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Improved Method for Interleaving Parameter Estimation in a Non-Cooperative Context

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ABSTRACT In a non-cooperative context, a sequence acquired from remote sensing through satellites and aircraft can be recognized as an unknown sequence to a receiver who lacks the information of the transmission parameters. Therefore, the transmission parameters have to be estimated to reconstruct the unknown sequence. This paper focuses on the estimation of an interleaving period among transmission parameters and proposes an improved method to blindly estimate the interleaving period. Through computer simulations, we validate the method by analyzing the estimation performance in terms of the detection probability and the false alarm probability in a fading channel.

INDEX TERMS Blind detection, non-cooperative context, remote sensing, spectrum surveillance.

I. INTRODUCTION

One of the representative applications of remote sensing through satellites and aircraft including unmanned aerial vehicles (UAV) is spectrum surveillance. A surveillance system gathers intelligence from foreign communication systems in non-cooperative contexts and requires blind estimation of transmission parameters [1], [2].

Channel coding and interleaving enable transmitted signals to better withstand the effects of various channel impairments such as noise, interference, and fading, and are essential to establish reliable communications performance [3]–[7]. In non-cooperative contexts such as spectrum surveillance systems, an interleaved sequence acquired from remote sensing can be recognized as an unknown sequence to a receiver who lacks information about the parameter of the interleaver. To reconstruct the unknown interleaved sequence, the parameter of the interleaver has to be estimated. Blind detection involves extensive work to estimate the many transmission parameters, including source coding, channel coding, interleaving, and modulation [8]–[16]. In this paper, we focus only on blind estimation of the interleaving parameter.

There have been various researches on the estimation of the interleaver parameter throughout the literature [12]–[16]. An algorithm in [12] estimates the interleaving period by using the rank deficiency of the matrices in an

error-free channel. Interleaving period estimation in [13] uses Gauss-Jordan elimination through pivoting (GJETP) in a binary symmetric channel. In [14], blind estimation of the convolutional and helical interleaver parameters using convolutionally encoded data is presented. Recently, by using the rank deficiency of rectangular matrices composed of the received data having fewer errors, the interleaving period is estimated in [15]. Most recently, an estimation algorithm using a binomial distribution to compare the rank distributions is proposed in [16].

Most of these methods have focused on estimating the interleaving period using the linear characteristics of the codeword in the interleaved sequence in noiseless or noisy channels. The interleaving parameter is estimated by using the received data without any error correction because the error correction is carried out after deinterleaving. We therefore expect the estimation performance to be ungracefully degraded by impairments in severe channel conditions.

In this paper, to improve the estimation performance, we propose an efficient estimation method in three steps: the first is to select the received data having fewer errors, the second is to estimate the interleaving period using a measure, the maximum difference selection (MDS), and the third is to verify the estimated interleaving period while controlling for false alarms using the Kullback-Leibler divergence (KLD).

Through computer simulations, we validate the proposed method by analyzing the estimation performance in terms of the detection probability and false alarm probability.

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This paper is organized as follows. Section 2 briefly introduces the basic idea for estimation of the interleaving period. Section 3 proposes an improved method for blind estimation of the interleaving period and shows the simulation results, followed by the conclusion in Section 4.

II. BASIC IDEA FOR ESTIMATION

Assume an arbitrarily predicted interleaving period \tilde{L} at the receiver side; the original interleaving period L , which is generally a multiple of the length of a codeword; and the number of received data bits M . Further assume that the data is to be block coded before interleaving at the transmitter side. Under these conditions, if we construct the vectors \mathbf{s}_i by grouping the received data by \tilde{L} bits in order, then the received data sequence \mathbf{r} and the i -th vector \mathbf{s}_i can respectively be written as

$$\mathbf{r} = \{\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_n\} \quad (1)$$

$$\mathbf{s}_i = \{m_1^i, m_2^i, \dots, m_{\tilde{L}}^i\}, \quad i = 1, 2, \dots, n \quad (2)$$

where m_j^i is the j -th bit of the i -th vector \mathbf{s}_i , $m_j^i \in \{0, 1\}$, $n = \lfloor \frac{M}{\tilde{L}} \rfloor$, in which $\lfloor x \rfloor$ is the largest integer not exceeding x , and $n > \tilde{L}$. In this case, we can generate an $\tilde{L} \times \tilde{L}$ square matrix \mathbf{R} by placing the randomly selected \tilde{L} different vectors from n vectors in the received data sequence \mathbf{r} row by row as

$$\mathbf{R} = \begin{bmatrix} \mathbf{s}_i \\ \mathbf{s}_j \\ \vdots \\ \mathbf{s}_h \end{bmatrix} = \begin{bmatrix} m_1^i & m_2^i & \dots & m_{\tilde{L}}^i \\ m_1^j & m_2^j & \dots & m_{\tilde{L}}^j \\ \vdots & \vdots & \ddots & \vdots \\ m_1^h & m_2^h & \dots & m_{\tilde{L}}^h \end{bmatrix}. \quad (3)$$

Meanwhile, if we assume an $\tilde{L} \times \tilde{L}$ matrix Λ composed of randomly-generated binary data, as $\tilde{L} \rightarrow \infty$, the probability P_ε that the rank of Λ becomes $\tilde{L} - \varepsilon$ is found to be [17]

$$P_\varepsilon = \begin{cases} 2^{-\varepsilon^2} \left[\prod_{i=\varepsilon+1}^{\infty} (1 - 2^{-i}) \right] \left[\prod_{i=1}^{\varepsilon} (1 - 2^{-i})^{-1} \right], & \varepsilon \neq 0 \\ \prod_{i=1}^{\infty} (1 - 2^{-i}), & \varepsilon = 0 \end{cases} \quad (4)$$

where ε is the rank deficiency. In (4), the probability of becoming full rank ($\varepsilon = 0$) is 0.288788, and the probabilities of the rank deficiencies being 1, 2, 3, and 4 are 0.577576, 0.128350, 0.005239, and 0.000047 respectively. Note the relatively low probability that ε exceeds 2. By using these results, we can obtain the rank distribution of Λ .

When $\tilde{L} \neq L$ in (3), the messages and parities are not aligned in the same columns, and the rank distribution of \mathbf{R} , which is obtained by the accumulation of the rank values of each \mathbf{R} , is similar to that of Λ . On the other hand, if $\tilde{L} = L$, the messages and parities are aligned, and the rank distribution of \mathbf{R} will be different from that of Λ [15]. Therefore, it is possible to decide whether the interleaving period is correctly estimated or not by comparing the rank distribution of \mathbf{R} with that of Λ .

III. PROPOSED ESTIMATION METHOD

A. PROCESS OF ESTIMATION FOR THE INTERLEAVING PERIOD

The estimation performance is degraded by the impairments in severe channel conditions because the interleaving parameter is estimated by using the uncorrected received data: error correction is carried out after deinterleaving. In this section, to improve the estimation performance, we propose an estimation method in three steps: the first is probabilistically selecting the received data having fewer errors, the second is estimating the interleaving period using the proposed measure, MDS, for detection, and the third is verifying the estimated interleaving period while controlling for false alarm probability using KLD.

1) SELECTION OF THE RECEIVED DATA HAVING FEWER ERRORS

When the received data sequence includes errors due to severe channel conditions, it is difficult to estimate the interleaving period because the linearity in the codewords is lost. To reduce the influence of errors, one of the best methods is to probabilistically select the vectors \mathbf{s}_i that contain fewer errors from the received data sequence \mathbf{r} for constructing \mathbf{R} .

In this paper, for the selection of \mathbf{s}_i having fewer errors, we adopt the method of [15]. When the rank deficiency of the matrix \mathbf{R} is larger than 2, the indices of \mathbf{s}_i used in constructing \mathbf{R} are stored. We can consider these \mathbf{s}_i as having fewer errors because the rank deficiency will be small if there are many errors in \mathbf{R} . By repeating this process, we construct a set of frequently selected vectors. Then, we construct the $\tilde{L} \times \tilde{L}$ matrix \mathbf{R} again by using the randomly selected \tilde{L} vectors from the frequently-selected set. Next, we again compare the rank distribution of \mathbf{R} with that of Λ by using the proposed measure called MDS which will be discussed in the next subsection.

2) MEASURE FOR DETECTION

In this subsection, we present a measure, MDS, to estimate the interleaving period with the vectors acquired from Section III-A-1. The MDS method checks the similarity of the two discrete probability distributions by using the measure D_{MDS} defined as

$$D_{MDS} = \sum_i |P(X = x_i) - P(Y = y_i)| \quad (5)$$

where $P(X = x_i)$ and $P(Y = y_i)$ are the probability mass functions (PMF) for the discrete random variables X and Y , respectively. If $P(X = x_i)$ and $P(Y = y_i)$ are equal in (5), D_{MDS} becomes zero, and if not, D_{MDS} has a non-zero value. Note that the more the two distributions differ, the larger D_{MDS} becomes.

We first consider \mathbf{R} , composed of the received vector having fewer errors, and Λ , composed of the randomly-generated data. If we denote the rank distribution of \mathbf{R} as $P_R(X = x_i)$

Algorithm 1 Estimation of the Interleaving Period Using MDS

Notation of Variables: $MaxCntSel$ denotes the maximum loop count for selection, and $MaxCntDist$ indicates the maximum loop count for calculating the rank distribution.

Input: The received data sequence \mathbf{r}

- 1: **for** $\tilde{L} = L_{min}; \tilde{L} \leq L_{max}$ **do**
 - 2: Divide \mathbf{r} to the vectors with length \tilde{L}
 - 3: **for** $i = 0; i \leq MaxCntSel$ **do**
 - 4: Construct the square matrix \mathbf{R} by randomly choosing the \tilde{L} vectors from \mathbf{r} and calculate the rank of \mathbf{R}
 - 5: If the rank deficiency is larger than 2, record indices of the vectors chosen in constructing \mathbf{R}
 - 6: **end**
 - 7: Choose the most recorded N vectors
 - 8: **for** $i = 0; i \leq MaxCntDist$ **do**
 - 9: Construct \mathbf{R} by using the \tilde{L} vectors from the N vectors chosen above
 - 10: Calculate the rank distribution of \mathbf{R}
 - 11: **end**
 - 12: Calculate the MDS measure in (6)
 - 13: Record \tilde{L} and $P_R(X = x_i)$ when the calculated D_{MDS} is larger than the previous maximum value of D_{MDS}
 - 14: **end**
 - 15: Calculate KLD by using $P_R(X = x_i)$ when D_{MDS} is the maximum in (7)
 - 16: If $D_{KL} > \gamma$, declare \tilde{L} as the original interleaving period L
 - 17: else, discard \tilde{L}
- Output:** Estimated interleaving period \tilde{L}

and that of Λ as $P_\Lambda(X = x_i)$ respectively, (5) becomes

$$D_{MDS} = \sum_i |(P_R(X = x_i) - P_\Lambda(X = x_i))|. \quad (6)$$

As we discussed in Section II, if $\tilde{L} = L$, the rank distribution of \mathbf{R} becomes different from that of Λ . Therefore, we can estimate \tilde{L} to be the original interleaving period L when D_{MDS} is seen to be maximized as we vary \tilde{L} from the lower limit L_{min} to the upper limit L_{max} of the estimation range of the interleaving period.

Meanwhile, the maximum D_{MDS} may happen by chance even if $\tilde{L} \neq L$. To control for these false alarms, we check the rank distribution once again by adopting KLD after estimating \tilde{L} as the original interleaving period.

3) FALSE ALARM CONTROL USING KLD

For the probability distributions $P_R(X = x_i)$ and $P_\Lambda(X = x_i)$, KLD, which is typically used to check the similarity of the two probability distributions, is expressed as [18]

$$D_{KL} = \sum_i P_\Lambda(X = x_i) \log \frac{P_\Lambda(X = x_i)}{P_R(X = x_i)}. \quad (7)$$

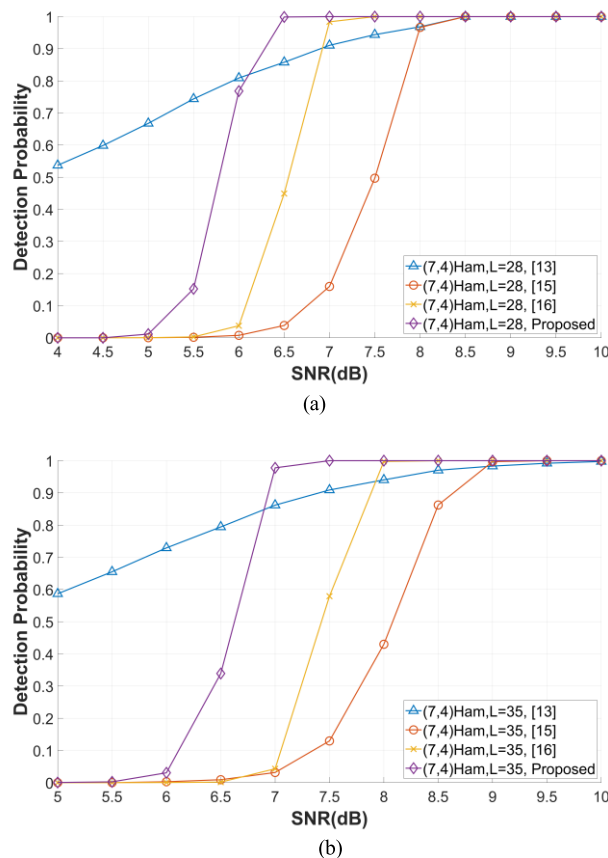


FIGURE 1. Detection probability of the interleaving period L with (7,4) Hamming code in Rayleigh fading channel. (a) $L = 28$. (b) $L = 35$.

Note that (7) denotes the relative entropy between the two probability distributions. In (7), KLD has a near-zero value for similar distributions and KLD increases as the differences in the distributions increase. We can therefore use KLD to control for false alarms. To do this, although \tilde{L} is chosen as the estimated period of the original interleaving period L when D_{MDS} is the maximum in (6), we check the similarity of the rank distributions of \mathbf{R} and Λ once again by using KLD. After checking the KLD, if D_{KL} is larger than γ , we then finally declare that the original interleaving period is \tilde{L} . Otherwise, we discard the decision where γ is the threshold value to control for the false alarm probability. Note that the false alarm probability decreases as γ increases.

We can formulate these steps of the proposed estimation method as Algorithm 1.

B. SIMULATION RESULTS

In this subsection, we validate the proposed method by showing the simulation results for the detection probability and false alarm probability. In these simulations, we assume BPSK modulation and Rayleigh fading channel, and include the results of other methods in [13], [15], and [16] for comparison.

Figs. 1 and 2 show the detection probabilities of the interleaving period of the proposed method. We use (7,4)

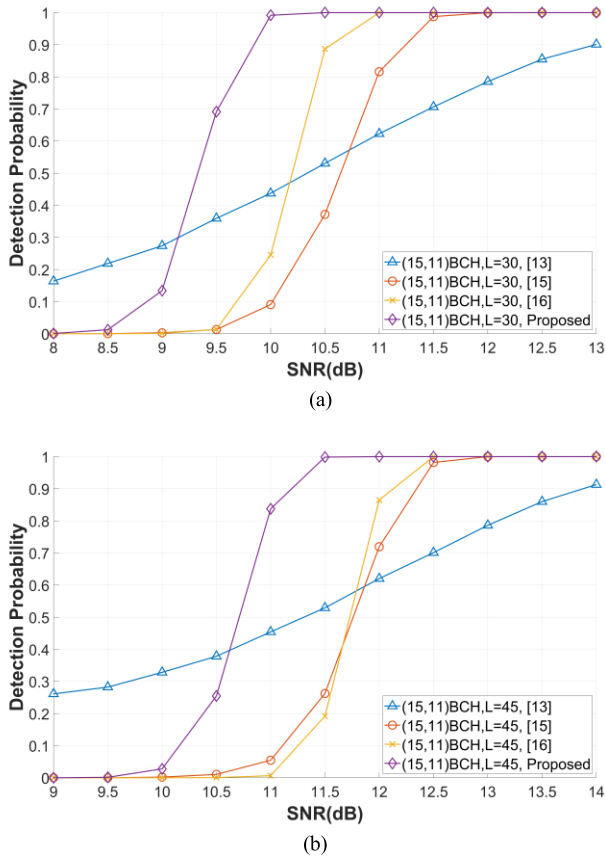


FIGURE 2. Detection probability of the interleaving period L with (15,11) BCH code in Rayleigh fading channel. (a) $L = 30$. (b) $L = 45$.

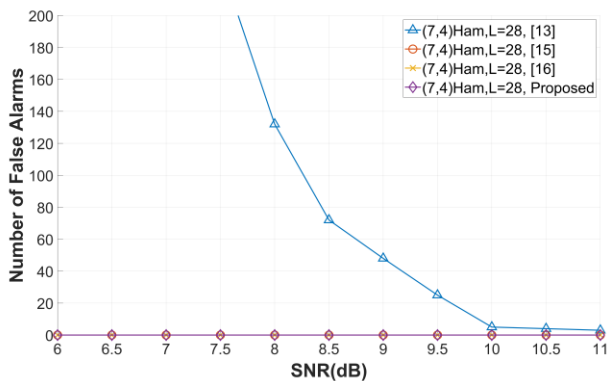


FIGURE 3. Number of false alarm events in 10,000 iterations with (7,4) Hamming code and interleaving period $L = 28$ in Rayleigh fading channel.

Hamming code and a random interleaver with periods of 28 and 35 in Fig. 1, and (15, 11) BCH code and a random interleaver with periods of 30 and 45 in Fig. 2. We set the number of received data bits to 50,000 and γ to 0.01.

From Figs. 1 and 2, we can see that the proposed method outperforms the other algorithms in detection probability. For example, in Fig. 1, at a detection probability of 0.9, we can achieve signal-to-noise ratio (SNR) gains of about 1.5 dB and 1.7 dB higher than that of [15] when the interleaving periods are 28 and 35, respectively. In Fig. 2, we can achieve

gains of about 2.8 dB and 3.2 dB over that of [13] when the interleaving periods are 30 and 45, respectively.

Fig. 3 depicts the number of false alarm events in 10,000 iterations when we use (7,4) Hamming code and an interleaving period of 28. Fig. 3 shows that the proposed method has about the same number of false alarms as [15] and [16]. Note well, however, that the detection probability of the proposed method is much higher.

IV. CONCLUSION

In this paper, we proposed an improved interleaving period estimation method that provides superior results. We first adopted the probabilistic selection of the received data having fewer errors. Then, we estimated the original interleaving period by using a simple and efficient measure, MDS, for detection. We verified and declared the interleaving period while controlling for false alarms by using KLD. Through computer simulations, we validated the proposed method by analyzing the estimation performance in terms of the detection probability and false alarm probability in Rayleigh fading channel.

The detection probability of the proposed method was improved up to 3.2 dB in examples, compared to the algorithms of [13], [15], and [16] at a detection probability of 90% while maintaining a very small false alarm probability. Therefore, it is expected that the proposed method can be efficiently applied to unknown signal reconstruction in non-cooperative contexts such as spectrum surveillance systems.

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