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Improved Method for Blind Interleaver Parameter Estimation Using Matrix Multiplication From Scant Data

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ABSTRACT Estimation of interleaver parameter from scant received data has recently been researched. In this paper, we propose an improved algorithm for blind estimation of interleaver parameter using matrix multiplication under the condition of scant received data. First, we generate a matrix from the received data and make arbitrary square submatrices by randomly deleting rows and columns from the generated matrix. We then compose additional square matrices by multiplying the square submatrices, and examine the rank deficiencies of the additional square matrices. Finally, we blindly estimate the interleaver parameter based on the average rank deficiency of the additionally composed square matrices. Through computer simulations, we validate the proposed algorithm in terms of detection probability and the number of false alarms, and show that the proposed algorithm outperforms conventional ones.

INDEX TERMS Blind detection, communication forensics, non-cooperative context, spectrum surveillance.

I. INTRODUCTION

In non-cooperative contexts, such as spectrum surveillance and cognitive radio, a receiver has to recover information from the received data without prior knowledge about the communication parameters, because the receiver does not know the parameters used in the transmitter. Communication forensics, the identification of communication parameters by blind estimation, is therefore essential if the receiver is to recover the information from the received data in non-cooperative contexts. Interleaver parameter is an important communication parameter to be blindly estimated because interleavers are usually used to make communicated data more resilient to noise, fading, and interference in communication channels.

Much research on blind estimation of interleaver parameters has been conducted [1]–[13]. Reference [1] uses the rank of a matrix composed of received data to estimate block interleaver parameter for a noiseless channel, and [2] uses an “almost dependent column” of the matrix to extend the method of [1] to a noisy channel. Further, [3]–[8] estimate various types of interleavers including block, convolutional, helical, and helical scan interleavers, by analysis

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of the number of ones or zeros in each row (or column). Another strategy for blind estimation of interleaver parameter is using rank deficiencies of square matrices generated from the received data [9]–[11]. Reference [9] chooses vectors having fewer errors to compose square matrices, [10] compares the rank deficiency distribution of the generated square matrices to that of random binary matrices, and [11] presents an improved blind estimation method for more severe channel conditions.

While the methods in [1]–[11] assume a sufficient amount of received data for the blind estimation of interleaver parameter, [12] and [13] blindly estimate interleaver parameter from scant data where the methods in [1]–[11] become infeasible. To solve the problem of scant received data, [12] generates additional data by combining received data, and [13] makes square submatrices from a matrix composed of received data. We expect that estimation performance can be improved if we can compose additional square matrices from the square submatrices in [13].

In this paper, we propose an improved algorithm for blind estimation of interleaver parameter using matrix multiplication under the condition of scant received data. We call the data scant if there is not enough received data to generate a single square matrix for observing rank deficiency.

First, we generate a matrix from the received data and make arbitrary square submatrices by randomly erasing rows and columns from the generated matrix. Then, we compose additional square matrices by multiplying the square submatrices, and examine the rank deficiencies of the additional square matrices. Finally, we blindly estimate the interleaver parameter based on the average rank deficiency of the composed additional square matrices. We validate the proposed method in terms of detection probability and the number of false alarms through computer simulations. Simulation results show that the proposed method is superior to conventional ones, with scant received data. Moreover, under the condition of an even more limited amount of received data, the proposed method can estimate the interleaver parameter while the conventional ones cannot yield a meaningful result.

This paper is organized as follows. Section II introduces the system model and briefly explains the previous methods for blind estimation of interleaver parameter under the condition of scant data. Section III proposes an improved method by using matrix multiplication. Section IV presents simulation results and Section V concludes the work.

II. SYSTEM MODEL

Let us assume that the transmitter uses an (n_c, k_c) linear block code and a random interleaver having an interleaving period of L , where n_c is codeword length, k_c is the length of message bits in a codeword, and L is a multiple of the codeword length n_c . In a non-cooperative context, the M -bit received data sequence \mathbf{r} can be partitioned into n row vectors of length \tilde{L} , where \tilde{L} is a predicted interleaving period, $n = \lfloor \frac{M}{\tilde{L}} \rfloor$, and $\lfloor \cdot \rfloor$ is the floor function. The received data sequence \mathbf{r} and the i -th row vector \mathbf{s}_i can respectively be expressed as

$$\mathbf{r} = \{\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_n\} \tag{1}$$

$$\mathbf{s}_i = \{c_1^i, c_2^i, \dots, c_{\tilde{L}}^i\}, \quad i = 1, 2, \dots, n \tag{2}$$

where c_j^i is the j -th bit of i -th row vector \mathbf{s}_i and $c_j^i \in \{0, 1\}$ for $1 \leq i \leq n, 1 \leq j \leq \tilde{L}$. If $n > \tilde{L}$, we can generate an $\tilde{L} \times \tilde{L}$ square matrix \mathbf{R} by selecting \tilde{L} different row vectors from n row vectors and placing the selected row vectors row by row. Repeating this process generates ${}_n C_{\tilde{L}}$ square matrices \mathbf{R} 's, where ${}_x C_y$ is the binomial coefficient.

Now, we examine the rank deficiency of \mathbf{R} for two cases: one is the case when $\tilde{L} = L$, the interleaving period matches exactly, and the other is when $\tilde{L} \neq L$, the interleaving period does not match. Here, the rank deficiency of \mathbf{R} is the difference between the rank of \mathbf{R} and the number of rows (or columns) in \mathbf{R} .

If the predicted interleaving period \tilde{L} is different from the original interleaving period L , the linearity in a codeword disappears. In this case, the rank deficiency distribution of \mathbf{R} 's resembles that of random binary matrices. In contrast, if \tilde{L} is equal to L , the linearity in a codeword maintains and the rank deficiency distribution of \mathbf{R} 's becomes different from that of random binary matrices. Using these properties, [9]–[11] estimate the interleaving period by comparing the

rank deficiency distribution of \mathbf{R} 's to that of random binary matrices.

However, under the condition of scant received data, not even a single $L \times L$ square matrix \mathbf{R} can be generated and the methods of [9]–[11] become infeasible: the condition of scant data is assumed that the number of received data bits is as limited to $M = L \times L \times \alpha$ bits for $0 < \alpha < 1$. This is because we need at least $L \times L$ -bit received data to compose a single square matrix \mathbf{R} , and a large number of \mathbf{R} 's are required in [9]–[11] to estimate the interleaver parameter. References [12] and [13] address this problem with methods for blind estimation of interleaver parameter requiring only a limited amount of received data. The method of [12] generates additional vectors by combining the row vectors \mathbf{s}_i 's to estimate the interleaving period, and the method of [13] improves estimation performance by composing square submatrices from the matrix generated from scant received data.

If we can compose additional square matrices from the square submatrices obtained in [13], it is expected that there is room for improvement in estimation performance. In Section III, we present an improved method for blind estimation of the interleaving period, by using matrix multiplication of the square submatrices obtained in [13], under the condition of scant received data.

III. PROPOSED ALGORITHM

In this section, we propose an improved method for blind interleaver parameter estimation using matrix multiplication. We begin with the idea based on [13]. From the received data sequence \mathbf{r} , if we place the n row vectors row by row, we can generate an $n \times \tilde{L}$ matrix \mathbf{R}_d as

$$\mathbf{R}_d = \begin{bmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \\ \vdots \\ \mathbf{s}_n \end{bmatrix} = \begin{bmatrix} c_1^1 & c_2^1 & \cdots & c_{\tilde{L}}^1 \\ c_1^2 & c_2^2 & \cdots & c_{\tilde{L}}^2 \\ \vdots & \vdots & \ddots & \vdots \\ c_1^n & c_2^n & \cdots & c_{\tilde{L}}^n \end{bmatrix}. \tag{3}$$

We can then construct different $l \times l$ square submatrices \mathbf{R}_s 's by randomly erasing rows and columns from the generated matrix \mathbf{R}_d , where l is the number of rows of the submatrix and an integer smaller than $\min(n, \tilde{L})$, and $\min(x, y)$ is the minimum operation [13]. For a given l , we can generate a total number of ${}_n C_l \times {}_{\tilde{L}} C_l$ different \mathbf{R}_s 's. The method in [13] uses \mathbf{R}_s 's to obtain rank deficiency distribution and estimate the interleaver parameter. As mentioned in Section II, if we can compose additional square matrices from \mathbf{R}_s 's under the condition of scant received data, we expect improved estimation performance. To do this, we compose additional square matrices by multiplying \mathbf{R}_s 's and observe their rank deficiencies.

Note that when we obtain a matrix \mathbf{Q} by multiplying matrices $\mathbf{S}_1, \mathbf{S}_2, \dots, \mathbf{S}_m$, the inherent linearities of the matrices $\mathbf{S}_1, \mathbf{S}_2, \dots, \mathbf{S}_m$ are well known to remain in the matrix \mathbf{Q} , and the

rank of \mathbf{Q} follows the rank inequality [14]:

$$\text{Rank}(\mathbf{Q}) \leq \min\{\text{Rank}(\mathbf{S}_1), \text{Rank}(\mathbf{S}_2), \dots, \text{Rank}(\mathbf{S}_m)\}. \quad (4)$$

Therefore, we can compose an additional square matrix \mathbf{R}_q by multiplying \mathbf{R}_s 's while maintaining their inherent linearities. If we select k different \mathbf{R}_s 's and multiply the selected \mathbf{R}_s 's, then we can have ${}^Y C_k$ additional square matrices \mathbf{R}_q 's where Y is the total number of different \mathbf{R}_s 's which can be constructed from \mathbf{R}_d . For example, if there are 2520 ($60 \times 60 \times 0.7$) bits of received data and the predicted interleaving period is 50, we can generate a 50×50 matrix \mathbf{R}_d . In this case, when l is $\min(50, 50) - 1$, we can generate a total number of ${}_{50}C_1 \times {}_{50}C_1 = 2500$ square submatrices \mathbf{R}_s 's. Moreover, if we select 2 different \mathbf{R}_s 's and multiply them, we can compose ${}_{2500}C_2 = 3\,123\,750$ additional square matrices \mathbf{R}_q 's about 1.2495×10^3 times more matrices than \mathbf{R}_s 's.

Now, we examine the rank deficiency of \mathbf{R}_q for two cases: one is the case when $\tilde{L} = L$, the interleaving period matches exactly, and the other is when $\tilde{L} \neq L$, the interleaving period does not match. When $\tilde{L} = L$, there is a linearity in a codeword in \mathbf{R}_s [13]. The linearity in a codeword remains in \mathbf{R}_q because \mathbf{R}_q is obtained by multiplying \mathbf{R}_s 's. Therefore, rank deficiency of \mathbf{R}_q occurs because of the linearity in a codeword and the rank deficiency distribution of \mathbf{R}_q 's differs from that of random binary matrices when $\tilde{L} = L$, as in [13]. On the other hand, when $\tilde{L} \neq L$, the linearity in a codeword is lost in \mathbf{R}_s [13], and therefore, the linearity is also lost in \mathbf{R}_q . However, rank deficiency of \mathbf{R}_q is different from that of \mathbf{R}_s because of the rank inequality in (4) and the rank deficiency distribution of \mathbf{R}_q 's becomes different from that of random binary matrices even when $\tilde{L} \neq L$, unlike [13]. Therefore, a different method from [13] is required to blindly estimate interleaver parameter.

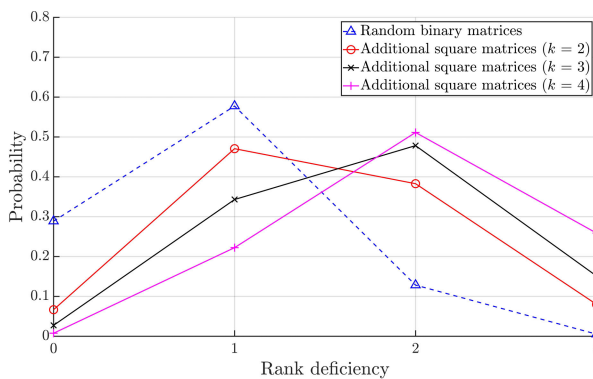


FIGURE 1. Rank deficiencies of additional square matrices and random binary matrices.

In order to examine the rank deficiency distribution of \mathbf{R}_q 's when $\tilde{L} \neq L$, we show the rank deficiency distribution of \mathbf{R}_q 's by varying k from 2 to 4 in Fig. 1, where we assume that the original interleaving period L is 60, predicted interleaving period \tilde{L} is 55, the number of scant received data is 3240

($60 \times 60 \times 0.9$) bits, (15, 11) BCH code is used, and l is $\min(58, 55) - 1$. For comparison, we also show the rank deficiency distribution of random binary matrices in Fig. 1. From Fig. 1, we can see that the rank deficiency distribution of \mathbf{R}_q 's is different from that of the random binary matrices even when $\tilde{L} \neq L$. Therefore, unlike the method in [13], we cannot estimate the interleaver parameter by comparing rank deficiency distributions. Although we began with the idea based on [13], we have to adopt a different method from [13] to estimate the interleaver parameter under the condition of scant data. Thus, instead of rank deficiency distribution of \mathbf{R}_q 's, we adopt the average rank deficiency of \mathbf{R}_q 's. We will now examine it in detail.

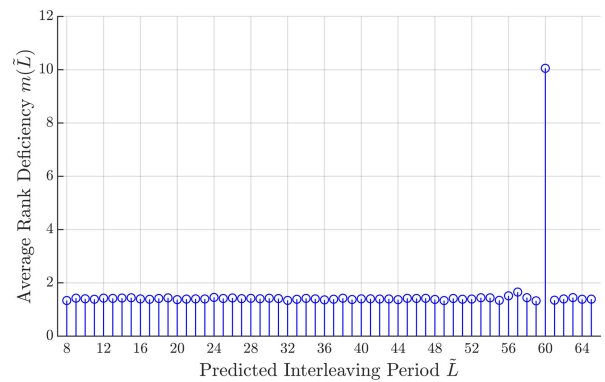


FIGURE 2. Average rank deficiency according to predicted interleaving period.

In order to examine the average rank deficiency of \mathbf{R}_q 's we show the average rank deficiency of \mathbf{R}_q 's by varying \tilde{L} from 8 to 65 in Fig. 2, when the original interleaving period is 60, the number of scant received data is 3240 ($60 \times 60 \times 0.9$) bits, (15, 11) BCH code is used, l is $\min(n, \tilde{L}) - 1$, and k is 2 for a noiseless channel. In Fig. 2, the average rank deficiency of \mathbf{R}_q 's is obtained by averaging over rank deficiencies of 1000 \mathbf{R}_q 's and we denote the average rank deficiency of \mathbf{R}_q 's for a given \tilde{L} as $m(\tilde{L})$. From Fig. 2, it can be seen that $m(\tilde{L})$ is largest when $\tilde{L} = L$, and $m(\tilde{L})$ s are all similar when $\tilde{L} \neq L$. Therefore, we can determine that \tilde{L} is the original interleaving period L when $m(\tilde{L})$ has the largest value as follows:

$$L = \arg \max_{\tilde{L}} m(\tilde{L}). \quad (5)$$

However, in a noisy channel, even if $\tilde{L} = L$, $m(\tilde{L})$ may not be the largest value. This is because the linearity in a codeword can be lost by error bits caused by noise. In this case, a false alarm will occur. Therefore, to control the false alarm occurrence, we use the gap between the largest value of $m(\tilde{L})$ and the second largest value of $m(\tilde{L})$. For this, we set the threshold as γ . Only when the gap between the largest value of $m(\tilde{L})$ and the second largest value of $m(\tilde{L})$ is greater than threshold γ , we declare that the interleaving period obtained by (5) is the original interleaving period L . Note that increasing the value of γ decreases the number of false

alarms, and we set γ to a design parameter to control false alarms.

Algorithm 1 provides a step-by-step summary of our proposed method in the context of the scant received data.

After estimating the interleaving period, we need to perform synchronization to blindly deinterleave the received data. We can synchronize the received data simply by repeating the proposed method with delay shifts of received data sequence \mathbf{r} [10]. For example, we can shift \mathbf{r} from 0 to $L - 1$ for synchronization when the interleaving period obtained by (5) is L .

Algorithm 1 : Blind Interleaver Parameter Estimation Using Matrix Multiplication From Scant Data

Notation of Variable: L_{min} and L_{max} are the minimum and maximum values of \tilde{L} , respectively, and Crd denotes the number of \mathbf{R}_q 's composed to calculate average rank deficiency

Input: The scant received data sequence \mathbf{r}

- 1: **for** $\tilde{L} = L_{min} : L_{max}$ **do**
- 2: Generate an $n \times \tilde{L}$ matrix \mathbf{R}_d from (3)
- 3: **for** $i = 1 : Crd$ **do**
- 4: Randomly erase rows and columns from \mathbf{R}_d and generate k different $l \times l$ square submatrices \mathbf{R}_s 's
- 5: Compose additional square matrix \mathbf{R}_q by multiplying generated k different \mathbf{R}_s 's
- 6: Calculate the rank deficiency of \mathbf{R}_q
- 7: **end**
- 8: Average the rank deficiencies of additional square matrices \mathbf{R}_q 's to calculate $m(\tilde{L})$
- 9: **end**
- 10: Decide L in (5) and calculate the gap between the largest value of $m(\tilde{L})$ and the second largest value of $m(\tilde{L})$
- 11: When the gap is larger than γ , declare L in (5) as the original interleaving period

Output: Estimated interleaving period L

IV. SIMULATION RESULTS

In this section, through computer simulations, we first examine the detection probability of the proposed method by varying k , the number of square submatrices \mathbf{R}_s 's to be multiplied to compose additional square matrices \mathbf{R}_q 's. Then, we investigate the detection performance of the proposed method according to γ , the threshold to control false alarms. Finally, we validate the proposed method according to M , the number of received data bits, in terms of detection probability and the number of false alarms, and compare the result of the proposed method to that of the conventional method in [13]. In the simulations, we assume a random interleaver with interleaving period L , binary phase shift keying modulation, and an additive white Gaussian noise channel. We further assume a number of received data bits as scant as $M = L \times L \times \alpha$ bits for $0 < \alpha < 1$ to show that the proposed method provides superior estimation performance of the interleaving period under scant received data.

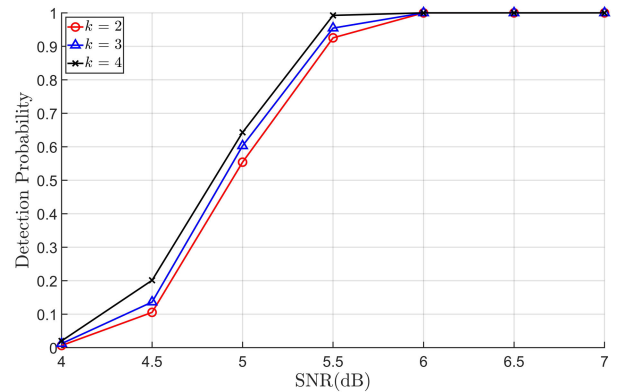


FIGURE 3. Detection probability according to k .

First, we show the detection probability of the proposed method by varying k from 2 to 4 in Fig. 3, when L is 60, (15, 11) BCH code is used, γ is 0.75, M is 3240 ($60 \times 60 \times 0.9$) bits, and l is $\min(n, \tilde{L}) - 1$. Fig. 3 shows that the detection probability improves as k increases. This is because we can construct more matrices for obtaining rank deficiencies as k increases. However, the complexity of the proposed method increases because we need more matrix multiplications as k increases. Therefore, we set k to a design parameter.

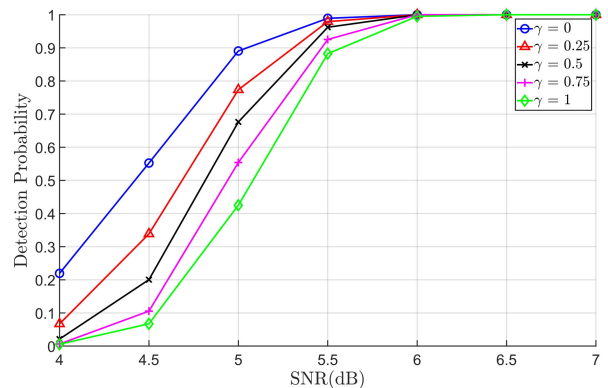


FIGURE 4. Detection probability according to γ .

Then, we present the detection probability and the number of false alarms of the proposed method for various values of γ in Figs. 4 and 5, respectively, when L is 60, (15, 11) BCH code is used, k is 2, M is 3240 ($60 \times 60 \times 0.9$) bits, and l is $\min(n, \tilde{L}) - 1$. We can see from Figs. 4 and 5 that, as γ decreases, the detection probability increases, but the number of false alarms also increases. Therefore, we can confirm that there is a trade-off between the detection probability and the number of false alarms according to the threshold γ ; we also set γ to a design parameter.

Finally, we validate the proposed method according to M by showing the detection probability and the number of false alarms in Figs. 6 and 7, respectively, when L is 60, (15, 11) BCH code is used, γ is 0.75, k is 2, and l is $\min(n, \tilde{L}) - 1$. For comparison, we include performance of the conventional

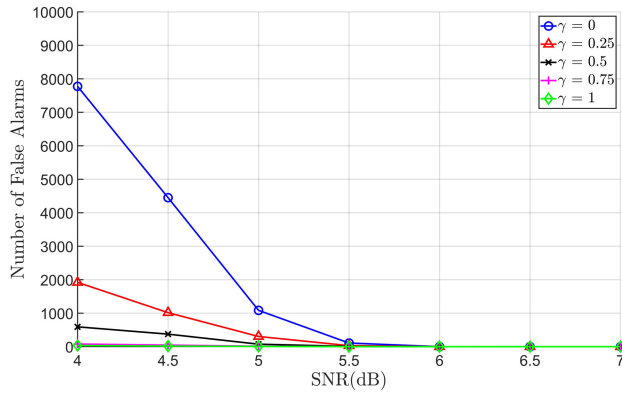


FIGURE 5. Number of false alarms in 10 000 iterations according to γ .

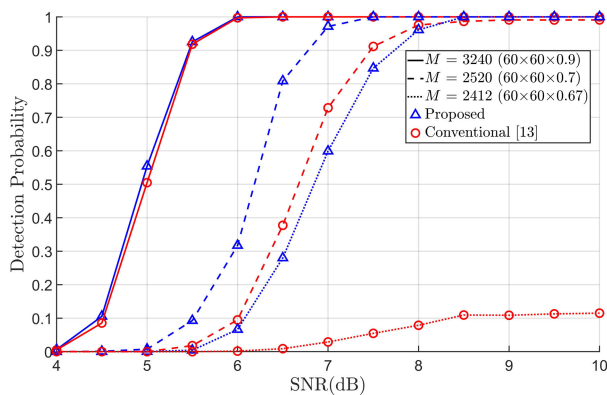


FIGURE 6. Detection probability according to M .

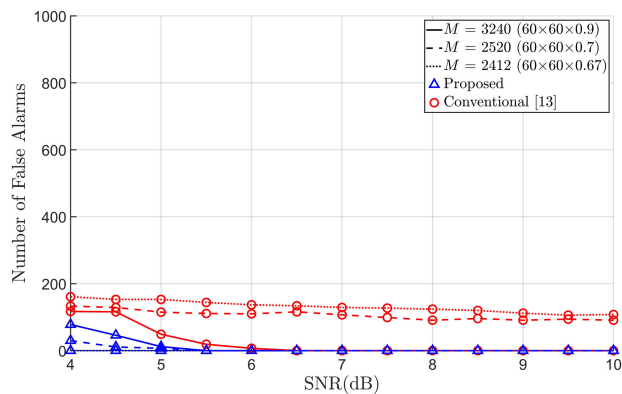


FIGURE 7. Number of false alarms in 10 000 iterations according to M .

method in [13]. From Figs. 6 and 7, we can see that the proposed method shows higher detection probability and lower false alarms than the conventional method in [13], where the results are obtained from 10 000 iterations for each M .

Note that the gap between the performances of the proposed method and the conventional method in [13] increases as M decreases. This can be explained as follows. According to the rank inequality in (4), the rank of \mathbf{R}_q becomes less than or equal to the minimum rank of \mathbf{R}_s 's which are being multiplied by each other to construct \mathbf{R}_q . In this respect,

the linearity remaining in \mathbf{R}_q becomes larger than the linearities remaining in \mathbf{R}_s 's. As the linearity remaining in \mathbf{R}_q increases, the rank deficiency of \mathbf{R}_q also increases, and therefore detection performance improves. This property becomes more apparent as M decreases, and so the performance gap between both methods increases as M decreases.

For example, in Fig. 6, when M is 3240 ($60 \times 60 \times 0.9$) bits, detection probability of the proposed method and that of the method in [13] reach 0.9 at signal-to-noise ratio (SNR) of about 5.5 dB. When M decreases to 2520 ($60 \times 60 \times 0.7$) bits, the proposed method achieves SNR gains of about 0.7 dB compared to [13] at a detection probability of 0.9. Moreover, using an even smaller number of received data, when M is 2412 ($60 \times 60 \times 0.67$) bits, the detection probability of the proposed method reaches 0.9 at SNR of about 7.7 dB, while the conventional method in [13] cannot give any meaningful result. The results in Figs. 6 and 7 indicate that the proposed method is better than the conventional methods under the same condition of scant received data.

V. CONCLUSION

In this paper, we proposed an improved blind interleaver parameter estimation method using matrix multiplication under the condition of scant received data. We first generated a matrix from the received data and made arbitrary square submatrices by randomly deleting rows and columns from the generated matrix. Then, we composed additional square matrices by multiplying the square submatrices and examined the rank deficiencies of the additional square matrices. Finally, we blindly estimated the interleaver parameter based on the average rank deficiency of composed additional square matrices.

To validate the proposed method, we presented detection probability and the number of false alarms through computer simulations. Simulation results showed that the proposed method works better than the conventional ones for scant received data. Moreover, under the condition of an even more limited amount of received data, the proposed method can estimate the interleaver parameter while the conventional ones cannot give a meaningful result. Since the proposed method uses the hidden linearity in the received data, which remains even in a limited amount of received data, it is straightforwardly applicable to other blind communication parameter estimation, such as estimation of channel code where intrinsic linearity resides.

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(Yongseok Jung and Mingyu Jang contributed equally to this work.)

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