EKF ALGORITHM FOR COMBINED CARRIER AND SAMPLING OFFSET TRACKING IN OFDM WLAN SYSTEMS

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ABSTRACT

In this paper we propose a new technique based on Extended Kalman Filtering(EKF) for residual carrier frequency offset and sampling clock offset tracking suitable for IEEE 802.11a and HiperLAN Type 2 WLAN systems. Initial coarse and fine carrier frequency offset estimation and correction is done using the short and long preambles that are part of the above Wireless LANs frame structure. However, the residual carrier frequency offset and the sampling time offset severely degrades the error rate performance of OFDM systems.The proposed EKF algorithm employs the phase variation of the received symbols induced due to these effects to derive the equivalent joint state-space model for both of the offsets in the frequency domain. The proposed technique gives a superior performance than conventional schemes especially under low signal to noise ratio conditions.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is an emerging multi-carrier modulation scheme, which has been adopted for wireless LAN standards such as IEEE 802.11a and HiperLAN2. OFDM is an effective technique to mitigate the effects of delay spread introduced by multipath.This is possible due to the fact that the frequency-selective channel is turned into a set of parallel narrowband channels which leads to a very simple frequency domain equalizer.

At high data rates, at a reduced inter-carrier spacing due to more number of sub carriers, the tolerance of OFDM systems to synchronization errors is very less. Carrier frequency offset is caused by oscillator inaccuracies and the Doppler shift due to mobility. Wireless LAN systems use the short and long preambles located at the beginning of a frame, to perform the initial carrier frequency offset estimation and compensation in two stages. The residual frequency offset, though small, can still cause appreciable amplitude reduction and phase rotation of the received symbols thereby degrading the system performance. On the other hand, the sampling time offset manifests in two ways - sampling phase offset and a sampling frequency offset. The sampling phase offset is estimated by channel estimation and is compensated by frequency domain equalization. However, the sampling frequency offset introduces a time-variant timing offset that also induces a phase rotation in the frequency domain and needs to be compensated.

Kalman filtering has been used across OFDM symbols in the frequency domain for timing offset estimation in [1]. Extended Kalman filtering(EKF) has been used for the coarse and fine estimation of the frequency offset in the time domain [2] and in the frequency domain [3], [4] . However, none of the above papers have addressed the issue of estimating the residual frequency offset and the sampling offset when present together in an OFDM system. Recently, a Least Squares (LS) scheme which estimates the residual carrier frequency offset by averaging over the pilot symbols available in every OFDM symbol of Wireless LAN systems (IEEE 802.11a and HiperLAN2) and the sampling clock offset by calculating the slope of the phases of the pilots was presented in [5]. We compare our proposed algorithm with this scheme.

In this paper, we consider the combined effect of the residual carrier frequency offset and the sampling time offset on the phases of the received pilot symbols in the frequency domain to

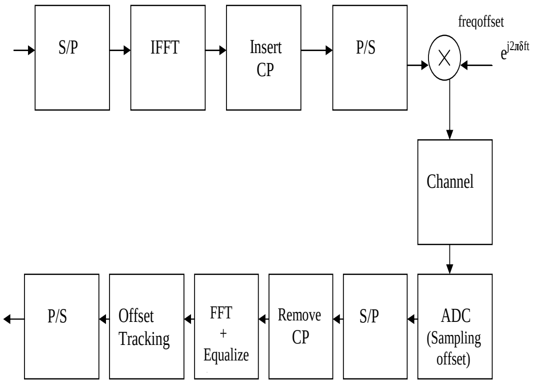

Fig. 1. OFDM System Model

develop a system model that uses the EKF algorithm. A decision directed mode is also applied. EKF is used due to the nonlinearity of the measurement equation in the frequency domain introduced by the residual frequency offset and the sampling time offset. In general, the EKF algortihm has no optimality properties and depends on the accuracy of the linearization. However it has been shown that EKF is a very useful method for obtaining phase estimates [2], [4]. Our proposed method is quite robust and gives better performance under low to moderate SNR conditions for an noisy channel.

This paper is organized as follows. A brief description of the OFDM system model is given next. In Section III, we present the state-space model and our proposed algorithm. Section IV describes the system parameters for the computer simulation. Section V reports the simulation results and we conclude the paper in Section VI.

II. OFDM SYSTEM MODEL

The OFDM system model used in this paper is given in Fig. 1. The transmitted OFDM complex baseband signal is expressed as

$$s(t) = \frac{1}{\sqrt{N}} \sum_{n=-\infty}^{n=\infty} \sum_{k=0}^{N-1} x_{n,k} e^{j2\pi f_k (t-nT_{sym}-T_{cp})} \tag{1}$$

where N is the total number of subcarriers, $x_{n,k}$ is the modulated symbol on the k-th subcarrier in the n-th OFDM symbol, $T_{sym} = T + T_{cp}$ is the duration of a whole OFDM symbol including the cyclic prefix, T is the duration of the data part of the OFDM symbol, T_{cp} is the duration of cyclic prefix, $f_k = k/T$ is the k-th subcarrier frequency and $1/T$ is the subcarrier spacing.

When T_{cp} is chosen longer than the channel delay spread, the inter-block interference is eliminated without affecting the orthogonality of the subcarriers under multi-path channel conditions. At the receiver, after removing the cyclic prefix, the signal is passed through an N-point FFT as shown in Fig. 1.

Assuming ideal synchronization at the receiver side, the k-th subcarrier output of the n-th OFDM symbol in the frequency domain is[6]

$$y_{n,k} = H_{n,k} x_{n,k} + w_{n,k} \tag{2}$$

where $y_{n,k}$ is the FFT-output of the k-th subcarrier in the n-th OFDM symbol, $H_{n,k}$ is the corresponding frequency domain channel response that is almost static for all n in case of wireless LANs and $w_{n,k}$ is complex AWGN. However in the presence of carrier and sampling frequency offsets, the received signal is [6], [7]:

$$\begin{aligned} y_{n,k} = \quad & H_{n,k} x_{n,k} \frac{\sin(\pi\delta f T)}{N \sin(\pi \delta f T/N)} e^{j2\pi\delta f \tau_n} e^{j2\pi k \tau_n / T} \\ & e^{j\pi\delta f T(N-1)/N} + I_{n,k} + w_{n,k} \end{aligned} \tag{3}$$

where δf is the carrier frequency offset, τ_n is the time-variant timing offset of the n-th OFDM symbol and $I_{n,k}$ is the inter-carrier interference (ICI). We can see that in the first component, the modulation data $x_{n,k}$ experiences an amplitude reduction and phase shift due to the offsets leading to a loss in the performance of the OFDM system. To compensate for this degradation, the frequency and timing offsets are acquired and estimated using the short and long preambles in two stages. However, residual synchronization frequency and timing offsets, which are the difference between the estimated and the correct offsets always exist. As the residual offsets are usually very small in practice, the received symbol(3) can be approximated as

$$y_{n,k} = H_{n,k} x_{n,k} e^{j2\pi k \tau_n / T} e^{j\pi\delta f T(N-1)/N} + w_{n,k} \tag{4}$$

where the amplitude reduction and the ICI terms are neglected. Hence, the observed phase of the rotated symbol in the kth subcarrier of the nth OFDM symbol is represented as

$$\theta_{n,k} = 2\pi k \tau_n / T + \pi \delta f T(N-1)/N + \varphi_{n,k} \tag{5}$$

where $\varphi_{n,k}$ is the corresponding phase rotation due to the Gaussian noise. It is observed from equation(5) that the residual frequency offset induces a constant phase rotation of all subcarriers in an OFDM symbol and the sampling time offset induces a phase rotation that increases linearly with the subcarrier index in an OFDM symbol. Also note from eqns.(3)-(5) that we consider non-fading, non-frequency selective channel models to illustrate the effects of frequency and timing offsets. While the proposed EKF technique is also applicable to frequency selective fading channels, we use only AWGN models for the sake of brevity and clarity.

III. OFFSET TRACKING USING EKF

In our work, we have considered the combined phase effects due to the residual carrier frequency and sampling time offsets on the received symbol and formulated the state-space model as follows

State Equations:

$$\theta_{n,k} = \theta_{n,k-1} + \alpha_{n,k-1} \quad (6)$$

$$\alpha_{n,k} = \alpha_{n,k-1} \quad (7)$$

Measurement equation:

$$\hat{y}_{n,k} = e^{j\theta_{n,k}} x_{n,k} + w_{n,k} \quad (8)$$

where $\hat{y}_{n,k}$ is the equalized FFT output of the pilot symbol in the kth subcarrier of the nth OFDM symbol, $x_{n,k}$ is the known pilot symbol in the kth subcarrier of the nth OFDM symbol, $\theta_{n,k}$ is the phase of the corresponding received symbol and $\alpha_{n,k}$ is the slope of the phase of that received symbol which is assumed to remain constant for all subcarriers in an OFDM symbol. Since in the measurement equation, the observation signal $\hat{y}_{n,k}$ has a non-linear relationship with the desired signal $\theta_{n,k}$, the EKF method is used to linearize the measurement equation by taking it's first order Taylor's approximation and truncating it after the linear term [8]. Here no state noise is assumed in the model and the measurement noise variance can be obtained from the FFT outputs of the null subcarriers present in every OFDM symbol.

Our algorithm proceeds in 3 steps.

Step 1. Rotate the subcarriers in the received OFDM symbol by their corresponding phase estimates obtained from the previous OFDM symbol. Instead, note that this can also be achieved by updating the channel estimates in every OFDM symbol.

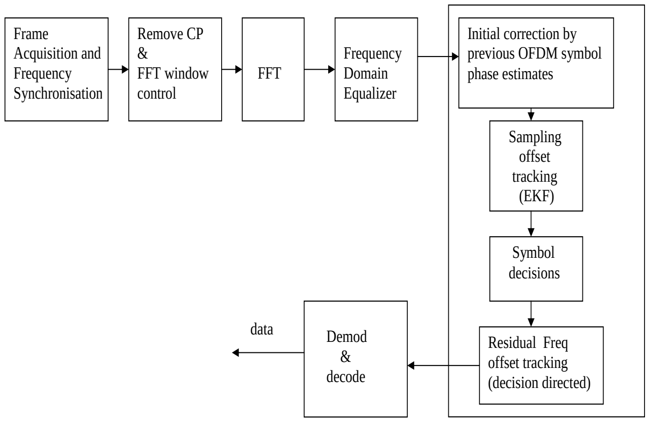

Fig. 2. Proposed Receiver structure

Step 2. Run the EKF algorithm described above over the 4 known pilot-subcarriers in every OFDM symbol to estimate the slope of the phases and use it to compensate the received OFDM symbol for the sampling frequency offset. If the estimated sample offset is greater than a sample duration, then its compensation can't be achieved by a simple phase rotation of the received symbol and so the receiver FFT window needs to be controlled accordingly. For good initialization of the state variables, so that convergence of this EKF algorithm is obtained faster, use the estimates obtained from the algorithm given in [5].

Step 3. Compensate for the residual carrier frequency offset by taking the average of the phase variation of all the subcarriers in the OFDM symbol in a decision directed mode.

The overall structure of this tracking algorithm is illustrated in Fig.2

IV. SIMULATION PARAMETERS

We have chosen the same parameters as those of the IEEE 802.11a specification[9].
Number of data subcarriers:48
Number of null subcarriers:12
Number of pilot symbols:4
Subcarrier frequency spacing(f_{sub}):0.3125MHz
OFDM symbol duration(T_{sym}):4μs
Modulation:QPSK
Residual frequency offset:2% of the subcarrier spacing
Sampling frequency offset:20 ppm
Frame Length:1000 bytes
Channel:AWGN
Perfect initial frame synchronization is assumed.

V. SIMULATION RESULTS

In our simulation studies we first compare the SER performance of the residual carrier frequency offset tracking schemes, assuming no sampling frequency offset for an AWGN channel. A residual frequency offset of 2% of the subcarrier spacing is assumed in our simulation. Fig. 3 shows that the decision-directed tracking algorithm performs much better at low to moderate SNRs than the scheme proposed in [5] which uses only the known 4 pilot symbols in every OFDM symbol to calculate the average of the phase variations. The EKF algorithm employs decision directed tracking over the other 48 non-zero data subcarriers as well to estimate the residual frequency offset. Fig. 4 compares the MSEs obtained for sampling offset(20 ppm) correction using both the slope method [5] and the EKF algorithm for an AWGN channel.

Next we compare the SER performance of our proposed EKF algorithm with and without decision-directed tracking with the average-slope method given in [5] for the combined tracking of residual carrier frequency and sampling frequency offsets in an AWGN channel. Fig. 5 confirms that the proposed EKF algorithm improves the SER performance at low to moderate SNRs. We also observe from Fig. 5 that the EKF scheme applied in a decision directed mode for the residual frequency offset correction yields a small performance improvement over the EKF technique which only uses the 4 known pilot tones for the residual offset tracking.

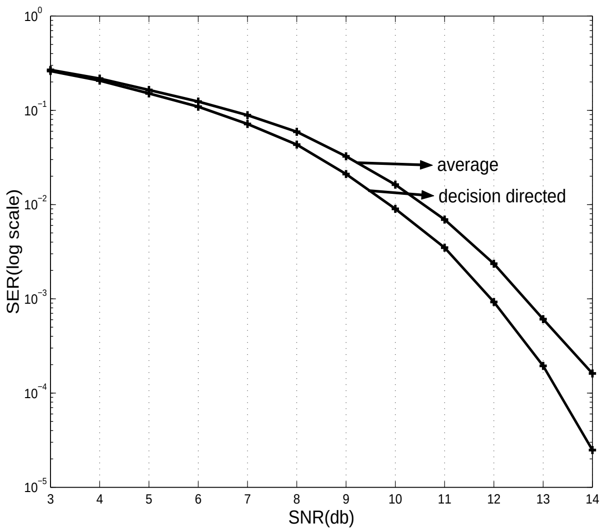

Fig. 3. SER performance of the residual carrier frequency offset tracking algorithms

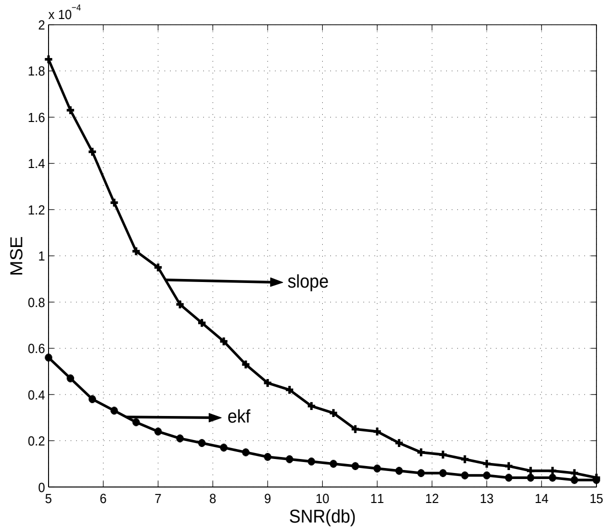

Fig. 4. MSE curves for the sampling offset tracking algorithms

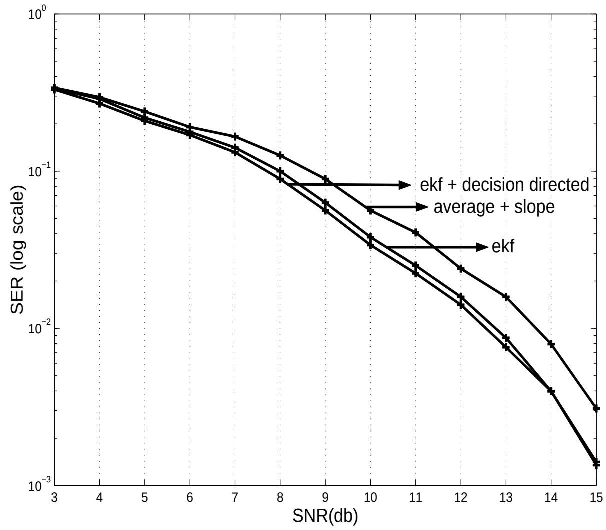

Fig. 5. SER performance of the different combined residual carrier frequency and sampling frequency offset tracking algorithms

VI. CONCLUSION

We have developed a robust, computationally efficient Extended Kalman Filtering scheme for joint tracking of residual carrier frequency and sampling frequency offsets which is directly extendable to fading and/or frequency selective OFDM channels as well. The EKF algorithm runs in the frequency domain and is employed only over the 4 known pilot symbols in every OFDM symbol. The method has fast convergence and performs better than the average-slope algorithm. The reliable performance of our technique is illustrated by computer simulations for AWGN channels.

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