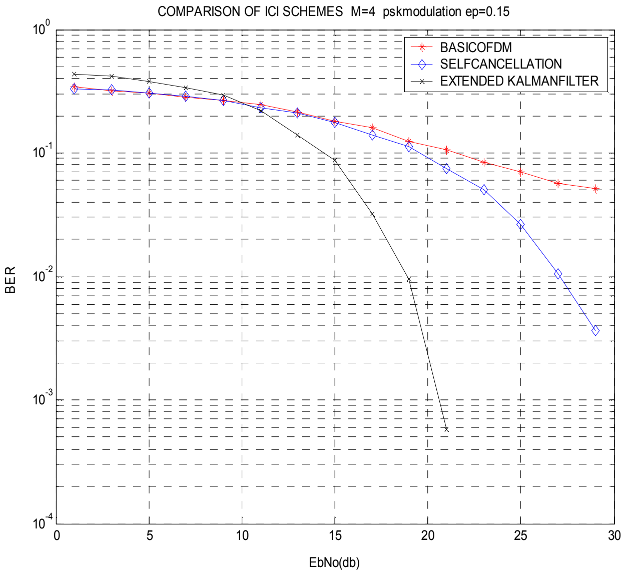

Fig 4.1a

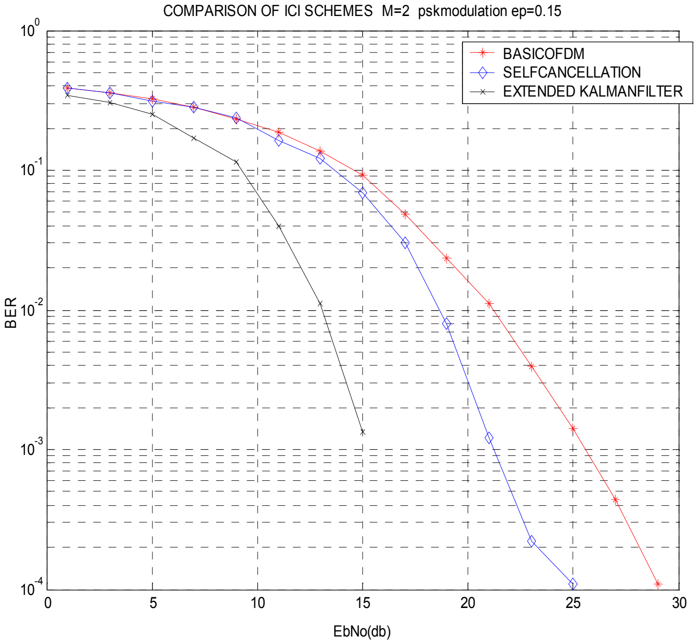

Fig 4.1b

Figure 4.1 a & b : BER Performance with ICI Cancellation, ε =0.15

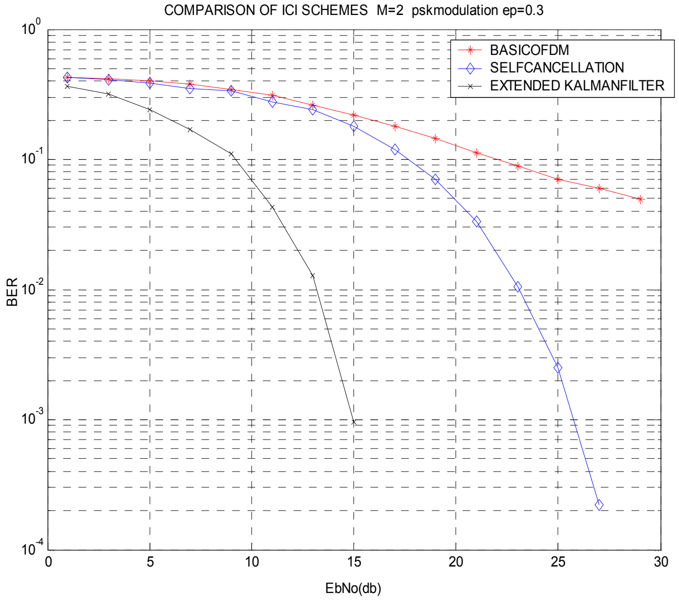

Fig 4.2a

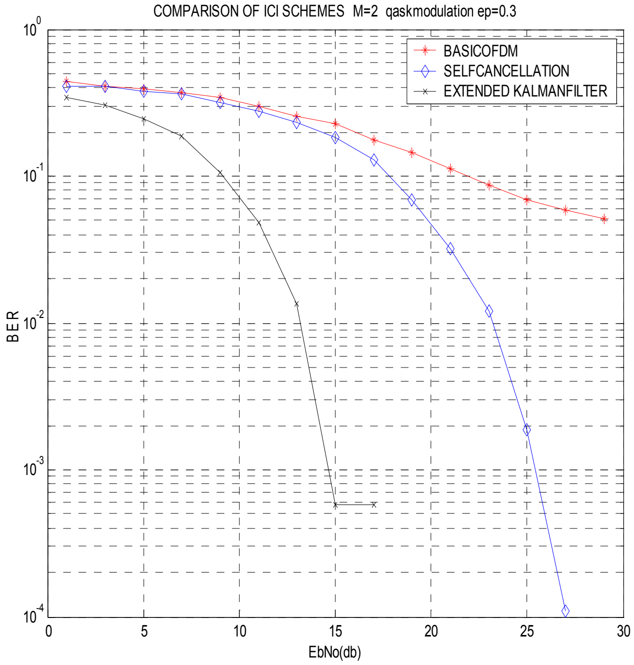

Fig 4.2b

Figure 4.2 a &b : BER Performance with ICI Cancellation, ε = 0.30

For M=2 PSK modulation in 5200 transmitted bits 1135 errors occur with a BER of 0.047473 for offset of 0.3 and E_BN_O = 15 for Basic OFDM. In the similar conditioned using self cancellation scheme 905 errors occur with a BER of 0.17407. If EKF estimation is used then only 4 errors occur with BER of 0.00076923.

For M=4 QASK modulation in 10400 transmitted 2042 bits errors occur with a BER of 0.19637 for offset of 0.05 and E_BN_O = 09 for Basic OFDM. In the similar conditioned using self cancellation scheme 1885 errors occur with a BER of 0.18121. If EKF estimation is used then 1094 errors occur with BER of 0.10519. Here we have used (7, 4) cyclic redundancy encoding. For the application of larger M two functions bin2dig and dig2bin functions were written[11]-[13].

Tables 4.1-4.2 summarize required values of SNR for BER specified at 10^{-2}. Significant gains in performance can be achieved using EKF methods for a large frequency offset.

Table 4.1: Required SNR and improvement for BER of 10^{-2} for 2-PSK

Method	ε=0	Gain	ε=0.05	Gain	ε=0.15	Gain	ε=0.3	Gain
None	17.8dB		18dB		21dB		31dB	
SC	17.6dB	0.2dB	17.6dB	0.4dB	18.8dB	2.2dB	23dB	8dB
EKF	13 dB	4.8dB	13dB	5 dB	12.9dB	8.1dB	13dB	18dB

Table 4.2: Required SNR and improvement for BER of 10^{-2} for 4-PSK

Method	ε =0	Gain	ε =0.05	Gain	ε =0.15	Gain	ε =0.3	Gain
None	20.8dB		21.8dB		31dB		35dB	
SC	20.5dB	0.3dB	21.6dB	0.2dB	27dB	4dB	31dB	4dB
EKF	19dB	1.8dB	18.5dB	3.3dB	19dB	12dB	19dB	16dB

Table 4.3: Required SNR and improvement for BER of 10^{-2} for 2-QAM

Method	ε =0	Gain	ε =0.05	Gain	ε =0.15	Gain	ε =0.3	Gain
None	17.8dB		18dB		21dB		35dB	
SC	17.8dB	0dB	18dB	0dB	19dB	2dB	23dB	11dB
EKF	13dB	4.8dB	13dB	5dB	13dB	8dB	13dB	22dB

Table 4.4: Required SNR and improvement for BER of 10^{-2} for 4-QAM

Method	E =0	Gain	ε=0.05	Gain	ε=0.15	Gain	ε=0.3	Gain
None	18dB		19dB		30dB		35dB	
SC	17.6dB	0.4dB	18.8dB	0.2dB	24dB	6dB	31dB	4dB
EKF	13dB	5dB	13.3dB	5.7dB	13.5dB	16.5dB	13dB	22dB

Table 4.5: BER Comparison of different Encoding schemes for 4-QAM for ε=0.05 and for the E_b/N_O=15 and total number of bits transmitted =10400

	Basic OFDM		Self Cancellation		EKF	
Coding	Errors	BER	Errors	BER	Errors	BER
Cyclic	145	0.013956	153	0.014725	17	0.0016346
BCH	149	0.014286	128	0.012308	21	0.0020192
Hamming	168	0.016154	136	0.013077	17	0.0016346
Linear	141	0.013516	139	0.013407	10	0.0010000

Table 4.6: BER Comparison of different Encoding schemes for 16-QAM for ε=0.05 and for the total sub carriers=52, E_b/N_o=15 and total number of bits transmitted =20800

	Basic OFDM		Self Cancellation		EKF	
Coding	Errors	BER	Errors	BER	Errors	BER
Cyclic	181	0.0086813	123	0.0059341	13	0.000625
BCH	203	0.0097802	64	0.0030769	31	0.0014904
Hamming	215	0.01033	114	0.0054945	17	0.00081731
Linear	345	0.016593	226	0.010879	182	0.00875

For small alphabet sizes (BPSK) and for low frequency offset values the SC and EKF techniques have good performance in terms of BER. However, for higher order modulation schemes, the EKF technique performs better. This is attributed to the fact that the EKF methods estimate the frequency offset very accurately and cancel the offset using this estimated value. However, the self-cancellation technique does not completely cancel the ICI from adjacent sub-carriers, and the effect of this residual ICI increases for larger offset values.

An error-correcting code (ECC) or forward error correction (FEC) code is a code in which each data signal conforms to specific rules of construction so that departures from this construction in the received signal can generally be automatically detected and corrected. It is used in computer data storage, for example in dynamic RAM, and in data transmission.

In this paper we have used four different codes to compare. Those are Cyclic code, linear code , Hamming code and Block code. All are (7, 4) codes.[14]-[16][23]

Let *C* be a linear code over a finite field *A* of block length *n*. *C* is called a cyclic code, if for every codeword $c=(c_1,...,c_n)$ from *C*, the word $(c_n,c_1,...,c_{n-1})$ in A^n obtained by a cyclic right shift of components is also a codeword from *C*.

Sometimes, *C* is called the *c*-cyclic code; if *C* is the smallest cyclic code containing *c*, or, in other words, *C* is the linear code generated by *c* and all code words obtained by cyclic shifts of its components.

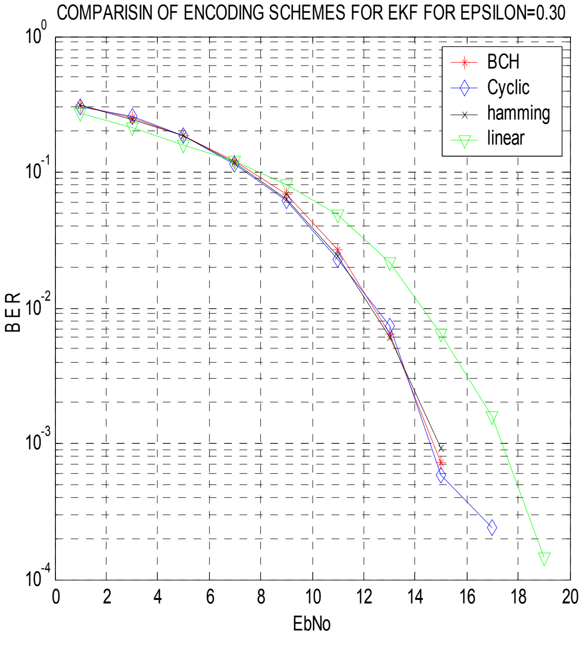

Figure 4.3: BER Performance of different encoding schemes applied to Basic OFDM with EKF for M=4 and ε=0.30

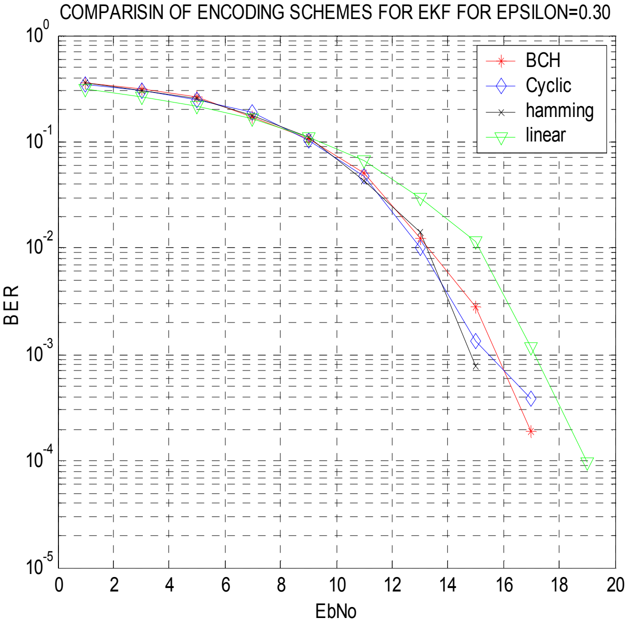

Figure 4.4: BER Performance of different encoding schemes applied to Basic OFDM with EKF for M=16 and ε=0.30

A BCH code is a polynomial code over a finite field with a particularly chosen generator polynomial. It is also a cyclic code as well.

Hamming codes can detect and correct single-bit errors. In other words, the Hamming distance between the transmitted and received code-words must be zero or one for reliable communication. Alternatively, it can detect (but not correct) up to two simultaneous bit errors. In contrast, the simple parity code cannot correct errors, nor can it be used to detect more than one error (such as where two bits are transposed). In mathematical terms, Hamming codes are a class of binary linear codes. For each integer $m > 1$ there is a code with parameters: $[2^m - 1, 2^m - m - 1, 3]$. The parity-check matrix of a Hamming code is constructed by listing all columns of length *m* that are pair-wise independent.

A Linear Block code consists of a set of fixed-length vectors called *code words.* The length of the code word is the number of elements in the vector and is denoted by b. There are 2^n possible code words in a binary block code of length n. From these 2^n codes, we may select $M=2^k$ code words(k<n). The comparison of these schemes is shown in figure 5.5 and 5.6.

Table 4.5-4.6 compares the performance of these schemes for different offsets and applied to different schemes.

5. CONCLUSIONS

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. Two methods were explored in this project for mitigation of the ICI. The ICI self-cancellation (SC) scheme was proposed in previous publication [6]. The extended Kalman filtering (EKF) method for estimation and cancellation of the frequency offset has been investigated in this project, and compared with basic OFDM and self cancellation. The choice of which method to employ depends on the specific application. For example, self cancellation does not require very complex hardware or software for implementation. However, it is not bandwidth efficient as there is a redundancy of 2 for each carrier. On the other hand, the EKF method does not reduce bandwidth efficiency as the frequency offset can be estimated from the preamble of the data sequence in each OFDM frame. However, it has the most complex implementation of the other methods. In addition, this method requires a training sequence to be sent before the data symbols for estimation of the frequency offset. The preambles are used as the training sequence for estimation of the frequency offset.

In this paper, the simulations were performed in an AWGN channel. This model can be easily adapted to a flat-fading channel with perfect channel estimation. Further work can be done by performing simulations to investigate the performance of these ICI cancellation schemes in multipath fading channels without perfect channel information at the receiver. In this case, the multipath fading may hamper the performance of these ICI cancellation schemes.

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