Variance Based OFDM Frame Synchronization

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Abstract. *The paper deals with a new frame synchronization scheme for OFDM systems and calculates the complexity of this scheme. The scheme is based on computing of the detection window variance. The variance is computed in two delayed times, so a modified Early-Late loop is used for the frame position detection.*

The proposed algorithm deals with different variants of OFDM parameters including guard interval, cyclic prefix, and has good properties regarding the choice of the algorithm's parameters since the parameters may be chosen within a wide range without having a high influence on system performance. The verification of the proposed algorithm functionality has been performed on a development environment using universal software radio peripheral (USRP) hardware.

Keywords

Frame synchronization, Orthogonal Frequency Division Multiplex.

1. Introduction

The Orthogonal Frequency Division Multiplexing (OFDM) is a modulation scheme used in modern communication systems such as Wireless Local Area Network (WLAN), Digital Video Broadcasting (DVB) or 3GPP Long Term Evolution (LTE) [1]. Frame detection is fundamental for proper OFDM system performance. Using an OFDM frame we understand time representation of N subcarriers. Frame synchronization is achieved by forcing the receiver to start its FFT at the right time. There exist several algorithms for achieving a frame synchronized system at the receiver side. These tracking algorithms can be primarily categorized into two main groups: training-based and correlation-based. The frequency domain correlation of the received pilot tones with known sequences can be employed, or autocorrelation properties of the received time domain samples imposed by the cyclic extension can be used for OFDM frame timing [2].

The first group is based on transmitting training information for synchronization [3]–[8]. However, because of transmitting the training data there is a waste of bandwidth in these algorithms. For example, in algorithm [7], half of the subcarriers are occupied by known information for timing synchronization.

The second category is based on using the redundancy of the cyclic prefix [9], [10], and these algorithms are generally based on correlation operation either in the time or in the frequency domain. The disadvantage of this approach is in possible inconsistence of a received signal part with a cyclic prefix. In the presence of a delay spread, the cyclic prefix would be affected by the previous OFDM frame resulting in performance degradation.

There are also blind algorithms that attempt to perform timing synchronization by using cylcostationary properties, without relying on the cyclic prefix or training information [11], [12]. The processing delay and computational complexity of these algorithms, however, can be high, making it unfeasible for high delay and Doppler spread environments. There are other methods that use cyclic prefix for coarse synchronization followed by fine tuning based on the impact on channel estimation [13], [14]. These algorithms also do not rely on training information.

The proposed frame detection scheme is based on the difference in variance for different positions of the FFT window. The simulations prove the applicability of the concept and the hardware implementation shows real system performance.

Section 2 describes the calculation of variance for the frame synchronization algorithm and presents some simulations for principle verification. Section 3 describes implementation of the proposed algorithm and boundaries for setting parameters. Mainly the steady state behavior of the loop is analyzed. The hardware evaluation proofs the usability in real environment even with transient effects.

2. Behavior of Variance for OFDM Frame

The basic idea is based on computing variance for an estimated FFT window. The calculated variance reflects the accuracy of the frame detection. We get different values of variance for an FFT window corresponding to OFDM frame or an FFT window out of frame boundaries. In the variance formula:

$$Var(|X|) = E\left[|X|^2\right] - (E[|X|])^2 , \tag{1}$$

the first part corresponds with the mean power of the signal and, for simplicity, we can say it is the same for all frames. For detection, the $(E[|X|])^2$ can be used (or even the expected value or mean value for finite numbers of samples).

The OFDM signal, at the output of the transmitter can be written as:

$$s(t) = \frac{1}{N} \mathrm{Re}\left\{ \sum_{i=-\infty}^{\infty} \sum_{n=0}^{N-1} a_{n,i} g(t - iT_s) e^{j2\pi(f_c + f_n)t} \right\} \tag{3}$$

where $a_{n,i}$ is the complex data symbol, $g(t)$ is the impulse response of the transmitter filters, f_c is the carrier frequency, $f_n = n/T_s$, $n = 0,...,N-1$ is the n-th subcarrier frequency, N is the number of OFDM channels and $1 / T_s$ is the symbol rate associated with each subcarrier.

The signal at the input of the receiver is:

$$r(t) = s(t - \tau) + n(t) \tag{4}$$

where τ represents the receiving time uncertainty in OFDM frame.

The expected value is approximated by computing the mean value for N samples computed according to (5). These values are used in Figs. 1-3.

$$e(\tau) = \frac{1}{N} \sum_{t=\tau}^{\tau+N} \left| FT_N\{r(t)\} \right| \tag{5}$$

where τ means window position for expectation calculation and $FT_N\{\}$ is the Fourier transform of length N. It means that we are sliding the window of the length equal to the OFDM frame length through the received signal and calculating the mean value for each sample step.

The expectation value for each FFT window position is simulated in Fig. 1.

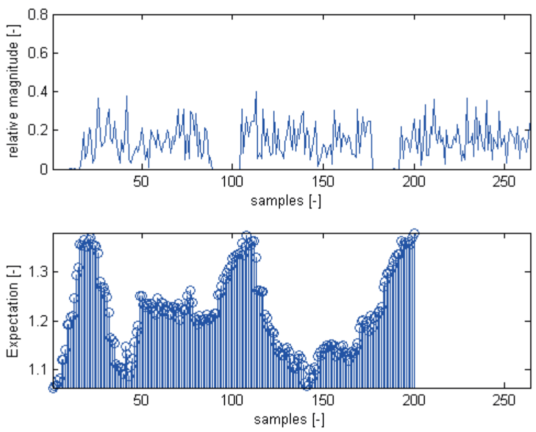

Fig. 1. The sequence of three OFDM frames (module) with guard intervals for separation and corresponding expectation plotted for FFT window offset.

The frame timing can be estimated from plotted expectation values, but it is not clear and probably not useful in this configuration. A big difference can be seen, if the expectation value is calculated for more frames and is averaged as shown in Fig. 2.

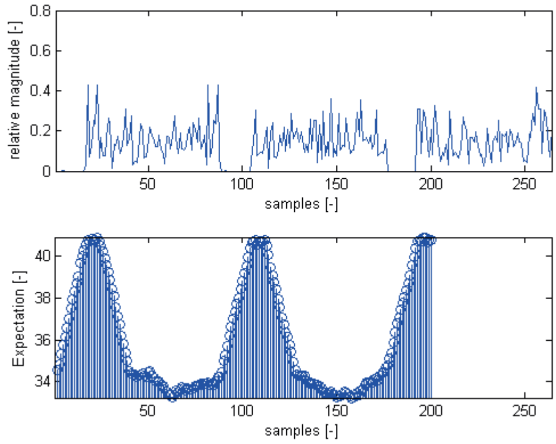

Fig. 2. The sequence of three OFDM frames (module) and corresponding expectation averaged for 10 frames.

The frame timing can be estimated also in a system with no guard interval (Fig. 3). Variance is changed even if a part of the FFT window is from one frame and a part from another. Also, cyclic prefix has no destructive impact on the frame detection (the peak of expectation values has a different shape – wider). This is an advantage comparing with systems based on utilizing cyclic prefix and/or guard interval. To simulate a complex system, the multipath and additive Gaussian noise is presented in the simulation and results can be seen in Fig. 3. The SNR for the simulation was 20 dB, 3 paths with 1, 0.5 and 0.2 magnitudes and 0, 5, 8 sample delay. Especially noise is not critical for this system because of the averaging.

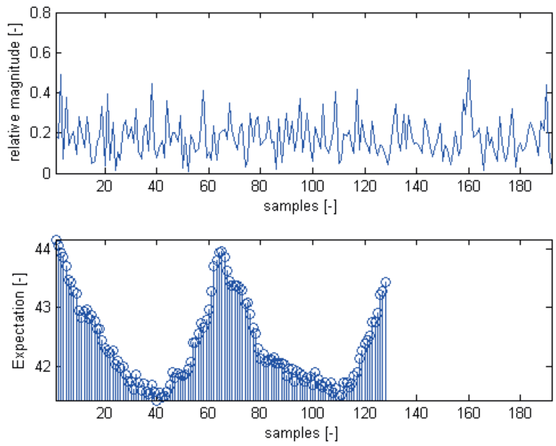

Fig. 3. The sequence of three OFDM frames (module) without guard interval and cyclic prefix and corresponding expectation averaged for 30 frames.

These properties of the OFDM signal indicate the possibility of forming early and late signals and a delay locked loop (DLL) for the synchronization of OFDM frame position.

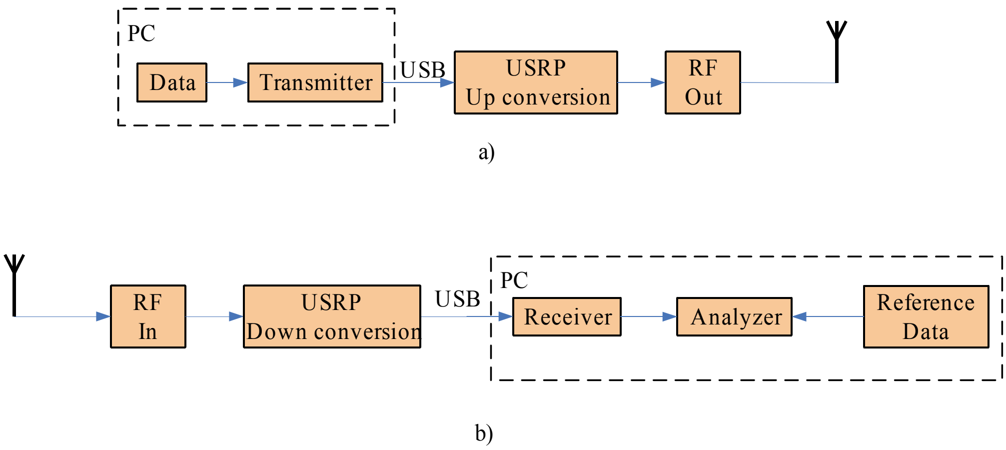

Fig. 4. Block diagram of the experimental setup.

3. Implementation

3.1 Algorithm Complexity

With computing the variance for frame detection, it is not necessary to compute variance every time a new sample arrives. Actually, the variance is calculated at time D samples before assumed frame start and D samples after. Comparing to the blind estimation (for example [12]) computing correlation with every new sample, this is much lower complexity solution (only two FFT and simple summing is needed per one frame). We can use three branches to calculate $\pm D$ variance and branch with assumed proper frame synchronization. The variance calculation complexity (or just simple expected value) is negligible compared to the FFT.

The averaging of variance or delay loop memory in realization means that the algorithm needs time (several frames) for proper frame tracing. In our implementation, the correction of time synchronization is made by steps corresponding to the sample interval. This means that for the worst case (tracking starts in the middle of the frame), the algorithm needs $N/2$ steps to find proper frame start time. This small stepping interval is optimal for the algorithm stability. After the first synchronization is made, the algorithm traces frame and is able to correct frame synchronization errors.

3.2 Software Description and Hardware Description

The block diagram of the experiment setup is shown in Fig. 4. The baseband processing is performed on a personal computer (PC), and up/down conversion is performed on Universal Software Radio Peripheral (USRP) [15] hardware. The PC part of the setup is written in C++ and runs on Linux. The block Data generates and repeats a pseudorandom sequence. The same sequence is generated within the Reference Data block. The block Transmitter performs baseband processing and generates the OFDM signal. The OFDM signal is then transferred to the USRP via USB interface. The communication via USB interface is performed using libusb library. USRP receives data from USB interface and performs digital to analog conversion and up-conversion to 2.4 GHz band. At the receiver chain, similar processing is performed. After down-conversion and analog to digital conversion in the USRP, the signal is transferred via USB interface to PC. The Receiver block performs demodulation and baseband processing. The received data are compared to the sent data in the Analyzer block.

In order to avoid problems with the difference between the theoretical fading channel model and the actual fading channel in the laboratory, we decided to consider an additive white Gaussian noise (AWGN) channel. Therefore, during the experiment, the transmitter and the receiver were connected by a coaxial cable.

The signal processing performed by the Receiver is shown in the block diagram in Fig. 5. As can be seen in the figure, there are three branches. The middle one is the detection branch, and the other two are used for the synchronization. The synchronization branches work with different signal delays. X_L is the signal delayed for $D \cdot T_S$, and X_E is the signal that advances for $D \cdot T_S$ compared to the detection branch. Time synchronization is carried out using DLL with the normalized gain K and with the first order low-pass filter having parameter A and the response:

$$y(k+1) = y(k) \cdot (1-A) + A \cdot \left(E|X_L| - E|X_E|\right) \quad (6)$$

where $y(k)$ is the output, and $x(k)$ is the filter input. The timing correction for the next frame detection $\delta(k+1)$ is calculated according to:

$$\delta(k+1) = \begin{cases} \delta(k) + K \cdot T_S, & y(k) > 0 \\ \delta(k) - K \cdot T_S, & y(k) \le 0 \end{cases}. \quad (7)$$

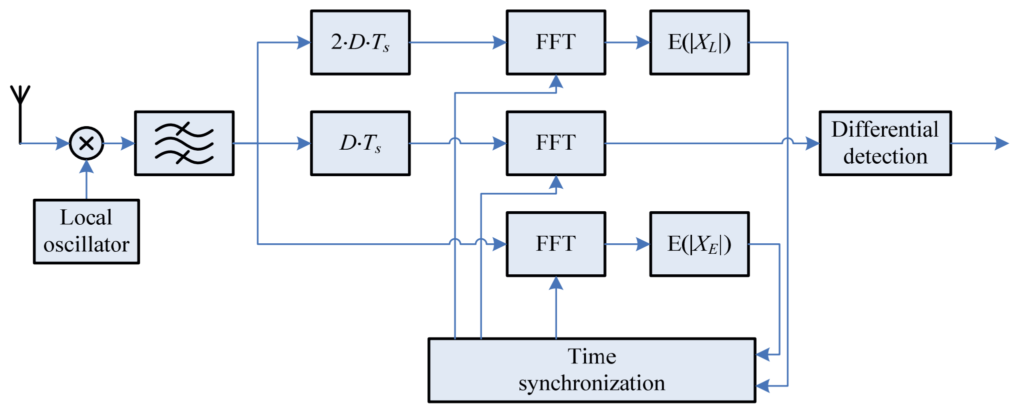

Fig. 5. Receiver block diagram.

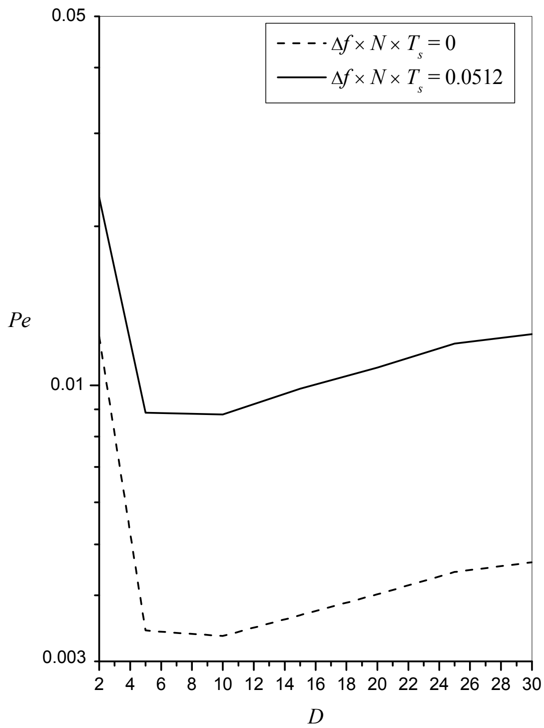

Fig. 6. Error probability as a function of the receiver parameter *D*.

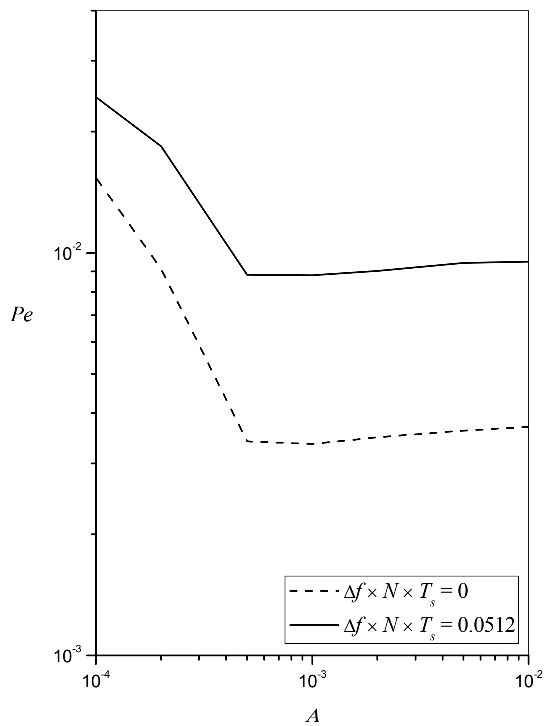

Fig. 7. Error probability as function of the receiver parameter *A*.

3.3 Implementation Results

The performance of the proposed algorithm is analyzed in the case of the OFDM with binary differential phase shift keying (BDPSK). The carrier frequency is equal to $f_c = 2.4$ GHz. There is neither cyclic prefix nor guard interval. Sampling period is $T_s = 4$ μs. The number of channels is N = 64, and there are no virtual channels. Total bitrate of the OFDM signal is 250 kb/s. Signal to noise ratio is set to 7 dB.

The influence of parameters D, A, and K is shown in the following figures. The results are obtained by the experiment. Although usually different metrics for frame synchronization are used, the error probability is used here because of our limitations at simulation and evaluation environment.

Fig. 6 shows the bit error probability as a function of the parameter D for different values of the normalized carrier frequency offset. Other receiver parameters are $A = 0.001$, and K = 0.001. The choice of the parameters A and K will be explained later. It can be seen that the error probability significantly decreases up to D = 4, then it slowly decreases up to D = 10, and after that the error probability rises. The behavior is the same with or without the frequency offset. Therefore, the optimal value for the parameter D is D = 10, and it will be used for the following figures.

Figs. 7 and 8 show the error probability as a function of DLL parameters A and K. It can be seen that there is an optimum value for both of these parameters, and it is approximately A = K = 0.001. Also, an important fact is that there is some flexibility with the choice of these

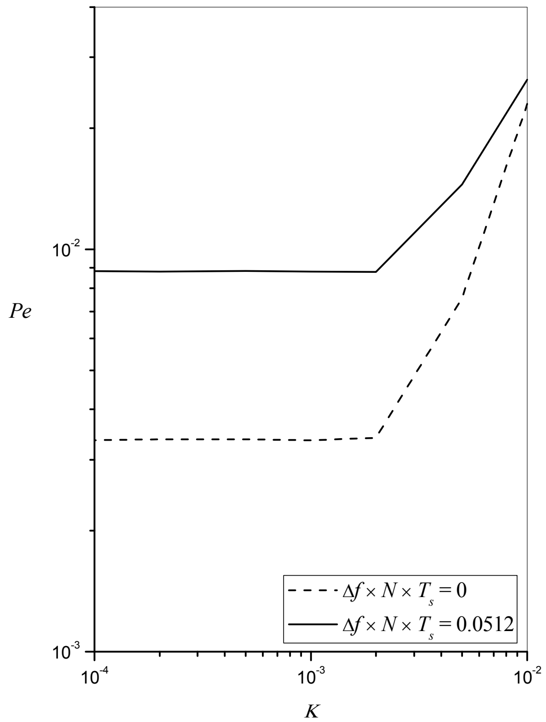

Fig. 8. Error probability as a function of the receiver parameter *K*.

parameters. Namely, the error probability is nearly the same for $A > 0.001$, and also for $K < 0.001$. Thus, we have some freedom during the design of the receiver, particularly during the design of the DLL.

4. Conclusion

The newly proposed OFDM frame synchronization algorithm is presented. The algorithm has low complexity (compared to blind synchronization schemes base on correlation), only two FFT and simple summing is needed per frame. But it needs some time ($N/2$ frames in worst case) to synchronize. The convergence time can be adjusted by the change of the DLL parameter K. Some variable parameter K, different for the acquisition time and different for the steady state of the DLL, can be introduced, but this is out of the scope of this paper. Thanks to the averaging in the DLL, the algorithm has low sensitivity to noise. In the case of normally distributed noise with zero mean, the noise is suppressed by summing and filtering in the DLL. The algorithm uses only the difference in variance calculation, it is not dependent on the guard interval, cyclic prefix or virtual carriers. With the implementation based on the Early-Late loop, only two computations of FFT and mean are needed.

The proposed algorithm has good properties regarding the choice of DLL parameters since the parameters may be chosen within a wide range without having a large influence on system performance. Also, the algorithm is not significantly sensitive to the choice of the parameter D for the frequency offsets of practical importance.

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