Continuous-Mode Frame Synchronization Using Multiple-Frame

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Abstract: In the traditional frame synchronization algorithms, single-frame detection is commonly used in the acquisition followed by verification using multiple-frame. However, when signal-noise-ratio (SNR) is low, the performance of single-frame detection will show dramatically degradation. In the applications that are not time stringent, we could resort to multiple-frame detection to improve the detection performance. Two multiple-frame detection methods, i.e. single-frame majority decision (SFMD) and statistical method have been researched.

Keywords: frame synchronization; multiple-frame detection; correlation rule; ML

1 Introduction

Frame synchronization is a critical issue in digital communication, since it is prerequisite of subsequent processes. The widely used technique for providing frame synchronization is to insert a frame synchronization sequence/pattern or "sync word" (SW) with special property[1] into the random data stream periodically or aperiodically, marking the start of frame. Based on the assumption that symbol synchronization has already been obtained, the receiver obtains frame synchronization by locating the position of the sync word in the received data stream. Thus, frame synchronization is actually a problem of detection of the known sync word.

In the past decades, there has been much research on continuous-mode frame synchronization. In the ideal case of perfect carrier recovery, the optimum approach for the synchronization sequence detection derives from the application of the maximum likelihood (ML) criterion, which performs correlation between the received signal and the locally generated SW, and introduces a corrective energy term. The optimum ML rule for frame synchronization in additive white Gaussian noise (AWGN) channels with binary phase-shift keying (BPSK) signaling was originally proposed by Massey[1]. Nielsen[2] subsequently reported that this ML rule and its high SNR approximation (high SNR ML rule) provided several decibels improvement over the well-known correlation rule. Many years later, Liu and Tan[3] extended these rules to M-ary phase-shift keying (PSK) modulations and corroborated Nielsen's conclusion. In addition, recently, based on the ML criterion, frame synchronization algorithms for flat fading channels[4] and frequency-selective channels[5] were also derived.

The above algorithms were almost based on single-frame observations. However, when SNR is low, the performance of single-frame detection will show dramatically degradation. The receiving environment is not always so good, in addition to noise or jamming, the SNR is sometimes low, so we need some frame synchronization methods that apply to a wider range of SNR, especially lower SNR. In the applications that are not time stringent, we could resort to multiple-frame detection to improve the detection performance. This paper is concerned with continuous-mode frame synchronization using multiple-frame observations.

The rest of the paper is organized as follows. Section 2 models the frame synchronization problem. In Section 3, common single-frame detection methods are first reviewed, and then two multiple-frame detection methods are elaborated. In Section 4, through Monte Carlo simulation, different frame synchronization techniques are compared. Finally, in Section 5, we conclude this paper.

2 Frame Synchronization Model

For simplicity, we consider a M-ary modulation AWGN channel communication system in which data transmission is formatted in successive frames. The data is transmitted

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in a stream of N-symbol frames, of which the first L symbols in each frame form a known synchronization sequence or SW $\boldsymbol{s}=[s_0,s_1,\cdots,s_{L-1}]$. The remaining N—L symbols are random data symbols $\boldsymbol{d}=[d_0,d_1,\cdots,d_{N-L-1}]$, which are assumed to be chosen randomly and uniformly from the signal set [See Figure 1]. We assume that SW symbols are selected from the same set as that of data symbols, i.e. $\{W_j, 0\le j\le M-1\}$, so that no restriction is made on the random data to prohibit the replication of the frame synchronization pattern in the portion of random data. It is generally desirable to choose a sync word with good autocorrelation property satisfying the condition,

$$\begin{gathered}(s_0,s_1,\cdots,s_{k-1})\neq(s_{L-k},s_{L-k+1},\cdots,s_{L-1})\\ k=1,2,\ldots,L-1\end{gathered}\tag{1}$$

which ensures the number of replications of the sync word amid random data to be minimized.

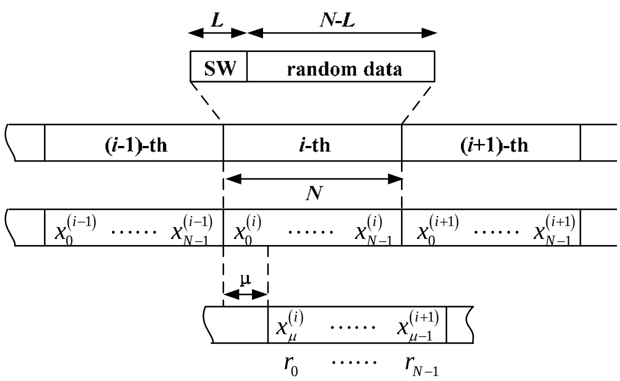

Figure 1. Frame synchronization model[5]

In the absence of a prior information, the received signal is a linear shift of the sequence $[x_k^{(i)},k=0,1\quad N-1]$ with an arbitrary delay $\mu\in[0,1,\cdots,N-1]$. Hence, the frame boundary may appear in any of the N positions with equal probability in an arbitrarily selected N-symbol span observed sequence $\boldsymbol{r}=[r_0,r_1,\cdots,r_{N-1}]$ which is the samples of coherent demodulator output (assuming that the symbol boundary is known). Therefore, the frame synchronization problem is to estimate the index μ from the selected segment.

3 Frame Synchronization Algorithm

The acquisition algorithm we consider is as follows: starting from a position k, the synchronizer observes a vector of N subsequent samples. Based on a suitable metric evaluated from this vector, it decides if the SW is in position k.

3.1 Review of Single-Frame Detection

In the case of periodically embedded SW, i.e. the case of fixed length frame of N—L data symbols delimited by SW of length L, frame synchronization can be performed through the search of the maximum of a metric in a window of N symbols. More precisely, for each of the possible positions of the SW in the observation window, a metric is evaluated over L consecutive (modulo N) received symbols. The position of the SW is chosen as the one corresponding to the maximum evaluated metric.

We will list two famous single-frame detection algorithms below: one is the traditionally correlation rule [see (2) and (3)] and the other is the high SNR ML rule [see (4), which assumes that data symbols are equal ergy].

$$\hat{\mu}=\arg\max_{\mu\in[0,N-1]}\left\{\sum_{i=0}^{L-1}r_{i+\mu}s_i\right\}\tag{2}$$

$$\hat{\mu}=\arg\max_{\mu\in[0,N-1]}\left\{\sum_{i=0}^{L-1}r_{i+\mu}s_i-\sum_{i=0}^{L-1}\left|r_{i+\mu}\right|\right\}\tag{3}$$

The above single-frame detection algorithms will be used in the simulation afterwards.

3.2 Multiple-Frame Detection

There are some reasons to research multiple-frame detection. On one hand, the resulting correct synchronization probability performance may not be adequate only based on one frame length observations. For example, in coherent BPSK signaling with frame length N=35 and the 7-bit Barker sequence, the best possible synchronization performance is bounded by $P_{RDL}=0.9165$ [3]. On the other hand, when SNR is low, the performance of single-frame detection will show dramatically degradation. Better performance can be obtained by using multiple-frame length observations to estimate the SW starting position. One method is to make individual SW starting position estimates based on single-frame observations for M successive frames and then to use a majority decision rule which decides on the majority of the *M* independent single-frame estimates as the SW starting position. We call this single-frame majority decision (SFMD) method. The individual frame boundary estimates can be achieved as before, using either ML, high SNR ML, or correlation rule. The other method is to decide the maximum of the statistic accumulated value as the SW starting position. We call this statistical method.

3.2.1 SFMD

The basic idea of SFMD is easy; we want to point out especially is that, the "majority decision rule" here is different from the traditional one which means exceed half, instead, we mean the most frequently occur which may be not exceed half here. If there are some elements that appear most frequently for the same times, then we cannot make the decision which one corresponds to the SW starting position, and the detection is fail. For example, in the vector [10,20,58,20,3,58,58,20], "20" and "58" appear most frequently, and both of them repeat for three times, then we cannot make the decision whether the SW starting position is at "20" or "58". Then we consider that the detection is fail.

3.2.2 Statistical Method

When the data quantity is adequate, we can make use of the idea of "statistics". We do not make SW starting position estimate on single-frame observations, instead, accumulate multiple-frame observations to make the decision. Figure 2 is the schematic diagram of multiple-frame detection using statistical method. Assume the length of a frame is N, shift data buffer can buffer data of length N; as the data stream shift enter into the buffer, the data in the buffer update. Single-frame detector is performed according to some single-frame detection algorithm, but only computes a test statistic $\Lambda(\mu)$ corresponding to the current frame in the buffer instead of making SW starting position estimate. Cyclic counter counts cyclically in the range of 1~N, indicating the position where the current frame is. The test statistic $\Lambda(\mu)$ is input in the corresponding accumulator i according to the index i. Comparator compares the accumulated value in all accumulators, finding the accumulator corresponding to the maximum accumulated value. And the index of that accumulator is regarded as the SW starting position.

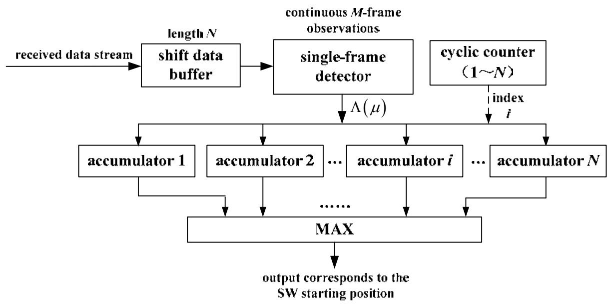

Figure 2. Schematic diagram of multiple-frame detection using statistical method

4 Simulation Result

Unfortunately, as Lui and Tan pointed out, an exact theoretical performance evaluation of these decision rules does not generally seem to be feasible. As alternative approaches, we have resorted to Monte Carlo simulations to aid in performance assessment.

We report in this section some examples of numerical results. Since the simulation results for single-frame detection have been presented in many literatures, we do not repeat them here. In particular, we compare the performance of the two multiple-frame detection methods, i.e. SFMD and statistical method. In the simulation, we consider the simplest scenario, involving continuous transmission of binary symbols over AWGN channel. The parameters chosen are as follows: N=162, L=15, s=[-1,-1,-1,1,-1,-1,1,1,-1,1,-1,1,1,1,1], which apparently conforms to the property presented in Section 2(1). All experiments are performed 1 000 Monte Carlo trails. And each curve shows the percentage of correctly synchronized frames for the different rules depending on the average channel SNR.

Experiment 1——Comparison of Single-Frame Detection and Multiple-Frame Detection:

First, we report in Figure 3 and Figure 4 the performance comparison of single-frame detection and multi-

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ple-frame detection, respectively for SFMD and statistical method. For single-frame detection, we use correlation rule and high SNR ML rule. For multiple-frame detection, we choose continuous ten frames observations for the detection; and in the individual estimation of SFMD we also used above two single-frame detection methods. From the two figures, it is apparently that the performance of multiple-frame detection is better than single-frame detection; the SNR range multiple-frame applied is larger than single-frame detection. For example, for high SNR ML rule, when SNR is -8 dB, detection probability of statistical method is 94.9%, while single- is only 9.3%. Yet again, it is confirmed that the high SNR ML rule performs better than the traditional correlation rule.

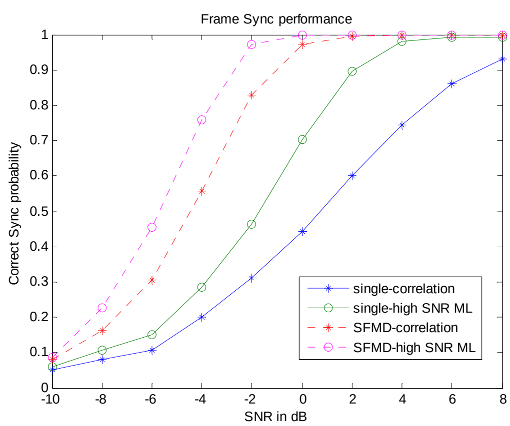


Figure 3. Comparison of SFMD and single-frame detection

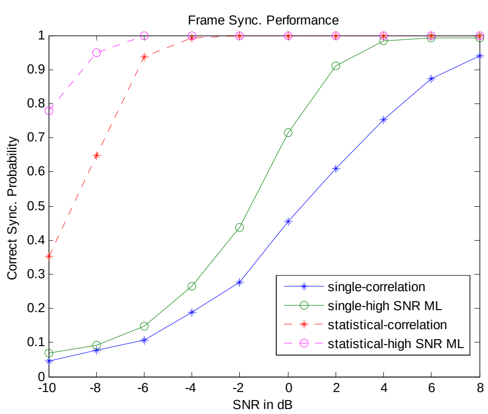


Figure 4. Comparison of statistical method and single-frame detection

In addition, we can see that for SNR lower than -2 dB, the difference between single- and statistical method is larger than the one between single- and SFMD. In other words, statistical method is better than SFMD. This will be further validated in the following by comparing the two multiple-frame detection methods.

Experiment 2——Comparison of two Multiple-Frame Detection Methods:

Here we'd like to compare the detection performance of the two multiple-frame detection methods. Frame number used in the simulation is just the same. We randomly choose ten continuous frame observations for detection. The result is showed in Figure 5. It is clearly confirmed the conclusion we get in Experiment 1 that statistical method performs better than SFMD when SNR is low. And we also note that high SNR ML is much better than correlation for statistical method than corresponding cases for SFMD method when SNR is low.

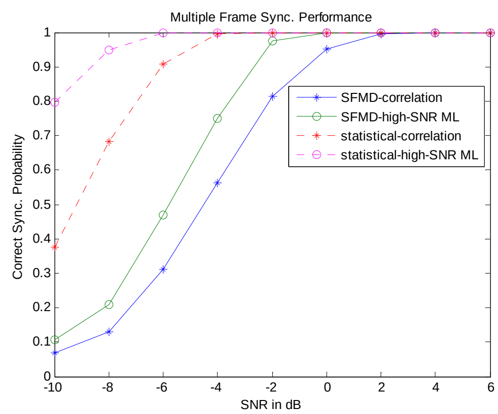
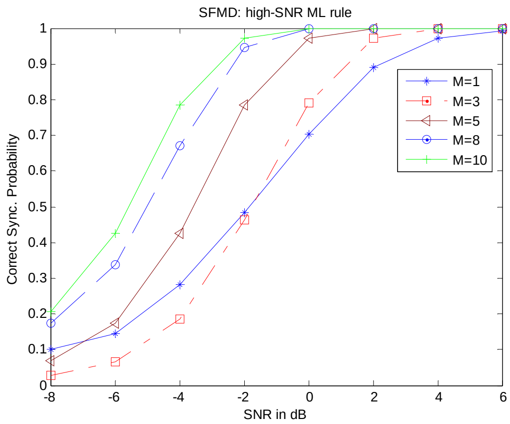


Figure 5. Comparison of the two multiple-frame detection method

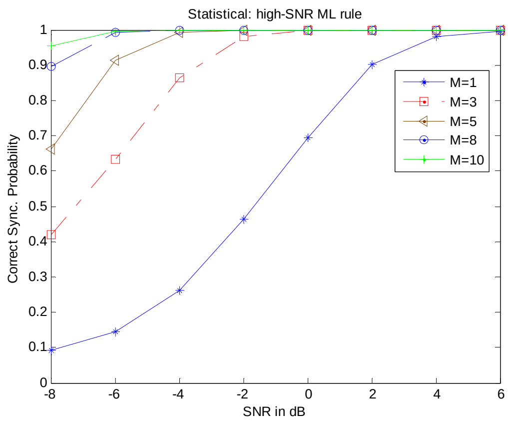
Experiment 3——Effect of Frame Number for Multiple-Frame Detection:

For multiple-frame detection, frame number we choose for detection is an important parameter which will influence the performance. Varying the number of frame for multiple-frame detection, *M*, we get the result showed in Figure 6. From Figure 6(a), for SFDM, we see that when SNR is lower than -2 dB, the performance of M=3 is worse than M=1, which corresponds to the case of single-frame detection. In this case, frame number is so small that there is no meaningless for *M*-frame detection. While, for statistical method, the performance of M=3 is much better than M=1. Moreover, we can arrive at a conclusion that *M* has more influence on statistical method than SFMD; in other words, SFMD is not sensitive to *M* relative to statistical method.

In general, no matter SFMD or statistical method, the more frame number, the better the performance.



(a) SFMD



(b) Statistical method

Figure 6. Effect of frame number M on detection performance

However, as frame number increased, the time for detection and complexity of computation will also increase. So we need choose proper frame number to compromise between them.

5 Conclusions

In this paper, we reviewed the common single-frame detection algorithms, such as traditional correlation rule and (almost optimal) high SNR ML rule. However, the performance may not be adequate only based on one frame length observations, and when SNR is low, the performance of single-frame detection will show dramatically degradation. In the applications that are not time stringent, frame synchronization using multiple-frame will improve the performance remarkably. Two multiple-frame detection methods, i.e. SFMD and statistical method, are compared by Monte Carlo simulation. And the effect of frame number on the detection performance is also studied. Simulations show that statistical method performs better than SFMD, and SFMD is not sensitive to frame number relative to statistical method.

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