Carrier Frequency Offset Estimation for OFDM System using Extended Kalman Filter

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***Abstract*—The ability of Orthogonal Frequency Division Multiplexing (OFDM) systems to achieve higher data rates and facilitate bandwidth friendly communication [1]-[3] is impaired by the presence of Carrier Frequency Offset (CFO) in the OFDM communication system. CFO can be caused by Doppler frequency shift, or by the differences of the transmitter and the receiver local oscillator frequencies. We propose a new method for CFO estimation for (OFDM) communication systems, with experimental proof which was gathered in the process of real world data transmission using the OFDM communication system in a simulation environment (MATLAB).**

***Keywords*—Carrier Frequency Offset (CFO), Orthogonal Frequency Division Multiplexing (OFDM), Extended Kalman Filter (EKF)**

I. Introduction

The CFO estimation bears a major importance in OFDM communication systems as OFDM is highly sensitive to CFO [4] and it would agitate the orthogonal nature of the OFDM sub carriers, violating the basics of OFDM communication systems. The above fact would leave the OFDM communication system vulnerable to the Inter carrier Interference (ICI), resulting in an increase in the Bit Error Rate (BER).

OFDM has been chosen for the European digital audio and video broadcasting standards, as well as for the wireless local-area networking standards IEEE 802.11a, HIPERLAN2 and WiMAX standards IEEE 802.16. Thus, CFO estimation and removal of the received data is highly critical in OFDM systems and has drawn significant attention in the recent past. There are quite a number of EKF based estimation systems in OFDM related areas. Some of these methods could be summarized as follows. An EKF based method has been used for channel estimation for MIMO-OFDM system. This has the capability to exploit the pilot symbols and provide the channel estimation using EKF without any prior knowledge of channel statistics [5].

The EKF has also been used to estimate the Common Phase Error (CPE) in OFDM communication system [6]. Once again a Kalman filter based method has been used for the estimation of time-frequency-selective fading channels in OFDM systems. And it was proposed to use a low-dimensional Kalman filter for the estimation of each subchannel. Then, a minimum mean square-error (MMSE) combiner was used to refine the Kalman estimates [7]. Along with all these EKF applications on OFDM communication system, this research is focused on the CFO estimation of OFDM communication system using the EKF.

II. OFDM Communication System

An OFDM system with N subcarriers and $1/NT_s$ frequency spacing is considered here, where T_s is the symbol period. Let $x(n)$ represent the OFDM symbol and X_m's represent the baseband symbols on each subcarrier.

$$x(n) = 1/N \sum_{m=0}^{N-1} X_m e^{(j2\pi nm/N)} \tag{1}$$

The digital to analog (D/A) converter then creates an analog time domain signal which is transmitted through an Additive White Gaussian Noise (AWGN) channel. Figure 1, depicts the baseband OFDM communication system which is thoroughly studied in this research.

As illustrated in Fig. 1, the signal is converted back to a discrete N point sequence $y(n)$, corresponding to the each subcarrier at the receiver. The demodulated symbol stream can be described as

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

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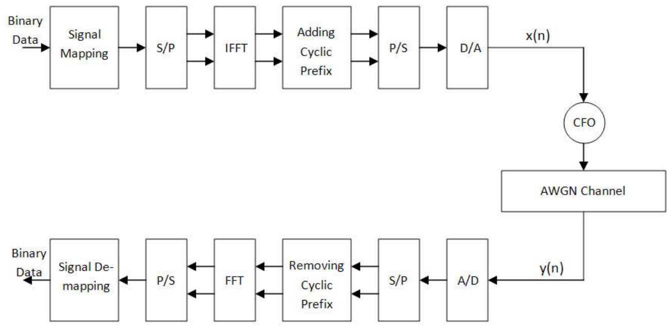

Fig. 1. Baseband OFDM Communication System

Where, $W(m)$ corresponds to the FFT of the samples of $w(n)$, which is the AWGN introduced in the channel. In this research frequency offset is modeled as a normalized frequency offset ε, which can be given by $\Delta f N T_s$ where Δf is the frequency difference between the transmitted and received carrier frequencies.

An Extended Kalman filter [8] is used to measure the normalized frequency offset with a training sequence method which is known to the transmitter and receiver. Preamble with 256 symbols is adopted as the training sequence. Since a training sequence method is used this mechanism is computationally simple and can be easily implemented on real time systems.

III. Extended Kalman Filter

Some of the most successful application of Kalman filtering have been in the situations that the process to be estimated and (or) the measurement relationship to the process is non -linear. The Kalman filter that linearizes about the current mean and covariance is referred to as an extended Kalman filter or EKF

In something akin to a Taylor series, we can linearize the estimation around the current estimate using the partial derivatives of the process and measurement functions to compute estimates even in the face of non-linear relationships. Lets us assume that process again has a state vector $A \varepsilon R^n$, but that the process again has a state vector $A \varepsilon R^n$, but that process is now governed by the non-linear stochastic difference equation.

$$A_k = g(A_{k-1}, U_{k-1}) \tag{3}$$

With a measurement $z \varepsilon R$ that is,

$$Z_k = h(A_k, V_k) \tag{4}$$

Where the random variables U_k and V_k again represent the process and measurement noise. In this case the non-linear function g in the difference Equation (3) relates the state at this previous time step k. It includes as parameter,the zero-mean process noise U_k the non-linear function h, the measurement Equation (4) relates the state X_k to the measurement Z_k [8].

The OFDM model

The received OFDM signal $y(n)$ can be expressed as

$$y(n) = x(n) \exp^{(j2\pi n \varepsilon(n)/N)} + w(n) \tag{5}$$

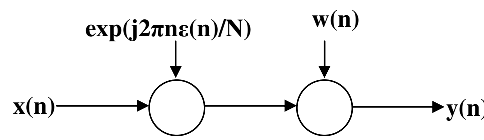

Fig. 2. Frequency Offset and AWGN Component

Here $\exp^{(j2\pi n \varepsilon(n)/N)}$ is the frequency shift. ε is the normalized frequency offset and represented as $\Delta f N T_s$ where Δf is the frequency difference between the transmitted and received carrier frequencies. $w(n)$ is the AWGN introduced in the channel and $y(n)$ has a linear relationship with the desired value $\varepsilon(n)$.

A state-space model

The normalized frequency offset ε in our OFDM system are estimated according to the following state space model.

$$\varepsilon(n) = \varepsilon(n-1) \tag{6}$$

$$y(n) = F[\varepsilon(n), x(n-1)] + w(n) \tag{7}$$

The EKF is to estimate the parameter because F is a nonlinear function and the EKF recursion is given by

$$\acute{\varepsilon}^{-}(n) = \acute{\varepsilon}(n-1) \tag{8}$$

$$P^{-}(n) = P(n-1) \tag{9}$$

Here *P(n)* is the state error covariance matrix

Let the time varying kalman gain be $K(n)$

$$K(n) = P^{-}(n) H^T(n) [H(n) P(n) H^T(n) + \sigma^2]^{-1} \tag{10}$$

Where σ^2 is variance of the AWGN and

$$\acute{\varepsilon}(n) = \acute{\varepsilon}^{-}(n-1) + K(n)y(n) - f[\acute{\varepsilon}(n), x(n)] \tag{11}$$

$$P(n) = P^{-}(n) - K(n)H(n)P^{-}(n) \tag{12}$$

Where

$$H(n) = \partial f[\varepsilon(n), x(n)]/\partial\acute{\varepsilon}(n) \tag{13}$$

$$H(n) = (j2\pi n)x(n)\exp^{(-j2\pi n\acute{\varepsilon}(n-1)/N)} \tag{14}$$

As the first step of mitigating the effect of CFO, a complex conjugate of the estimated frequency offset (ε) is multiplied with the received data symbols $y(n)$. Then FFT is applied shown in equation (15).

$$\acute{x}(n) = FFT\{y(n)\exp^{(-j2\pi n\varepsilon/N)}\} \tag{15}$$

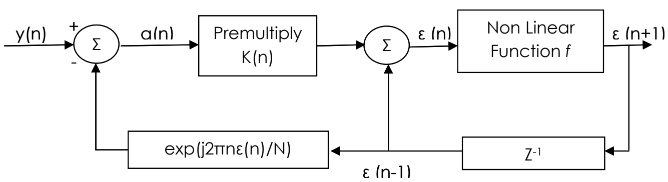

Fig. 3. Kalman Filter

IV. Simulation and Results

The extended Kalman Filter used as the estimator in this research is evaluated in an environment where the symbols are transmitted continuously with a preceding set of preambles. The system has a 64 FFT length and 64 sub carriers. The frequency offset is considered to be constant throughout the duration of a frame thus allowing the usage of the preamble as a training sequence. And all the results are obtained via transmitting the signals through an AWGN channel.

The simulation results consist of outcomes of audio data transmission as well as text data transmission via the OFDM communication system. The performance of the research model is evaluated by analyzing the quality and the accuracy of the received signal at the receiver side.

A. Audio Data Transmission

The hearing quality of the received signal is the main concern in evaluating the performance of audio data transmission scenario. The spectrums of the received signal, transmitted signal and the signal affected by CFO are used below to illustrate the efficiency and the accuracy of the proposed CFO estimation method. The simulation is carried where the normalized frequency offset is 0.25 and SNR is 8.

Under these conditions the correlation coefficients are analyzed and the results are as follows. The correlation coefficient of the original and the received signal is obtained as 0.1835 where as the correlation coefficient of the original and the corrected signal is obtained as 0.9969. This shows that both the original wave and the corrected wave are closely related.

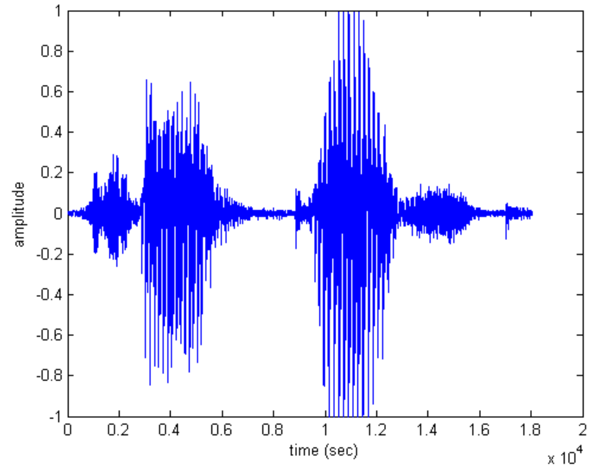

Fig. 4. Transmitted Audio Signal

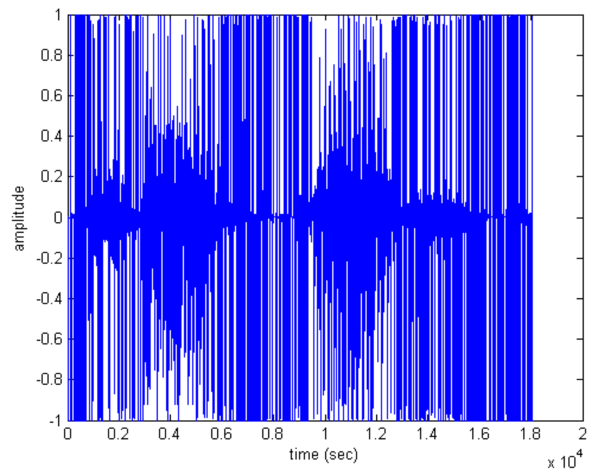

Fig. 5. Received Audio Signal

It also shows that the proposed Kalman filter based estimation system is capable of rectifying the effects of CFO in situations where the correlation coefficients of the original and the received signals are very close to 0, which implies that there is no relationship between the two signals.

B. Text Data Transmission

A text string stored in a .txt file is transmitted through the OFDM communication system and the differences between the received and the transmitted information is analyzed similarly as in audio data transmission, at a normalized frequency offset of 0.25 and SNR of 8.

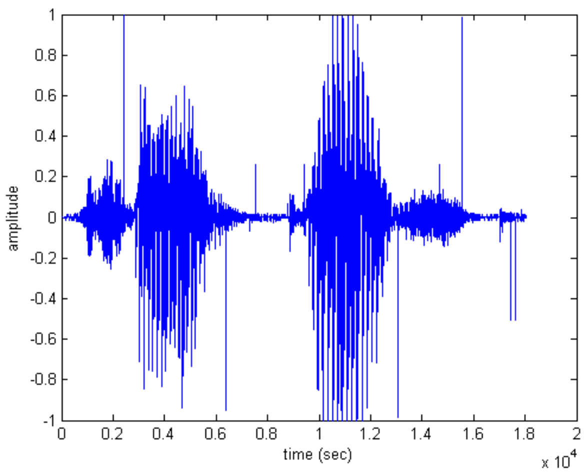

Fig. 6. Corrected Audio Signal

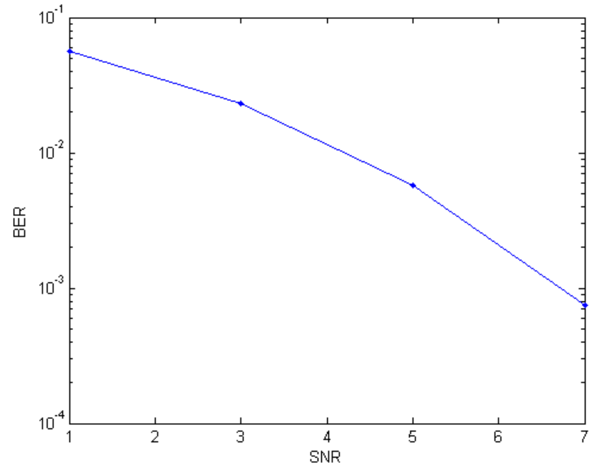

Fig. 7. BER Vs. SNR

Transmitted Text
Carrier Frequency Offset Estimation for Orthogonal Frequency Division Multiplexing.

Received Text
arriEr requEnc OffSdt EstiM‘ton fOr rthoGnnl FrEpuncy Dhvsion

Corrected Text
Carrier Frequency Offset Estimation for Orthogonal Frequency Division Multiplexing.

The above output proves that, under the prior mentioned system parameters the performance of the OFDM communication system could be drastically improved using the aid of the extended Kalman Filter.

The results obtained from both the Text and Audio data transmission confirm that the proposed estimator could be effectively used in OFDM communication systems to handle the CFO issue.

V. Analytical Results

The performance of the proposed system could be further analyzed in statistical means using the BER Vs SNR plots.

Figure 7 illustrates the relationship between the BER and the SNR in the research model, obtained under a normalized frequency offset of 0.25 and for a set of SNR values ranging from 1 to 10 and keeping all the other factors as similar to the demonstrations carried out previously.

VI. Conclusion

This research focuses on the performance enhancement of the OFDM communication systems in the presence of CFO. Since the estimation could be done using the preamble of the data sequence, the proposed system model is capable of estimating the CFO in OFDM communication system without reducing the bandwidth efficiency. Still it would need a complex implementation at the receiver side which requires a high processing speed.

This model is put forward with the assumption of having an AWGN channel for transmission. As a future improvement researchers could explore the avenues for the improvement of this model to be used in any other communication channel.

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