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Research Article

Robust Frame Synchronization for Low Signal-to-Noise Ratio Channels Using Energy-Corrected Differential Correlation

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Recent standards for wireless transmission require reliable synchronization for channels with low signal-to-noise ratio (SNR) as well as with a large amount of frequency offset, which necessitates a robust correlator structure for the initial frame synchronization process. In this paper, a new correlation strategy especially targeted for low SNR regions is proposed and its performance is analyzed. By utilizing a modified energy correction term, the proposed method effectively reduces the variance of the decision variable to enhance the detection performance. Most importantly, the method is demonstrated to outperform all previously reported schemes by a significant margin, for SNRs below 5 dB regardless of the existence of the frequency offsets. A variation of the proposed method is also presented for further enhancement over the channels with small frequency errors. The particular application considered for the performance verification is the second generation digital video broadcasting system for satellites (DVB-S2).

1. Introduction

Reliable synchronization is one of the key factors determining the transmission performance in communication channels, and various schemes for time, frequency, and phase estimation for imperfect communication links have been proposed and implemented. Although time and frequency estimation can be jointly performed at an increased complexity, frequency synchronization is usually preceded by the symbol and frame synchronization. A classic result on coherent detection for the frame synchronization has been presented by Massey [1], which suggests the usage of a data correction term for the optimal maximum likelihood (ML) statistics. The result has subsequently been verified, extended to specific modulation schemes, and approximated to suboptimal solutions [2–5]. In many practical receivers, the suboptimal metrics become preferred choices due to their simplicity and reasonable performance. The approximation of ML statistics using the low SNR assumption leads to a simplified computation of the correction term in the form of received signal energy [1, 2, 5].

While these coherent detection schemes provide optimal or near-optimal performance in the static additive white Gaussian noise (AWGN) channel, a performance loss is experienced when the frequency error exists in the channel. Under such circumstances, differential correlation metrics provide robustness to frequency and phase errors. In particular, detection methods in [6] are derived from the approximated ML metrics, and give a lower detection error probability than other known schemes. Reduced-complexity schemes are also extensively studied [7–10]. Differential postdetection integration (DPDI) techniques [8] are shown to provide a good performance-complexity tradeoff, and generalized DPDI including average postdetection integration (APDI) schemes has also been proposed and analyzed [9, 10].

On the other hand, the requirements for the initial synchronization performance are becoming more stringent. As advanced transmission schemes including efficient modulation and powerful error-correction coding are developed, target operating SNRs tend to decrease to allow data transmission even in hostile channel environment and to maximize the bandwidth usage. The recent DVB-S2 standard [11, 12] adopted the low-density parity-check (LDPC) coding for adaptive coding and modulation (ACM), which includes high-density amplitude phase shift keying (APSK) as well as conventional phase shift keying (PSK). These techniques lowered the minimum operating SNR down to −2.35 dB for the lowest ACM level. Since initial synchronization should reliably be performed for all ACM levels, it is important to verify the detector performance at this low SNR range.

In this paper, we propose detection strategies for robust frame synchronization under the effects of severe noise and frequency offsets and verify the corresponding performance. The proposed detector is constructed via appropriate adjustments of the correction term, and variational methods for further performance enhancement are also suggested. It is demonstrated that the methods provide a substantial gain over existing schemes for the SNR range of interest. The organization of the paper is as follows. The signal model, frame structure, and channel conditions used for performance evaluation are introduced in Section 2. In Section 3, a brief review and comparison of existing decision metrics for the frame synchronization are given, and the proposed method is presented. In Section 4, we discuss properties and parameter optimization issues of the proposed method. The detection performance is evaluated for different channel conditions to quantify the gain in Section 5, and the conclusions are given in Section 6.

2. Signal Model

We consider successive transmission of frames of length L over the AWGN channel, and each frame includes a synchronization sequence of length N in its header. Figure 1 shows the frame structure for the DVB-S2 standard. The frame consists of the physical layer header (PL Header) followed by the forward error correction frame (FEC Frame), which is an LDPC encoded sequence of payload data symbols. The PL Header includes the synchronization sequence named as the Start-of-Frame (SoF), consisting of $N = 26$ symbols, and the physical layer signaling code (PLSC) used for the frame-specific information indication such as the modulation type, coding rate, and the length of the frame. The PL Header symbols are modulated using $\pi/2$-binary PSK, whereas the FEC Frame symbols are modulated by PSK or APSK. More specifically, one of quadrature PSK (QPSK), 8-PSK, 16-APSK, or 32-APSK modulation schemes is used based on the transmission channel condition.

Assuming perfect symbol-time synchronization is performed at the receiver, the discrete sample at the kth symbol time can be expressed as follows:

$$r_k = b_k e^{j(2\pi k f_0 T_s + \phi_0)} + n_k, \tag{1}$$

where b_k is the modulated symbol with normalized power $\mathbb{E}|d_k|^2 = 1$ and n_k is the AWGN sample with variance σ_n^2. Then the received SNR E_s/N_0 is determined as $1/\sigma_n^2$. Parameters f_0 and ϕ_0, respectively, denote the frequency offset and the phase offset, and T_s is the symbol duration.

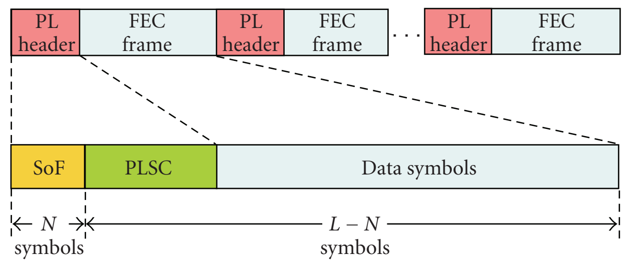

Figure 1: The frame structure for DVB-S2 which includes the start-of-frame (SoF) synchronization sequence of length $N = 26$.

We assume that f_0 takes one of the values from $[-f_m, +f_m]$ where f_m represents the maximum amount of frequency offset, and ϕ_0 takes one of the values from $[-\pi, +\pi]$. The frame detection includes the correlation of N consecutive received samples with the synchronization sequence symbols $s_0, s_1, \ldots, s_{N-1}$.

For the performance evaluation, the SoF of length $N = 26$ is used as the synchronization sequence. A particular attention is given to mid to low SNR values, including the minimum required operational SNR of −2.35 dB for DVB-S2. The maximum frequency offset is 20% of the transmission bandwidth; that is, the normalized maximum frequency offset is given by $f_m T_s = 0.2$. Unless otherwise stated, the frequency offset is uniformly generated from the range $[-0.2/T_s, +0.2/T_s]$.

3. Correlation Methods for Frame Synchronization

A simple yet effective solution for the frame synchronization utilizes the direct correlation between the sequence of received samples and the synchronization sequence [4], and the correlation value c_k at the kth symbol time is obtained using N consecutive received samples $r_k, r_{k+1}, \ldots, r_{k+N-1}$ as follows:

$$c_k = \sum_{i=0}^{N-1} r_{i+k}^* s_i \tag{2}$$

and the frame boundary is detected using the variable $z_k = |c_k|$. The decision can either be made via hypothesis testing using a threshold value or by choosing the location at which the maximum value of z_k occurs. It has been reported by Massey [1] that the ML detection requires the decision variable $z_k = |c_k| - e_k$, where e_k is called the *correction term*. For small values of SNR $E_s/N_0 \ll 1$, it has been shown that the correction term takes the form of

$$e_k = \frac{\sqrt{E_s}}{N_0} \sum_{i=0}^{N-1} |r_{i+k}|^2, \tag{3}$$

which accounts for the energy correction of the received sequence. It has also been confirmed by Gansman et al. [5] that the correction term of the ML detector reduces to a function of the received signal energy when the low SNR approximation is applied.

To effectively mitigate the influence of frequency offsets, frame synchronization detectors based on the differential correlator structure have been developed. The differential version of the coherent correlation in (2) can be written as follows:

$$d_k = \sum_{i=1}^{N-1} r_{i+k}^* s_i r_{i+k-1} s_{i-1}^* \tag{4}$$

and more generally, the *n-span differential correlation* is defined as follows:

$$d_k(n) = \sum_{i=n}^{N-1} r_{i+k}^* s_i r_{i+k-n} s_{i-n}^*. \tag{5}$$

Such correlation has been utilized in the decision variable $z_k = d_k(0) + 2\sum_{n=1}^{m} |d_k(n)|$ suggested in [9], where parameter m ($<L$) determines the performance versus complexity tradeoff. Related discussion can also be found in [10], which presents the variable $z_k = \sum_{n=1}^{m} |d_k(n)|$ for enhanced detection performance under a severe effect of frequency offset.

Although these detection schemes offer a reasonable performance at decreased complexity, improvement can be made by using the decision variable derived from the ML criterion. By approximating the Bessel function in the likelihood function to a fourth-degree polynomial, the decision variable is derived as [6]

$$\text{[C1]} \quad z_k = \sum_{n=1}^{N-1} \left\{ |d_k(n)|^2 - \sum_{i=n}^{N-1} |r_{i+k}|^2 |r_{i+k-n}|^2 \right\} \tag{6}$$

and subsequently modified to

$$\text{[C2]} \quad z_k = \sum_{n=1}^{N-1} \left\{ |d_k(n)| - \sum_{i=n}^{N-1} |r_{i+k}|\, |r_{i+k-n}| \right\} \tag{7}$$

by dropping the squares, which results in performance enhancement over the original for many cases of practical interest. The frame detectors using the decision variables in (6) and (7) will, respectively, be called C1 and C2 detectors. At an increased complexity caused by additional computation of the correction terms, C1 and C2 detectors outperform all the other aforementioned detection strategies in the presence of frequency offsets.

Our proposal of new detector structures is motivated by the facts that (i) a significant performance improvement occurs by modifying the correction term in (7) from that in (6) to perform the "energy correction operation" (i.e., the correction term has the unit of energy) which is in agreement of the related discussions in [1, 5], and (ii) dropping the squares from the received power $|r_i|^2$ is not the only possible way of such modification and alternative variations may exist. By defining

$$\varepsilon_k(n) = \sum_{i=n}^{N-1} |r_{i+k}|^2 |r_{i+k-n}|^2 \tag{8}$$

and by taking the square-root of the correction term in (6), we obtain a new decision variable

$$\text{[L1]} \quad z_k = \sum_{n=1}^{N-1} \left\{ |d_k(n)| - \sqrt{\varepsilon_k(n)} \right\} \tag{9}$$

for the frame detection and call the corresponding detector L1. Multiple appearances of identical received samples in the decision variable result in highly correlated statistical characteristics, and an exact analytic evaluation of the statistics for each decision variable seems difficult. Nevertheless, the advantage of the proposed variable is immediately observable from the distributions experimentally obtained, as discussed in the following.

4. Properties and Variations of Proposed Correlation

4.1. Distribution of the Decision Variables. The detection performance is strongly related to the statistical distribution of the decision variable. Reliable detection is expected when the values of the decision variable at the synchronous (i.e., frame boundary) and asynchronous symbol positions are (i) sufficiently separated and (ii) distributed with small variances. It can be shown from the expression in (7) that neglecting the effect of noise,

$$\mathbb{E}[z_k] = \begin{cases} -\dfrac{N(N-1)}{2}, & \text{(asynchronous)} \\ 0 & \text{(synchronous)} \end{cases} \tag{10}$$

for the C2 decision variable. Similarly, the L1 decision variable in (9) satisfies

$$\mathbb{E}[z_k] = \begin{cases} -\dfrac{(8N-3)\sqrt{(4N-3)}-5}{24}, & \text{(asynchronous)} \\ \dfrac{N(N-1)}{2} - \dfrac{(8N-3)\sqrt{(4N-3)}-5}{24} & \text{(synchronous).} \end{cases} \tag{11}$$

Thus for both C2 and L1 decision variables, the difference between the averages for synchronous and asynchronous distributions is equal to $N(N-1)/2$. As the SNR decreases, not only the difference between the averages becomes smaller, but variances increase to result in a significant overlap of synchronous and asynchronous distributions. Figure 2 gives such an illustration by showing the probability density functions (PDFs) for both the synchronous and asynchronous decision variables, obtained from repeated simulations of C2 and L1 variables at −2.35 dB SNR. Although it can be verified that the separation between the averages of two distributions is identical for both C2 and L1 detectors, the variance of L1 decision variable is sufficiently smaller than the variance of C2 decision variable. This gives a smaller overlapped area between two distributions, which enhances the detection performance. Figure 3 compares the variances of C2 and L1 for different SNR values, which confirms that the proposed L1 decision variable has a strictly smaller variance for the low SNR range.

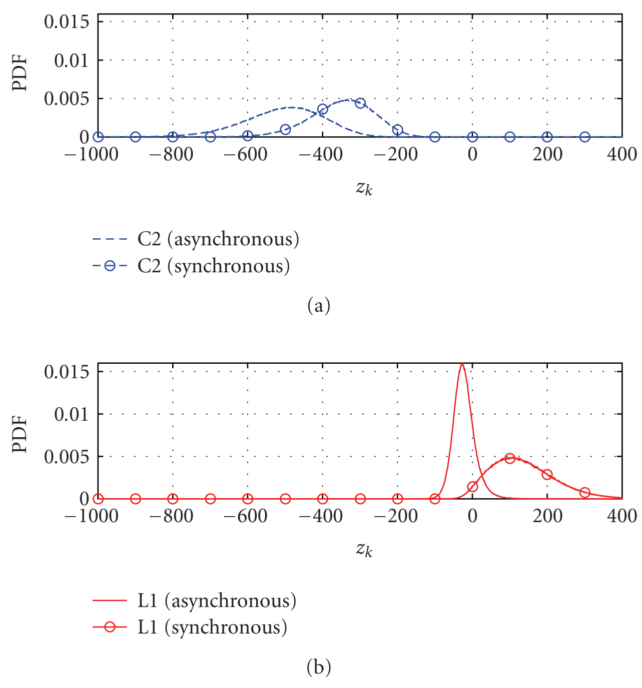

Figure 2: Probability density functions of the decision variables for (a) C2 detector and (b) L1 detector at −2.35 dB SNR ($f_m T_s = 0.2$).

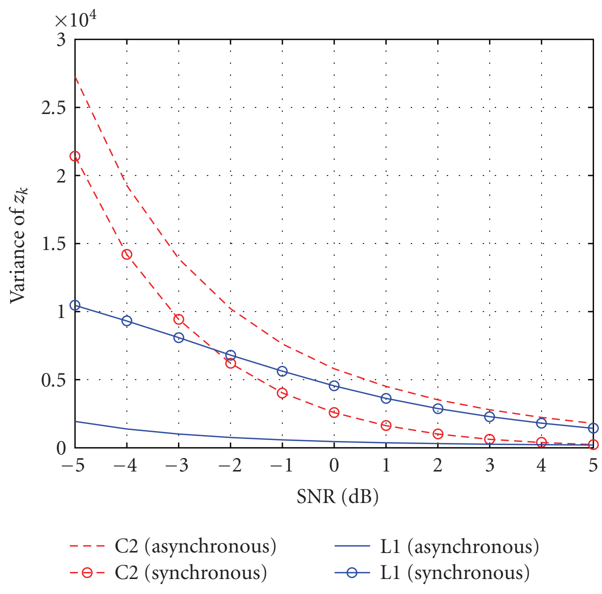

Figure 3: Variance of the decision variables for C2 and L1 detectors over different SNR values ($f_m T_s = 0.2$).

4.2. Utilization of the Vector Sum. Instead of summing their magnitudes, n-span differential correlation values can be coherently combined to produce another modified decision statistics. Such combining corresponds to the summation of vectors representing complex values $\{d_k(n)\}$. The "L2" detector in proposition uses the decision variable associated with the vector sum of n-span differential correlation

$$\text{[L2]} \quad z_k = \left| \sum_{n=1}^{M} d_k(n) \right| - \sqrt{\sum_{n=1}^{M} \varepsilon_k(n)}, \tag{12}$$

where integer parameter M needs to be appropriately chosen to maximize the performance of the detection. When the frame is synchronized under the noise-free condition, $d_k(n)$ is represented by a vector with phase angle $-2\pi n f_0 T_s$, and the complex sum of the n-span differential correlation in the first term of (9) becomes

$$\sum_{n=1}^{M} (N-n) e^{-j2\pi n f_0 T_s}. \tag{13}$$

To maximize the magnitude of the vector sum in (13), a smaller value of M is desired as the frequency offset f_0 increases, since otherwise the sum of vectors with widespread angles results in a reduced magnitude. It can be observed that the magnitude of the vector sum begins to diminish as the terms with angular phase exceeding π radians are added; thus parameter M needs to be chosen to satisfy $M f_0 T_s < 0.5$. As the frequency offset increases, a smaller number of n-span differential correlation values contribute to the decision variable, and the reliability of the statistics decreases. Thus L2 exhibits improved performance over L1 when the frequency offset is small but is eventually outperformed by L1 as f_0 increases.

4.3. Weighted Energy Correction. The amount of energy correction can further be adjusted by introducing a multiplicative weight factor. To account for the weighted energy correction, the decision variable for L1 is modified as follows:

$$\text{[L3]} \quad z_k = \sum_{n=1}^{N-1} \left\{ |d_k(n)| - \alpha \sqrt{\varepsilon_k(n)} \right\} \tag{14}$$

and the decision variable for L2 is modified as follows:

$$\text{[L4]} \quad z_k = \left| \sum_{n=1}^{M} d_k(n) \right| - \beta \sqrt{\sum_{n=1}^{M} \varepsilon_k(n)} \tag{15}$$

using respective weight factors α and β. Since the performance of L3 and L4 detectors varies based on the choice of these parameters, proper parameter values need to be determined for the optimized performance at target operating points.

5. Performance Evaluation

The false alarm rate (FAR) and the misdetection probability (MDP) at a given symbol time are used as key measures for the detection performance. Denoting the threshold for the frame boundary detection by Γ, the FAR is given by

$$P_{\text{FA}}(\Gamma) = \int_{\Gamma}^{\infty} f_{z_k}(x \mid H_0) dx \tag{16}$$

which is the probability that the decision variable exceeds the threshold for a given asynchronous symbol index k. Here

$f_{z_k}(x \mid H_0)$ is the PDF for the asynchronous decision variable. The MDP is the probability that the decision variable is below the threshold for the synchronous symbol position and is given by

$$P_{\text{MD}}(\Gamma) = \int_{-\infty}^{\Gamma} f_{z_k}(x \mid H_1)dx, \tag{17}$$

where $f_{z_k}(x \mid H_1)$ is the PDF for the synchronous decision variable. For the evaluation of FAR, random QPSK data symbols are generated and noise samples are added. The noise-corrupted data symbols are correlated with the SoF symbols; then the decision variable is computed and threshold tested. In the case of MDP, a similar procedure is performed, by generating noise corrupted SoF symbols instead of random data symbols for correlation.

An effective way of identifying the detection performance is to determine the MDP for a given constant FAR (CFAR). Figure 4 shows the MDP at CFAR of 10^{-3} for the L3 detector, using different values of weight α. The MDPs for the C1 and C2 detectors are also plotted for comparison. It is clearly indicated in the figure that the proposed L3 detector outperforms both C1 and C2 detectors for appropriately chosen values of α. The MDP for L3 lies strictly below those of C1 and C2 when $0.4 < \alpha < 2.2$, at the minimum operating SNR of −2.35 dB. The performance gain of L3 increases with a sufficient margin at 0 dB SNR. It is observed that the optimal value of α depends on SNR, suggesting parameter adaptation may be desired. However, initial frame synchronization is usually done without any prior knowledge of the channel, and we choose to select the parameter optimized for the worst channel condition, that is, SNR of 0 dB or below. For all remaining performance evaluation, $\alpha = 1.6$ is used for L3. The MDP for L4 using different values of weight β is shown in Figure 5. Since L4 detection is mainly applicable to channels with no or small frequency offsets, parameter dependency of the performance is evaluated when $f_m = 0$. Significant performance improvement is observed for both SNR values, and the gain over conventional schemes is more substantial for L4. For the remainder of discussion, $\beta = 6.0$ is applied. Also note that $\alpha = 0$ or $\beta = 0$ corresponds to no energy correction for decision variables.

The receiver operating characteristics (ROCs) are shown in Figure 6, which are obtained by evaluating MDP and FAR pairs using varying values of the detection threshold for −2.35 dB and 3 dB SNRs. The ROC gain of L3 in comparison to existing schemes under the effects of frequency offsets is shown in the figure. Although L4 does not provide any gain in this case, L4 detection can be more advantageous when there exists no frequency offset. Therefore the usage of L3 detection is suggested for general channel conditions with unknown frequency offsets, and L4 is applicable for further performance enhancement when the channel is known to have a small frequency offset. More precisely, the normalized frequency offset at which L4 begins to outperform L3 can be found from the MDP curves in Figure 7, which is evaluated at 0 dB SNR with 10^{-3} FAR. It is indicated in the figure that L4 exhibits the performance gain when normalized offsets are less than 5.7% at 0 dB SNR, and L3 becomes the preferred choice of detection for frequency offsets larger than those values.

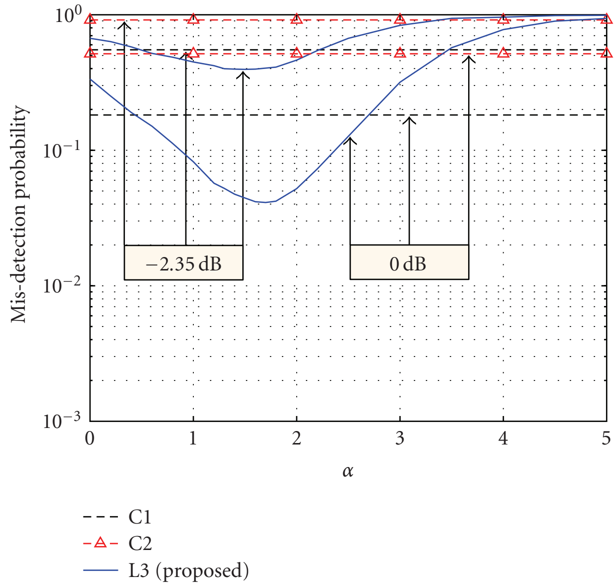

Figure 4: Misdetection probability of the L3 detector for different correction weights at CFAR of 10^{-3} ($f_m T_s = 0.2$).

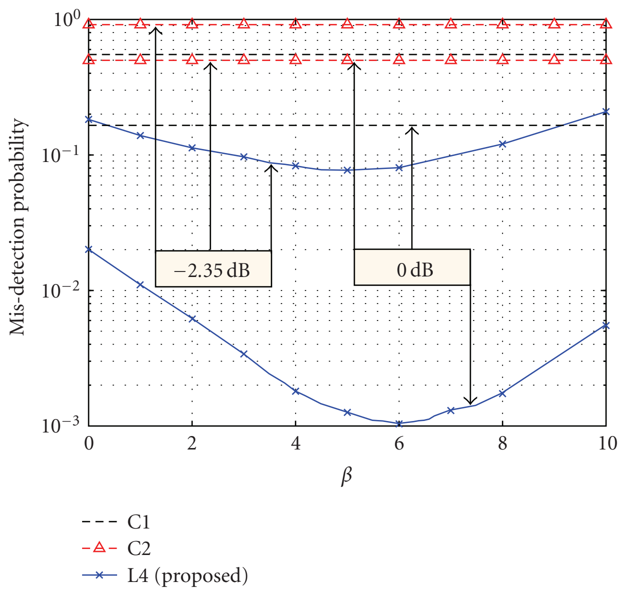

Figure 5: Misdetection probability of the L4 detector for different correction weights at CFAR of 10^{-3} ($f_m T_s = 0$).

The detection performance under different SNR values is shown in Figure 8, where MDPs are plotted when the CFAR is 10^{-3} with maximum normalized frequency offset of 0.2. The amount of gain for L3 over other methods is shown to be substantial over the entire range of interest. For reliable transmission to mobile users under various channel conditions, integrating mobility in satellite applications is gaining more attention [13–15], and performance verification under the effects of fading is necessary. Figure 9 gives the

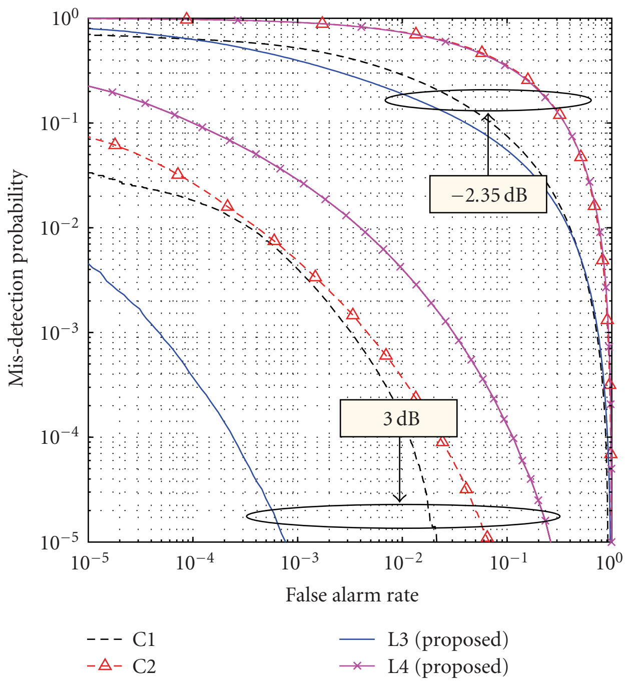

Figure 6: Receiver operating characteristics of the proposed and conventional detectors under severe frequency offsets ($f_m T_s = 0.2$).

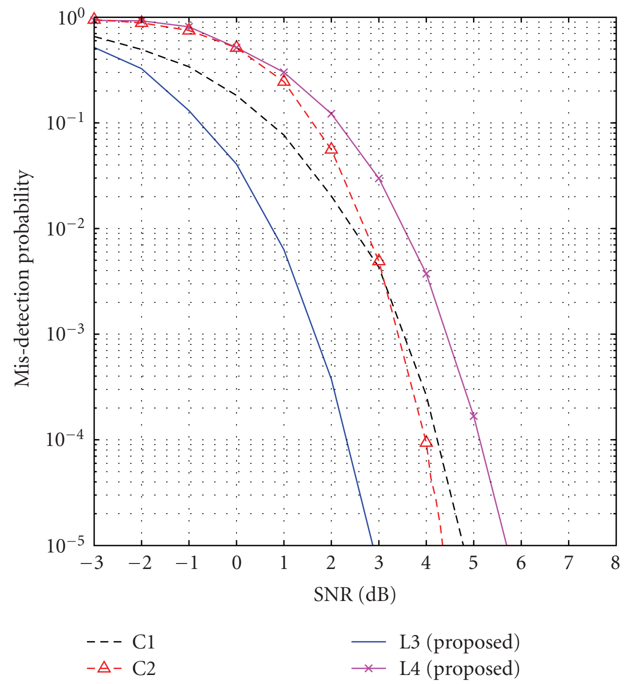

Figure 8: Misdetection probability at different SNR values (FAR= 10^{-3}, $f_m T_s = 0.2$).

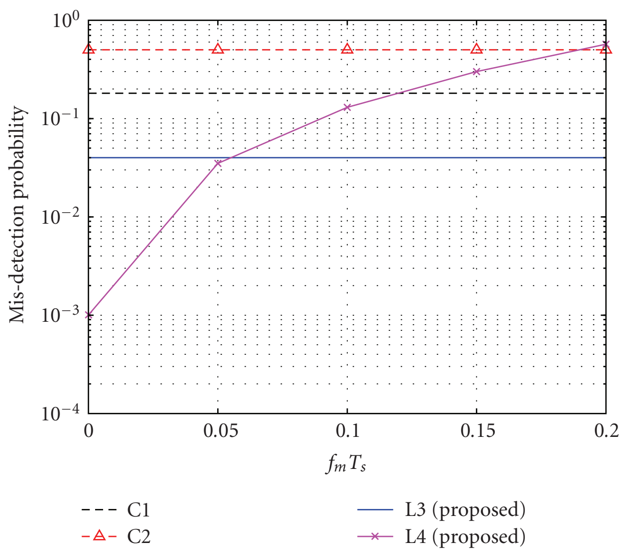

Figure 7: Detection performance as a function of frequency offsets (FAR= 10^{-3}, SNR = 0 dB).

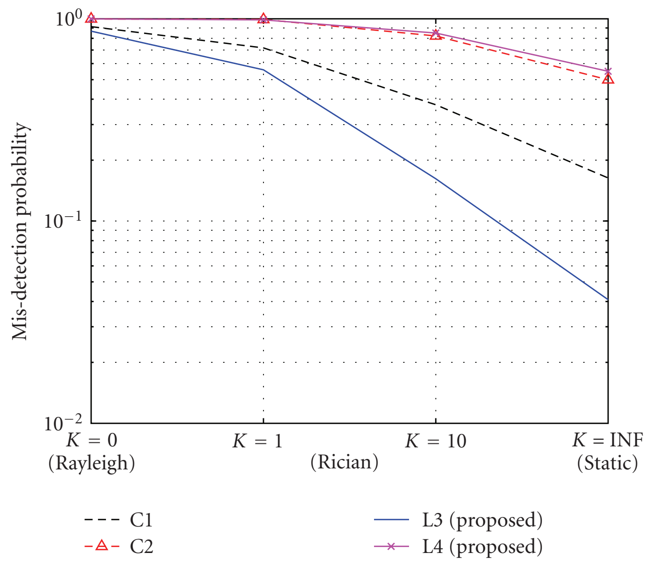

Figure 9: Detection performance under fading channel conditions (FAR= 10^{-3}, $f_m T_s = 0.2$, SNR = 0 dB).

performance comparison for different values of K-factors, where $K = \infty$ case corresponds to the static AWGN channel. As the K-factor decreases, effects of faded signal become dominant and performance degradation occurs. However, the performance advantage of L3 over other detectors holds for all channel conditions.

It is worthwhile to make performance comparisons with a larger group of differential as well as fully coherent detectors previously reported. In [16], authors utilize both the SoF and PLSC symbols for the frame detection. Although the PLSC symbols are not known to the receiver a priori, each pair of two consecutive symbols are either repeated or inverted, thus such patterns can be exploited for the detection. In addition, a pipelined structure for efficient implementation of the peak search algorithm is proposed in the paper. However, the detector is based on the single-span correlation ($N = 1$) and no correction term is applied, resulting in degraded performance when compared

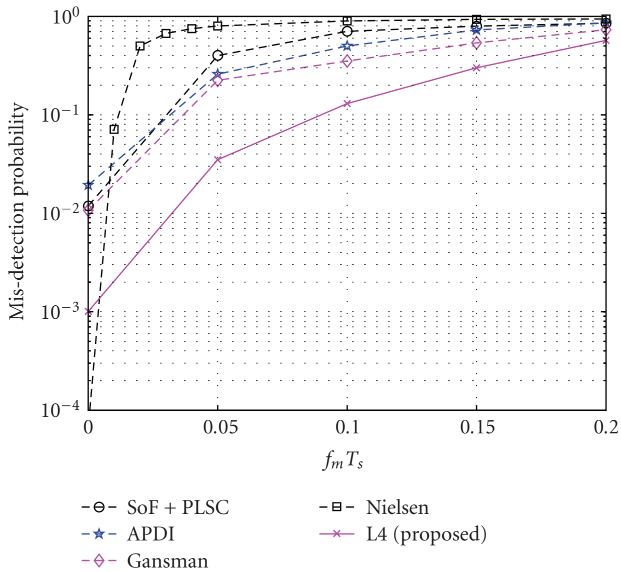

FIGURE 10: Performance comparison with coherent, differential, and mixed-type detectors (FAR= 10^{-3}, SNR = 0 dB).

to L4. In Figure 10, the detector MDP of [16] at a given symbol location is labeled by "Sof+PLSC" and shown with error probabilities of other schemes including L4. While our proposed detectors are intended for any general frame structure, the utilization of the PLSC symbols can be applied to L3 and L4 for further performance enhancement when the DVB-S2 frame structure is specifically considered.

The detector proposed by Nielsen [2] performs fully coherent correlation which is targeted for channels without frequency offsets. As indicated in Figure 10 (Nielsen), it outperforms all other schemes at zero frequency offset. Nevertheless, very rapid performance degradation is experienced as the offset increases, and more than 50% MDP occurs when the normalized frequency offset exceeds 0.05. Gansman's detector [5] (labeled Gansman) performs multispan correlation with the energy correction term included. Because of the existence of the coherent correlation term in addition to differential terms, performance tends to become degraded as the frequency offset increases. Another mixed-type detector is APDI [8, 9] which efficiently controls the detection complexity and its MDP is also shown in the figure.

6. Conclusion

We have presented the correlation schemes for improved detection performance over various channel conditions. The proposed L3 detector is shown to provide a substantial gain over all existing detection methods, regardless of the existence of frequency offsets. Further performance enhancement is achievable by using the L4 detector when the amount of frequency offset is relatively small. Presented results confirm that an appropriate energy correction in correlating detectors has a significant impact on the detection performance.

Acknowledgments

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