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Parameter Estimation of Convolutional and Helical Interleavers in a Noisy Environment

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ABSTRACT Forward error correction (FEC) codes followed by an interleaver play a significant role in improving the error performance of the digital systems by counteracting random and burst errors. In most of the applications, interleaver and FEC code parameters are known at the receiver to successfully de-interleave and decode the information bits. However, in certain non-cooperative applications, only partial information about the code and interleaver parameters is known. Furthermore, in cognitive radio applications, an intelligent receiver should adapt itself to the transmission parameters. Hence, there is a need to blindly estimate the FEC code and interleaver parameters in the mentioned applications from the received data stream with the availability of partial knowledge about the transmission parameters at the receiver. In this paper, a blind recognition of convolutional and helical interleaver parameters is carried out using innovative algorithms for unsynchronized, convolutionally encoded data in the presence of bit errors. In addition, the proposed algorithms also estimate the starting bit position for achieving proper synchronization. In a nutshell, it has been observed from the numerical results that the interleaver parameters have been estimated successfully over erroneous channel conditions from the proposed algorithms. Finally, the performances of the proposed algorithms for both the interleavers considering various bit error rate values have also been analyzed.

INDEX TERMS Blind recognition, convolutional interleaver, cognitive radio, forward error correction (FEC) codes, helical interleaver.

I. INTRODUCTION

To improve the error performance of the digital systems, forward error correction (FEC) codes play a significant role in nullifying the randomly distributed errors. However, if the data is communicated over burst-error channels, then the receiver will encounter significant degradation in the symbol error probability (SEP) performance. Interleaver, which follows the FEC encoder, plays a vital role in protecting the digital communication or storage systems against the burst errors, thereby improving the reliability. Therefore, both the random and burst errors are nullified by a sequential combination of FEC encoder and interleaver. Various types of interleavers such as block interleaver, helical scan interleaver, convolutional interleaver, helical interleaver, random interleaver, etc. had been designed, analyzed, and studied in the literature. In this paper, our discussions are restricted to convolutional and helical interleavers for convolutionally encoded data.

The accurate information about the code and interleaver parameters is critical to decode and de-interleave the received information symbols. However, in a non-cooperative context such as military and spectrum surveillance applications as mentioned in [1]–[3], the FEC code and interleaver parameters are either not known or only partially known at the receiver. Further, in cognitive radio applications as indicated in [4] and [5], the receiver should adapt itself to the transmission parameters. Hence, blind/semi-blind estimation is mandatory for such applications in order to successfully decode and de-interleave the received information symbols. Usually, a control channel will be used to signal the transmission parameters to the receiver in the case of adaptive modulation and coding (AMC) based systems. Thus, the blind estimation techniques at the receiver will lead to conservation of channel resources in AMC-based applications thereby improving the spectral efficiency. It is to be noted that the convolutional interleaver is prominently used in digital video broadcasting (DVB) systems [6] and possible application of helical interleaver includes interleave-division multiple access (IDMA) systems [7]. The AMC framework is
adopted in popular DVB-S2 systems [8] and wireless sensor networks [9]. The blind estimation algorithms at the receiver will reduce the energy consumption of the sensor nodes. This is because, the sensor nodes need not frequently transmit the overhead information to indicate changes in the code and interleaver parameters. Moreover, the parameter extraction techniques are also useful to identify possible error correcting codes in the genetic code of DNA sequences [10]. Since FEC codes and interleavers are extensively used in digital storage applications, the blind estimation of parameters will provide a lot of flexibility in designing the receiver decoding system.

The FEC code parameter estimation techniques were extensively studied in the literature. In [3], innovative algorithms for estimating the parameters of various FEC codes were proposed over non-erroneous scenario. In [4], [5], [11], and [12], the estimation of convolutional code parameters was carried out for erroneous scenario based on the dual code concept. In addition, the blind recognition of puncturing pattern was also proposed in [13] and [14] for punctured convolutional codes. But the estimation algorithms were limited to Galois field GF(2). However, the algorithms were extended to GF(2^n) case in [15] and [16] assuming non-binary convolutional and block codes, respectively. In [17]–[19], novel code parameter recognition techniques for low-density parity-check (LDPC) codes and convolutional codes was studied. It was observed that the proposed techniques were based on the computation of average logarithm likelihood ratios (LLRs) of the syndrome a posteriori probability and average likelihood difference of the parity checks. However, the LLR-based techniques are not strictly blind. This is because, a predefined set of encoders should be assumed to be known at the transmitter and receiver. The parameter estimation techniques for turbo codes based on iterative expectation-maximization and least square methods were proposed in [20] and [21], respectively.

In the prior works reported in [1], [22], and [23], innovative algorithms for the blind recognition of block interleaver parameters were discussed. In particular, the parameter estimation of block interleaver considering Hamming block code was investigated in [1]. Furthermore, the estimation of block interleaver size was carried out for non-binary coded data streams in [22]. In [23], innovative algorithms for the parameter estimation of block interleavers, which include matrix and helical scan interleavers, from convolutionally encoded data in the presence of bit errors were proposed. There are other interleaver types such as convolutional and helical interleavers whose parameter estimation techniques were not rigorously discussed in the literature. In [24] and [25], the algorithms for blind identification of convolutional interleaver parameters such as interleaver depth and width were reported for linear block coded data. The proposed algorithm in [24] to estimate the convolutional interleaver parameters was based on recognizing the data bits of a particular codeword from the row and column indices of the data matrix. However, the delay of the received data sequence to achieve synchronization was not recovered. Moreover, the proposed methodology in [24] was applicable only to block coded symbols due to its code dependent features. In [25], the algorithm was proposed for non-erroneous channel conditions. In our manuscript, we propose innovative algorithms for the blind recognition of convolutional interleaver parameters based on the rank deficiency property of convolutionally encoded data symbols [4]. Further, the delay of the received data sequence is also recovered to achieve synchronization using the proposed algorithms.

A. MOTIVATION

The main motivations behind the proposed work are as follows:

- In a non-cooperative scenario such as military and spectrum surveillance applications, it is always mandatory to recognize the coding and interleaving parameters at the receiver, as complete knowledge about the same may not be available for decoding and de-interleaving.
- In the earlier works, the proposed approach for the parameter estimation of convolutional interleaver was applicable only to block coded symbols due to its code dependent features. To the best of our knowledge, the parameter estimation of convolutional interleaver under erroneous channel conditions had not been investigated for convolutionally encoded data with and without puncturing.
- The parameter estimation was reported only for a special case assuming codeword length \( n = B \times M \), where \( B \) and \( M \) denote the interleaver depth and width, respectively.
- Finally, to the extent of our knowledge, the parameter estimation of helical interleaver had not been investigated in the prior works.

B. CONTRIBUTION

The main contributions of the proposed work are as follows:

- In this paper, we assume a non-cooperative scenario, where the data symbols are encoded using convolutional codes and interleaved using convolutional or helical interleaver at the transmitter. We assume that the receiver has only a limited knowledge about the FEC codes and interleavers used at the transmitting end.
- Therefore, we propose algorithms for the blind recognition of convolutional and helical interleaver parameters in the presence of bit errors. It is to be noted that the type of interleaver is assumed to be known at the receiver.
- Unlike the prior works, the interleaver parameter estimation process is carried out for a generic case without any restriction on the codeword length \( n \).
- Using the proposed algorithms, the convolutional interleaver parameters \( B \) and \( M \) are estimated in the presence of bit errors. In addition, the helical interleaver parameters such as the number of columns in helical array \( (C) \), group size \( (N) \), and helical array step size \( (d) \) are also estimated.
The identification of interleaver parameters from punctured and unpunctured convolutional codes are given for various test cases. Finally, by varying the bit error rate (BER) values, the performances of both the interleavers are shown for different values of constraint length $K$ of convolutional codes.

C. STRUCTURE

The rest of the paper is organized as follows. In Section II, a brief introduction is given for both the interleavers. Section III gives an overview of the parameter estimation process with the help of a generic block diagram. In Section IV and V, the algorithms for estimating the convolutional and helical interleaver parameters are given. In addition, the complexity analysis of the proposed algorithms is also carried out in Section V. In Section VI, the simulation results and related discussions are given for various test cases. Finally, the concluding remarks are given in Section VII.

II. CONVOLUTIONAL AND HELICAL INTERLEAVERS

In the case of $(B, M)$ convolutional interleaver, the coded data stream is stored sequentially into a bank of $B$ registers and the $i^{th}$ register has $(i-1)M$ delay units. With each incoming new coded symbol, the commutator switches to the subsequent register such that the new incoming symbol will be stored and the oldest symbol will be shifted out for transmission. The de-interleaver performs the inverse operation at the receiver. Note that the interleaver and de-interleaver switches should be operated synchronously. The structure of a $(B, M)$ convolutional interleaver and de-interleaver is shown in Fig. 1. In the case of $(N_{\text{row}}, N_{\text{col}})$ block interleaver, the end-to-end delay between the restored and original sequence is $2N_{\text{row}}N_{\text{col}} - 2N_{\text{row}} + 2$ as stated in [26], where $N_{\text{row}}$ and $N_{\text{col}}$ indicate the number of rows and columns of the interleaver matrix, respectively. In addition, the block interleaver requires memory which can store $N_{\text{row}}N_{\text{col}}$ symbols at each end (i.e. transmitter and receiver). In the case of convolutional interleaver, the end-to-end delay and memory requirements are $B(B-1)M$ and $B/2(B-1)M$, respectively [26]. It is observed that one-half of the delay and memory requirements is reduced in the case of a $(B, M)$ convolutional interleaver compared to a $(B, BM)$ block interleaver which can correct burst errors of the same length.

The Helical Interleaver permutes the incoming symbols in a helical fashion by placing them in an array, which comprises of $C$ columns and unlimited rows, and then outputs the symbols row by row to the output port. The incoming symbols are partitioned into consecutive groups of $N$ symbols, where $N$ is the group size parameter, and stored in an array. At each time step, the interleaver accepts an input of length $CN$ and places the $p^{th}$ group of $N$ symbols in the array along $(p \mod C)^{th}$ column. The placement is helical because the first symbol in the $p^{th}$ group is in $(1 + (p-1)d)^{th}$ row, where $d$ indicates the helical array step size parameter. The vacant positions in the array are filled with some default values, which is assumed to be zero in our case. The de-interleaver performs the inverse operation at the receiver. In Fig. 2, the helical

![FIGURE 1. Structure of convolutional interleaver and de-interleaver considering interleaver depth $B$ and interleaver width $M$.](image1)

![FIGURE 2. Helical interleaver [27] operation assuming $C = 3$, $N = 2$, and $d = 1$ for input values $[1 : 18]$.](image2)
interleaver operation is shown using an example considering \( C = 3, N = 2, \) and \( d = 1 \) and the output of the interleaver is also shown for input values \([1 : 18]\). From the figure, it is observed that the interleaver outputs few symbols which are not from the current input and it leaves few symbols in the current input without placing them at the output. The helical interleaver is different from a helical scan interleaver proposed in [23]. Unlike helical interleaver, the helical scan interleaver follows block interleaving methodology which segregates the incoming data stream into multiple blocks of size equal to \( N_{\text{row}} N_{\text{col}} \). In contrast to the helical interleaver, the helical scan interleaver stores the incoming symbols by filling a \( N_{\text{row}} \times N_{\text{col}} \) matrix row by row and outputs all the stored symbols diagonal-wise in a helical fashion according to the step size \( d \). The parameter estimation of block interleavers, which include matrix and helical scan interleavers, in the presence of bit errors has already been investigated in [23]. In this manuscript, our discussions are restricted to convolutional and helical interleavers.

### III. INTERLEAVER PARAMETER ESTIMATION PROCESS

A generic block diagram showing the necessary blocks required to carry out the parameter estimation process considering convolutional and helical interleavers is shown in Fig. 3. After the reception of convolutionally encoded data symbols, it should be reshaped into a matrix form and the resultant matrix is termed as data matrix \( S \). After that the difference between the number of columns of \( S \) resulting in rank deficiency, which is termed as rank-deficiency-difference, considering a particular interleaver need to be estimated. Subsequently, the estimated rank-deficiency-difference will be given as an input parameter to the algorithms which are proposed to estimate the interleaver parameters. It is to be noted that the number of bits to be shifted for achieving proper synchronization can also be estimated using the same algorithm. Finally, after estimating all the interleaver parameters, the convolutional code parameters should be estimated after de-interleaving. In this manuscript, our discussions are restricted to the parameter estimation of convolutional and helical interleavers. The code parameter estimation of convolutional codes has not been discussed here and the same has already been discussed extensively in [4], [5], and [11]–[14].

### IV. RANK-DEFICIENCY-DIFFERENCE ESTIMATION

For non-erroneous scenario, the rank-deficiency-difference of convolutional or helical interleaver is estimated using algorithm 1 (refer to next page).

**Algorithm 1 Rank-Deficiency-Difference Estimation**

**Notations:** \( b \) and \( a \) indicate the number of columns and rows of data matrix \( S \), respectively. The rank and rank ratio of \( S \) are denoted by \( \rho(S) \) and \( p \), respectively. \( \zeta \) and \( F \) denotes the rank-deficiency-difference and column echelon form of \( S \), respectively.

**Assumptions:** \( a \geq 2b \) and the data stream is assumed to be encoded using convolutional encoder and interleaved using convolutional or helical interleaver at the transmitter.

1. The received data stream is reshaped into a data matrix \( S \) of size \( a \times b \).
2. Apply Gauss-Jordan elimination through pivoting (GJETP) algorithm [28] in GF(2) and convert \( S \) into \( F \).
3. Compute \( \rho(S) \) from the number of non-zero columns in \( F \).
4. Compute \( p = \rho(S)/b \).
5. Evaluate \( p \) for different values of \( b \).
6. Observe the difference between the successive number of columns with rank deficiency and the same gives \( \zeta \).

From algorithm 1, Gauss-Jordan elimination through pivoting (GJETP) algorithm eliminates all the dependent columns. It is also to be observed that \( \zeta = \beta \) or \( \zeta = \text{lcm}(n, \beta) \) for helical interleaver, where \( \beta = C \times N \), and \( \zeta = B \)
or \( \zeta = \text{lcm}(n, B) \) for convolutional interleaver. The reason for rank deficiency in the case of convolutional and helical interleavers is explained using the following propositions.

### A. CONVOLUTIONAL INTERLEAVER: PROPOSITION 1

By varying \( b \), if \( B \) is a multiple of \( n \), then rank deficiency will be obtained for the case when \( b = \alpha B \), where \( \alpha \) is a positive integer. The deficient rank depends on the number of complete codewords contained within \( b \). If \( b = \alpha B \) and \( b = \gamma n \), where \( \gamma \) is a positive integer, then the interleaved stream will contain less than \( \gamma \) complete codewords within \( b \) due to the structural properties of convolutional interleaver. For instance, if there are \( \chi \) complete continuous codewords in all the rows, where \( \chi < \gamma \), aligned properly in the same column, then \( \rho(S) \) is given by

\[
\rho(S) = \chi k + m + (n(\gamma - \chi)) \\
= \chi k + m + (b - \gamma n), \tag{1}
\]

where \( m \) is the memory of the convolutional encoder, \( k \) denotes the code dimension of the convolutional codes. However, if \( b \neq \alpha B \), then full rank will be obtained.

### B. EXPLANATION

The data and parity bits are aligned properly in the same column only for the case when \( b \) is a multiple of \( B \) (i.e. \( b = \alpha B \)) assuming that \( B \) is a multiple of \( n \). If \( \chi \) complete continuous codewords in all the rows are aligned properly in the same column, then \( \chi n \) columns of \( S \) will be converted into \( \chi k + m \) independent columns through GJETP algorithm. This is because, the output \( n \) data bits depend on \( k + m \) bits (i.e. \( k \) present and \( m \) previous input bits) in the case of convolutional codes as indicated in [4] and [5]. Hence, \( \chi n \) output data bits or \( \chi \) complete codewords in each row will depend on \( \chi k + m \) input bits. Due to proper alignment of the data and parity bits, there will be only \( \chi k + m \) non-zero columns after converting \( S \) into \( F \), since GJETP algorithm will remove \((\chi n) - (\chi k + m)\) dependent columns. It is also to be noted that before applying GJETP algorithm, already \( S \) will consist of \( b - \chi n \) independent columns due to incomplete codewords. Therefore, if \( b \) is a multiple of \( B \), then \( \chi k + m + b - \chi n \) non-zero columns out of \( b \) will be observed in \( F \). Since the number of non-zero columns in \( F \) or the number of independent columns in \( S \) gives the rank of a matrix, \( \rho(S) \) is given by \( \chi k + m + b - \chi n \) as mentioned in (1). However, if \( b \neq \alpha B \), then the data and parity bits of \( \chi \) complete codewords will be segregated in different rows and will not be aligned properly in the same column. Due to improper alignment of data and parity bits, full rank will be obtained.

The above phenomenon is also explained using an example in Appendix A.

### C. CONVOLUTIONAL INTERLEAVER: PROPOSITION 2

By varying \( b \), if \( B \) is not a multiple of \( n \), then rank deficiency will be obtained for the case when \( b = \alpha \text{lcm}(n, B) \). Assuming \( b = \gamma n \), if there are \( \chi \) complete continuous codewords contained within \( b \), where \( \chi < \gamma \), then \( \rho(S) \) is given by (1). However, if \( b \neq \alpha \text{lcm}(n, B) \), then full rank will be obtained.

### D. EXPLANATION

Since \( B \) is not a multiple of \( n \), it is intuitive that the rank deficiency will be obtained when \( b \) is a multiple of \( \text{lcm}(n, B) \).

Rest of the explanation is similar to that of proposition 1. The proposition 2 for convolutional interleaver is also explained using an example in Appendix B.

### E. HELICAL INTERLEAVER: PROPOSITION 3

Similar to convolutional interleaver, while varying \( b \), if \( \beta \) is a multiple of \( n \) (i.e. \( \beta = \gamma n \)), then rank deficiency for helical interleaved data stream is obtained for the case when \( b = \alpha \beta \). Therefore, if there are \( \chi \) complete codewords, where \( \chi < \gamma \), contained within \( b \) and if \( b = \alpha \beta \), then \( \rho(S) \) is given by (1). In addition, if \( \beta \) is not a multiple of \( n \), then rank deficiency will be obtained only for the case when \( b = \alpha \text{lcm}(n, \beta) \). However, if \( b \neq \alpha \beta \) or \( b \neq \alpha \text{lcm}(n, \beta) \), then full rank will be obtained.

The explanation for rank deficiency in the case of helical interleaver is similar to convolutional interleaver. In addition, the above phenomenon for helical interleaver is further explained using an example in Appendix C.

### F. ESTIMATION OF \( \zeta \)

Let \( b = \alpha \beta \) and \( b' = (\alpha + 1)\beta \) indicate two successive columns with rank deficiency for helical interleaver. By observing \( b' - b \), \( \zeta = \beta \) is estimated for helical interleaver considering the case when \( \beta \) is a multiple of \( n \). For the case when \( \beta \) is not a multiple of \( n \), \( \zeta = \text{lcm}(n, \beta) \) is estimated by observing \( b' - b \). Similarly, \( \zeta = B \) or \( \zeta = \text{lcm}(n, B) \) for convolutional interleaver can be estimated as mentioned in Step 6 of algorithm 1 by observing \( b' - b \). The above three propositions based on the rank deficiency approach are applicable only for non-erroneous scenario. For erroneous case, \( S \) will have full rank for all values of \( b \) due to erroneous bits. It is to be noticed that the rank deficient data matrix under erroneous channel conditions will have more number of zeros compared to the full rank matrix. Therefore, the data matrix \( S \) with deficient rank will be identified by evaluating the zero-mean-ratio of column echelon form \( F \), which is denoted by \( \mu(b) \), and the same is given by

\[
\mu(b) = \frac{\sum_{c=1}^{b} \sigma(c)}{b}, \tag{2}
\]

where \( \sigma(c) = \frac{2\phi(c)}{d} \) indicates the mean value of number of zeros in the \( c \)th column of \( F \) and \( \phi(c) \) denotes the number of zeros in the \( c \)th column. Now \( \zeta \) will be estimated based on the values of \( \mu(b) \) under erroneous channel conditions using algorithm 2.

### V. ESTIMATION OF INTERLEAVER PARAMETERS

After recognizing \( \zeta \), the interleaver parameters such as \( B \) and \( M \) for convolutional interleaver and \( C \), \( N \), and \( d \) for helical interleaver should be estimated. In addition, the number of bit positions to be shifted for achieving proper synchronization
Algorithm 2 Estimation of $\zeta$ for Erroneous Case

**Notations:** $\mu'(b)$ denotes the normalized zero-mean-ratio.

**Assumptions:** $a \geq 2b$ and the received data stream is assumed to have bit errors.

1: Convert $S$ into $F$ using GJETP algorithm.
2: Evaluate $\mu(b)$ as given by (2).
3: Compute $\mu'(b)$ by normalizing $\mu(b)$ with respect to the maximum value $\mu_{\text{max}}$. Now, the normalized zero-mean-ratio $\mu'(b)$ is given by
   \[
   \mu'(b) = \frac{\mu(b)}{\mu_{\text{max}}}. \tag{3}
   \]
4: Observe the difference between the zero-dominant columns or the successive number of columns with higher values of $\mu'(b)$ and the same gives $\zeta$ for erroneous case.

Algorithm 3 Convolutional Interleaver

**Notations:** $M_{\text{max}}$ denotes the maximum value of interleaver width, $\phi$ indicates the bit position adjustment to achieve synchronization, and $\delta(B', \phi, M')$ denotes the difference between the zero-dominant columns or the difference between the successive number of columns with higher values of $\mu'(b)$ for convolutional interleaver;

**Assumptions:** $B' > 1$, $M' \in [1, M_{\text{max}}]$, $\phi \in [0, \zeta - 1]$, $b \in [b_{\text{min}}, b_{\text{max}}]$;

**Input:** $\zeta = \text{lcm}(n, B)$;

**Output:** $B^{\text{est}}, M^{\text{est}}, \phi^{\text{est}}$ and $\rho^{\text{est}}$;

1: \textbf{for} $i = 1:n_{\text{max}}$ \textbf{do}
   \begin{align*}
   & \text{Get all possible unique values of } B' \text{ that satisfy } \\
   & \text{lcm}(i, B') = \zeta; \\
   \end{align*}
2: \textbf{end}
3: \textbf{for} each possible combinations of $[B', \phi, M']$, de-interleave and evaluate $\mu'(b)$ for different values of $b$;
4: \textbf{for} each possible checks, obtain $\delta(B', \phi, M')$;
5: $\rho^{\text{est}} = \delta(B^{\text{est}}, \phi^{\text{est}}, M^{\text{est}})$;

Next, we propose another algorithm to estimate the convolutional interleaver parameters with reduced number of search operations (refer to algorithm 4).
The assumptions and notations given in algorithm 3 is also valid for algorithm 4. Since \( b \) is fixed as a multiple of \( \zeta = \text{lcm}(n, B) \), \( \mu(b) \) is maximum due to rank deficiency for \( B' = B, M' = M \), and synchronized bit position. By de-interleaving with correct interleaver and synchronization parameters, the data symbols will be convolutionally encoded. We know that for convolutional codes, the rank deficiency will be obtained only for the case when \( b \) is a multiple of \( n \). Since \( \zeta = \text{lcm}(n, B) \) is also a multiple of \( n \), rank deficiency will be observed when \( b \) is fixed as a multiple of \( \zeta \). Further, it has already been mentioned that \( \mu(b) \) will be higher for rank deficient matrix under erroneous channel conditions. Thus, \( \mu(b) \) is maximum when de-interleaved using correct interleaver parameters as mentioned in step 4 of algorithm 4.

From algorithm 4, the number of search operations \( T_2 \) required for successful estimation of convolutional interleaver parameters is given by

\[
T_2 = R \zeta M_{\text{max}}
\]  

From the computational complexity analysis of the two algorithms given for convolutional interleaver, it can be inferred that algorithm 4 is computationally efficient compared to algorithm 3, since \( T_1 \) is greater than \( T_2 \). Despite the fact that algorithm 4 is computationally efficient, additional information about \( n \) can also be extracted using algorithm 3.

To estimate the helical interleaver parameters along with \( n \), algorithm 5 is proposed.

**Algorithm 5 Helical Interleaver**

| Notations: | \( d_{\text{max}} \) indicates the maximum value of step size \( d \) and \( \delta(C', N', \phi, d') \) denotes the difference between the zero-dominant columns or the difference between the successive number of columns with higher values of \( \mu' \) for helical interleaver; |

| Assumptions: | \( \beta = CN, C' > 1, N' > 1, d' \in [1,d_{\text{max}}], \phi \in [b_{\text{min}}, b_{\text{max}}], \text{and } \phi \in [0, \zeta - 1]; \) |

| Input: | \( \zeta = \text{lcm}(n, \beta) \); |

| Output: | \( C^{\text{est}}, N^{\text{est}}, d^{\text{est}}, \phi^{\text{est}}, \text{and } n^{\text{est}}; \) |

1: for \( i = 1:n_{\text{max}} \) do

1.1: Get all possible combinations of two factors \( C' \) and \( N' \) such that \( C'N' = \frac{\zeta}{\beta} \)

2: For each possible combinations of \( [C', N', \phi, d'] \), de-interleave and evaluate \( \mu(b) \) for different values of \( b \);  
3: For each possible checks, obtain \( \delta(C', N', \phi, d') \);  
4: \( [C^{\text{est}}, N^{\text{est}}, \phi^{\text{est}}, d^{\text{est}}] = \arg\min (\delta(C', N', \phi, d')); \)  
5: \( n^{\text{est}} = \delta(C^{\text{est}}, N^{\text{est}}, \phi^{\text{est}}, d^{\text{est}}); \) 

As expected, algorithm 6 is computationally efficient compared to algorithm 5 in terms of the number of search operations. However, it is to be noticed that \( n \) can also be identified along with interleaver parameters using algorithm 5.

**Algorithm 6 Helical Interleaver**

| Input: | \( \zeta = \text{lcm}(n, \beta); \) |

| Output: | \( C^{\text{est}}, N^{\text{est}}, d^{\text{est}}, \phi^{\text{est}}; \) |

1: for \( i = 1:n_{\text{max}} \) do

1.1: Get all possible combinations of two factors \( C' \) and \( N' \) such that \( C'N' = \frac{\zeta}{\beta} \)

2: Fix \( b = a \zeta; \)  
3: De-interleave and evaluate zero-mean-ratio \( \mu(b) \) by simultaneously varying the parameters \( [C', N', \phi, d']; \)  
4: \( [C^{\text{est}}, N^{\text{est}}, \phi^{\text{est}}, d^{\text{est}}] = \arg\min (\mu(b)); \)  

VI. SIMULATION RESULTS AND DISCUSSIONS

The convolutional encoder is defined as \( C(n, k, K)[g_1, \ldots, g_r, \ldots, g_k], \) where \( n, k, \) and \( K \) are defined as codeword length, code dimension, and constraint length of the convolutional codes, respectively. Further, \( g_i \) denotes the octal representation of generator sequence between input \( i \) and output \( j \). The present work analyzes the performance of the interleaver parameter estimation algorithms over noisy transmission environment. It is a known fact that to achieve a given quality of service (QOS), different transmission standards specify allowable BER values. We also know that convolutional interleaver is more prominently used in DVB receiver and for desirable operation of DVB receiver, the post-FEC BER requirement is \( 2 \times 10^{-4} \) [6]. Considering the allowances of coding gain, the pre-FEC BER values will be usually greater than \( 10^{-3} \). Hence, a safe BER value of \( 10^{-2} \) is considered in our simulation study to account the worst case scenario. Further, the performance of the proposed
algorithms is investigated for different BER values within the range of $5 \times 10^{-3}$ to $6 \times 10^{-2}$. In our simulation study, we have fixed $d_{\text{max}} = 5$ and $M_{\text{max}} = 5$ for convolutional and helical interleavers, respectively, as well as $n_{\text{max}} = 5$. The parameter estimation algorithms are also tested successfully for different cases as listed in Table 1.

### TABLE 1. Test code set.

<table>
<thead>
<tr>
<th>No.</th>
<th>Code rate ($r$)</th>
<th>$n$</th>
<th>$k$</th>
<th>$K$</th>
<th>$g_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>[3,7]</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>[15,17]</td>
</tr>
<tr>
<td>3</td>
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<td></td>
<td></td>
<td>5</td>
<td>[23,35]</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>[65,57]</td>
</tr>
<tr>
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<td></td>
<td></td>
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<td>[73,53]</td>
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<td></td>
<td></td>
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<td>[133,171]</td>
</tr>
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<td>7</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>[345,237]</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>[561,753]</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>[1367,1545]</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>[2335,3661]</td>
</tr>
<tr>
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<td>1/3</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>[15,15,17]</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>[133,165,171]</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>[2335,2671,3375]</td>
</tr>
<tr>
<td>14</td>
<td>1/4</td>
<td>4</td>
<td>1</td>
<td>7</td>
<td>[133,171,117,165]</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>[1117,1565,1633,1653]</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>[4767, 5723, 6265, 7435]</td>
</tr>
</tbody>
</table>

### A. SIMULATION RESULTS FOR CONVOLUTIONAL INTERLEAVER

According to algorithm 2, the normalized zero-mean-ratio $\mu'(b)$ is evaluated for different values of $b$ as shown in Fig. 4(a). The variation of $\mu'(b)$ with respect to $b$ before de-interleaving is shown for convolutional interleaver assuming $C(3, 1, 7)[133, 165, 171]$, $BER = 10^{-2}$, $B = 6$, $M = 3$, and $\Delta = 7$. From the figure, it is inferred that the difference between the zero-dominant columns or the difference between the successive number of columns with higher values of $\mu'(b)$ is equal to 6. According to proposition 1, if $B$ is a multiple of $n$, then $\zeta = B$ and hence, $\zeta$ is identified successfully from the erroneous convolutional interleaved data. In Fig. 4(b), the variation of $\mu(b)$ is shown after de-interleaving with all possible combinations of $[B', \phi, M']$ according to algorithm 4. The possible values of $B'$ that satisfy $\text{lcm}(i, B') = 6$, where $i = 1 : n_{\text{max}}$, are $B' = [2, 3, 6]$. By varying $B'$ along with $M'$ and $\phi$, where $M' \in [1, 5]$ and $\phi \in [0, 5]$, it is observed that for $B' = 6$, $M' = 3$, and $\phi = 0$, $\mu(b)$ reaches maximum. Since the received data stream is already synchronized with $1 = t \zeta + 1$, where $t = 1$ for this case, it is not necessary to shift the bit position (i.e. $\phi = 0$). Hence, the synchronization parameter and the convolutional interleaver parameters are estimated successfully using algorithm 4.

According to algorithm 3, for each possible combinations of $[B', \phi, M']$, the coded data symbols are de-interleaved and $\mu'(b)$ is evaluated for different values of $b$ in Fig. 5. In Fig. 5(a), the variation of $\mu'(b)$ with respect to $b$ after de-interleaving using correct interleaver and synchronization parameters (i.e. $B' = 6$, $M' = 3$, and $\phi = 0$) is shown. It is observed that the difference between the successive number of columns with higher values of $\mu'(b)$ is equal to 3, which is the codeword length of the convolutional code assumed in this case. In Fig. 5(b), Fig. 6(a), and Fig. 6(b), the variation of $\mu'(b)$ with respect to $b$ is shown by de-interleaving using incorrect possible combinations of $[B', \phi, M']$. From the figures, it is inferred that after de-interleaving...
using inaccurate parameters, $\delta(B', \phi, M')$ is observed to be equal to $\zeta$, where $\zeta = 6$, which is greater than $n$. Note that among 90 possible combinations of $[B', \phi, M']$, we have shown only 3 combinations. It is also observed that for the rest of the incorrect possible combinations, $\delta(B', \phi, M') = \zeta$. Therefore, the interleaver and synchronization parameters for which $\delta(B', \phi, M')$ is minimum are $B' = 6$, $M' = 3$, and $\phi = 0$. It is also observed that the estimated parameters exactly match with the parameters successfully identified using algorithm 4 shown in Fig. 4.

In Fig. 7(a) and Fig. 7(b), the convolutional interleaver parameter estimation is carried out based on the
algorithms 2 and 4, respectively, with BER = 10^{-2} assuming C(4, 1, 12)[4767, 5723, 6265, 7455], B = 5, M = 4, BER = 10^{-2}, and Δ = 6. From Fig. 7(a), it is observed that the difference between the successive number of columns with higher values of μ′(b) is equal to 20 (i.e. lcm(n, B)) according to proposition 2. Hence, ζ is successfully estimated for the case when B is not a multiple of n. In Fig. 7(b), the variation of μ(b) is shown for all possible combinations of [B′, φ, M′] and it is noticed that the convolutional interleaver parameters B'_{est} = 5, M'_{est} = 4, and the number of bits to be shifted for achieving proper frame synchronization (i.e. φ_{est} = 15) are estimated successfully.

In Fig. 8(a), μ′(b) is evaluated for convolutional interleaver based on algorithm 2 and the variation with respect to b is shown for punctured convolutional code assuming C(2, 1, 3)[5, 7], BER = 10^{-2}, B = 4, M = 2, Δ = 6, and puncturing pattern = [1;1;0;1]. Firstly, the zero-dominant-column difference ζ as indicated in the figure is observed to be equal to 12. After puncturing using the pattern [1;1;0;1], rate 1/2 convolutional code will be converted into rate 1/3 code, where punctured codeword length n_p = 3 and punctured input bits k_p = 2. Therefore, ζ = lcm(n_p, B) instead of lcm(n, B). Fig. 8(b) shows the variation of μ′(b) for all possible combinations of [B′, φ, M′]. As expected, using algorithm 4, the convolutional interleaver parameters B'_{est} = 4, M'_{est} = 2 and synchronization parameter φ_{est} = 7 are detected successfully from the punctured convolutional code.

**B. SIMULATION RESULTS FOR HELICAL INTERLEaver**

In Fig. 9(a), μ′(b) for helical interleaver is computed based on algorithm 2 and the variation of μ′(b) with respect to b is shown for C(2, 1, 5)[23, 35], BER = 10^{-2}, C = 3, N = 2, d = 5, and Δ = 6. Since β = C × N = 6 is a multiple of n = 2, it is observed that the successive difference between the number of columns with higher values of μ′(b) is equal to β according to proposition 3. Therefore, ζ, which is equal to β for this case, is estimated correctly. In Fig. 9(b), the variation of μ(b) is shown by de-interleaving with all possible combinations of [B′, φ, M′] assuming C(4, 1, 12)[4767, 5723, 6265, 7455], BER = 10^{-2}, B = 5, M = 4, and Δ = 6.

**FIGURE 7.** (a) Variation of μ′(b) with respect to b before de-interleaving for convolutional interleaver assuming C(4, 1, 12)[4767, 5723, 6265, 7455], B = 5, M = 4, BER = 10^{-2}, and Δ = 6. (b) Variation of μ(b) after de-interleaving with all possible combinations of [B′, φ, M′] assuming C(4, 1, 12)[4767, 5723, 6265, 7455], BER = 10^{-2}, B = 5, M = 4, and Δ = 6.
Fig. 11(a) and Fig. 11(b) show the zero-mean-ratio plots before and after de-interleaving, respectively, for helical interleaver considering $C(3, 1, 11)[2353, 2671, 3175]$ with $C = 5, N = 3, d = 3, \text{BER} = 10^{-2}$, and $\Delta = 9$. Since $\beta$ is a multiple of $n$, $\zeta = \beta$ according to proposition 3. It is inferred from Fig. 11(a) that $\zeta = 15$ has been identified successfully using algorithm 2. In Fig. 11(b), the variation of $\mu(b)$ is shown by de-interleaving with all possible combinations of two factors $C'$ and $N'$ that satisfy $\frac{15}{5}$ as mentioned in step 1 of algorithm 6. The de-interleaving is performed together with varying $d'$ from 1 to 5 and $\phi$ from 0 to 14. It is noticed from the figure that for $C' = 5, N' = 3, d' = 3,$ and $\phi = 7$, $\mu(b)$ reaches maximum. Therefore, the helical interleaver parameters are estimated successfully using algorithm 6. Further, the incoming data stream is also synchronized by appropriately shifting correct number of bit positions.
In Fig. 12(a), the variation of \( \mu'(b) \) with respect to \( b \) is for helical interleaver assuming punctured convolutional code \( C(2, 1, 3)[5, 7] \) with puncturing pattern \( = [1; 1; 0; 1; 1; 0] \), \( BER = 10^{-2} \), \( C = 4 \), \( N = 4 \), \( d = 2 \), \( \Delta = 9 \), \( k_p = 3 \), and \( n_p = 4 \). From the figure, \( \zeta \) is observed to be equal to 16. Since \( \beta \) is a multiple of \( n_p \), \( \zeta = \beta \) has been identified correctly using algorithm 2. Fig. 12(b) shows the variation of \( \mu(b) \) for all possible combinations of \([C', N', \phi, d']\). Using algorithm 6, the helical interleaver parameters \( C^{est} = 4, N^{est} = 4, d^{est} = 2 \) and synchronization parameter \( \phi^{est} = 8 \) are detected successfully from the punctured convolutional code, since \( \mu(b) \) is maximum for \([C', N', \phi, d'] = [4, 4, 8, 2] \).

**C. ACCURACY OF ESTIMATION OF BOTH THE INTERLEAVERS**

In Fig. 13(a) and Fig. 13(b), the probability of correct detection of interleaver parameters is shown against
BER considering different values of $K$ for convolutional and helical interleavers, respectively. Firstly, from the figures it can be observed that as $K$ increases, the probability of estimating the interleaver parameters decreases for both the interleavers and the trend remains the same irrespective of the interleaver parameters and $r$. Moreover, when the number of rows $a$ of data matrix $S$ increases with respect to the number of columns $b$ from $a = 2 \times b$ to $a = 10 \times b$, the probability of detecting the correct interleaver parameters also increases as expected. By averaging more number of rows, the difference between the zero-dominant columns can be predicted more accurately to estimate $\zeta$ without any intermediate peaks and hence, the estimation improves with increase in the data size. It is also to be noted that the estimation of $\zeta$ plays a vital role in estimating the interleaver parameters. Further, as $K$ increases, the rank value associated with a particular value of $b$ also increases as mentioned in [4] and [5]. Hence, the number of dependent columns decreases, which in turn
decreases $\mu'(b)$ for erroneous case. If $\mu'(b)$ is very less for a rank deficient column, then the accuracy in predicting $\zeta$ or the difference between the zero-dominant columns deteriorates for higher constraint length case due to the existence of intermediate peaks.

VII. CONCLUSION

In this paper, the parameter estimation of helical and convolutional interleavers is investigated in a noisy transmission environment considering convolutionally encoded data. A generic block diagram explaining the estimation process is given. Then algorithms for estimating the rank-deficiency difference are proposed for non-erroneous and erroneous channel conditions. Further, based on the estimated value of rank-deficiency difference, more algorithms are given for estimating the parameters of convolutional and helical interleavers. Using the proposed algorithms, bit position adjustment is also identified for achieving proper frame synchronization. From the numerical results, it is observed that the interleaver parameters are estimated successfully with 100% accuracy until BER of $2 \times 10^{-2}$. In addition, the interleaver parameters are also correctly estimated from the punctured convolutionally encoded data. Finally, the accuracy of estimation of the proposed algorithms is shown by varying the BER values for two different values of constraint length and number of rows of the data matrix. From the performance plots, an improvement in the estimation accuracy of the interleaver parameters is observed with decrease in the constraint length and increase in the data size.

APPENDIX A

CASE STUDY 1: CONVOLUTIONAL INTERLEAVER

In this Appendix, the reason for rank deficiency considering the case when $B$ is a multiple of $n$ as mentioned in proposition 1 for convolutional interleaver has been explained using an example. Firstly, Fig. 14 shows the variation of $\rho(S)$ with $b$ for convolutional interleaver considering $C(2, 1, 3)[5, 7]$, $B = 2$, and $M = 2$ for non-erroneous and synchronized scenario. Note that $\rho(S)$ is computed based on algorithm 1. Let us denote the output codewords of rate $1/2$ convolutional codes corresponding to the input symbols $A, B, \cdots, X, \cdots, a, b, c$ as $A_{1,2}, B_{1,2}, \cdots, X_{1,2}, \cdots, a_{1,2}, b_{1,2}, c_{1,2}$, respectively. In Table 2, the output codewords are convolutionally interleaved and reshaped into a data matrix $S$ of size $a \times b$ assuming $b = 14$, 15, and 16 with number of rows $a = 3$. It is to be noted that the convolutional interleaving operation is carried out as shown in Fig. 1. For better understanding, we have shown only three rows. From the interleaved data stream, $\chi = 5$ complete continuous codewords (i.e. $H_1 H_2, I_1 I_2, J_1 J_2, K_1 K_2, L_1 L_2$ in the second row and $Q_1 Q_2, P_1 P_2, Q_1 Q_2, R_1 R_2, S_1 S_2$ in the third row) are observed. It is also noticed that all 5 complete continuous codewords are aligned properly in the same column. As $\chi n$ output data bits or $\chi$ codewords depend on $\chi k + m$ input bits for convolutional codes as mentioned in [4] and [5], here, $\chi = 5$ complete continuous codewords or $\chi n = 10$ output data bits depend on 5 present and 2 previous bits. We assume $K = 3$ for this case and $m = K - 1$ for rate $1/n$ convolutional codes. Therefore, when the convolutionally interleaved data matrix $S$ is converted into column echelon form $F$ through GJETP algorithm, 10 columns will be converted into 7 (i.e. $\chi k + m$) non-zero columns. This is because, GJETP algorithm eliminates all the dependent columns. Moreover, it is also observed in Table 2 that there are 4 incomplete codewords which are segregated in different rows and are not aligned properly in the same column. This will result in another 4 (i.e. $b - \chi n$) non-zero columns in $F$. Hence, after Gauss elimination process, column echelon form of $S$ will consist of 11 non-zero columns for the case when $b = 14$. Since the number of non-zero columns in $F$ indicates the rank of a matrix, $\rho(S) = \chi k + m + b - \chi n$ (refer to (1)) as mentioned in proposition 1. Note that the number of independent columns in $S$ or the number of non-zero columns in $F$ gives the rank of a matrix.

In Table 2, the convolutionally interleaved data stream for the case when $b = 16$ assuming $r = \frac{1}{2}$, $B = 2$, and $M = 2$ is also shown considering synchronized and non-erroneous scenario. Similar to $b = 14$ case, here, $\chi = 6$ continuous complete codewords are observed (i.e. $I_1 I_2, J_1 J_2, K_1 K_2, L_1 L_2, M_1 M_2, N_1 N_2$ in the second row and $Q_1 Q_2, R_1 R_2, S_1 S_2, T_1 T_2, U_1 U_2, V_1 V_2$ in the third row are aligned properly in the same column). Hence, after converting $S$ into $F$, 12 columns (i.e. $\chi n$) will be reduced to 8 non-zero columns ($\chi k + m$) for the case when $K = 3$. Furthermore, there are 4 incomplete codewords (i.e. $b - \chi n$) which are segregated in different rows and the same will result in 4 non-zero columns in $F$. So totally 12 (i.e. $\chi k + m + b - \chi n$) non-zero columns will be observed out of 16 in $F$ or $\rho(S) = 12$, which justifies (1) given in proposition 1.

Since $b$ is a multiple of $B$, rank deficiency is observed for the cases when $b = 14$ and $b = 16$. In Table 2,
TABLE 2. Convolutionally interleaved data stream assuming $B = 2$ and $M = 2$.

<table>
<thead>
<tr>
<th>$b$</th>
<th>$A_1$</th>
<th>$S$</th>
<th>$A_2$</th>
<th>$R_1$</th>
<th>$S$</th>
<th>$A_3$</th>
<th>$R_2$</th>
<th>$S$</th>
<th>$A_4$</th>
<th>$R_3$</th>
<th>$S$</th>
<th>$A_5$</th>
<th>$R_4$</th>
<th>$S$</th>
<th>$A_6$</th>
<th>$R_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
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<td>0</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
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<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Convolutionally interleaved data stream assuming $B = 2$ and $M = 2$. Even though there are 5 continuous complete codewords in a single row (i.e. $I_1I_2, J_1J_2, K_1K_2, L_1L_2, M_1M_2$ in the second row and $P_1P_2, Q_1Q_2, R_1R_2, S_1S_2, T_1T_2$ in the third row), all the codewords are not aligned correctly in the same column unlike $b = 14$ and $b = 16$ cases. This will result in full rank as mentioned in proposition 1.

Further, the rank values obtained for the case when $b = 14, 15$, and $16$ in this case study well agree with the rank values shown in Fig. 14. It is to be noted that the difference between two successive columns with rank deficiency is observed to be equal to 2 (i.e. $B$). Therefore, from Table 2, it is observed that if $b$ is a multiple of $B$, then rank deficiency is obtained and $\rho(S) = \chi k + m + b - \chi n$. However, if $b$ is not a multiple of $B$, then full rank is obtained.

APPENDIX B

CASE STUDY 2: CONVOLUTIONAL INTERLEAVER

In this Appendix, the reason for rank deficiency considering the case when $B$ is not a multiple of $n$ as mentioned in proposition 2 for convolutional interleaver has been explained using an example. Here, the convolutionally interleaved data stream assuming $r = \frac{1}{2}, B = 3$ and $M = 2$ for the case when $b = 18, B = 20$, and $b = 24$ with $\alpha = 3$ is shown in Table 3 for synchronized and non-erroneous scenario. Moreover, the variation of $\rho(S)$ with $b$ for convolutional interleaver considering $C(2, 1, 3)[5, 7], B = 3$, and $M = 2$ is shown in Fig. 15 by varying $b$ from 10 to 30 and $\rho(S)$ is evaluated using algorithm 1. From Table 3, $\chi = 5$ complete continuous codewords are observed in the second and third rows. Since all are aligned properly in the same column, rank deficiency will be observed. Therefore, after converting $\chi$ into $F$, $\chi = 5$ complete continuous codewords which will occupy 10 columns (i.e. $\chi \times n$) will be reduced to 7 non-zero columns (i.e. $\chi k + m$). In addition, there are 8 incomplete columns in $S$ (i.e. $b - \chi n$) due to 8 incomplete codewords in a particular row as observed in Table 3. Therefore, out of 18 columns, 15 non-zero columns (i.e. $\chi k + m + b - \chi n$) will be noticed in $F$ and hence, $\rho(S) = 15$. Similarly, for the case when $b = 24$, $\chi = 8$ complete continuous codewords are observed in a single row and are aligned properly in the same column. After applying GJETP algorithm, $\chi = 8$ complete continuous codewords which will occupy 16 columns (i.e. $\chi \times n$) will be reduced to 10 non-zero columns (i.e. $\chi k + m$). Furthermore, there are 8 incomplete codewords (i.e. $b - \chi n$) which are segregated in different rows and the same will result in 8 non-zero columns in $F$. So totally 18 (i.e. $\chi k + m + b - \chi n$) non-zero columns will be observed out of 24 in $F$ or $\rho(S) = 18$ for the case when $b = 24$. Therefore, the deficient rank values obtained for $b = 18$ and $b = 24$ validate (1).

In Table 3, the convolutionally interleaved stream is also shown for the case when $b = 20$. Since all the complete codewords are not aligned in the same column, full rank will be obtained. Similar to the previous case study, the rank values obtained for the case when $b = 18, 20$, and $24$ well

TABLE 3. Convolutionally interleaved data stream assuming $B = 3$ and $M = 2$.

<table>
<thead>
<tr>
<th>$b$</th>
<th>$A_1$</th>
<th>$S$</th>
<th>$A_2$</th>
<th>$R_1$</th>
<th>$S$</th>
<th>$A_3$</th>
<th>$R_2$</th>
<th>$S$</th>
<th>$A_4$</th>
<th>$R_3$</th>
<th>$S$</th>
<th>$A_5$</th>
<th>$R_4$</th>
<th>$S$</th>
<th>$A_6$</th>
<th>$R_5$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
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<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
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</tr>
<tr>
<td>18</td>
<td>1</td>
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<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
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<td>5</td>
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<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

FIGURE 15. Variation of rank with number of columns ($b$) for convolutional interleaver ($C(2, 1, 3)[5, 7], B = 3, M = 2, BER = 0$).

TABLE 3. Convolutionally interleaved data stream assuming $B = 3$ and $M = 2$. 

<table>
<thead>
<tr>
<th>$b$</th>
<th>$A_1$</th>
<th>$S$</th>
<th>$A_2$</th>
<th>$R_1$</th>
<th>$S$</th>
<th>$A_3$</th>
<th>$R_2$</th>
<th>$S$</th>
<th>$A_4$</th>
<th>$R_3$</th>
<th>$S$</th>
<th>$A_5$</th>
<th>$R_4$</th>
<th>$S$</th>
<th>$A_6$</th>
<th>$R_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

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TABLE 4. Helical interleaved data stream assuming $C = 3$, $N = 2$, and $d = 1$.

<table>
<thead>
<tr>
<th>$k = 1.8$</th>
<th>$A_1$</th>
<th>$B_1$</th>
<th>$C_1$</th>
<th>$D_1$</th>
<th>$E_1$</th>
<th>$F_1$</th>
<th>$G_1$</th>
<th>$H_1$</th>
<th>$I_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_2$</td>
<td>$B_2$</td>
<td>$C_2$</td>
<td>$D_2$</td>
<td>$E_2$</td>
<td>$F_2$</td>
<td>$G_2$</td>
<td>$H_2$</td>
<td>$I_2$</td>
<td></td>
</tr>
<tr>
<td>$k = 1.8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_3$</td>
<td>$B_3$</td>
<td>$C_3$</td>
<td>$D_3$</td>
<td>$E_3$</td>
<td>$F_3$</td>
<td>$G_3$</td>
<td>$H_3$</td>
<td>$I_3$</td>
<td></td>
</tr>
<tr>
<td>$k = 1.5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_4$</td>
<td>$B_4$</td>
<td>$C_4$</td>
<td>$D_4$</td>
<td>$E_4$</td>
<td>$F_4$</td>
<td>$G_4$</td>
<td>$H_4$</td>
<td>$I_4$</td>
<td></td>
</tr>
</tbody>
</table>

agree with the rank values shown in Fig. 15. Moreover, it is to be noted that the difference between two successive columns with rank deficiency is equal to 6 (i.e., lcm($n, B$)). Therefore, it has been inferred from Table 3 and Fig. 15 that if $b$ is a multiple of lcm($n, B$), then rank deficiency is obtained and $\rho(S) = \chi k + m + b - \chi n$ as mentioned in proposition 2. However, if $b$ is not a multiple of lcm($n, B$), then full rank is obtained as stated in proposition 2.

FIGURE 16. variation of rank with number of columns $b$ for helical interleaver ($k(2, 1, 3)[5, 7], c = 3, n = 2, d = 1, \text{ber} = 0$).

APPENDIX C

CASE STUDY 3: HELICAL INTERLEAVER

In this Appendix, the reason for rank deficiency considering the case when $\beta$ is a multiple of $n$ for helical interleaver has been explained using an example. Fig. 16 shows the variation of $\rho(S)$ with respect to $b$ for helical interleaver assuming $C(2, 1, 3)[5, 7], C = 3, N = 2, \text{and } d = 1$ considering non-errorneous and synchronized scenario. Similar to previous case studies, $\rho(S)$ for helical interleaver is computed using algorithm 1. In addition, the helical interleaved data stream considering $r = 1/2$ is reshaped into a matrix of size $a \times b$ with $a = 3$ and $b = 12, 15$, and 18 as shown in Table 4. Firstly, for the cases when $b = 12$ and $b = 18$, $\chi = 5$ and $\chi = 8$ complete continuous codewords, respectively, are observed in second and third rows aligned properly in the same column. This will result in rank deficiency and $\rho(S) = 9$ and 12 for $b = 12$ and $b = 18$, respectively assuming $K = 3$. This is because, after converting $S$ into $F$, $\chi = 5$ complete continuous codewords that occupy 10 columns or $\chi n$ columns in $S$ will be converted into 7 or $\chi k + m$ non-zero columns in $F$ through GJETP algorithm. Similarly, $\chi = 8$ complete continuous codewords for the case when $b = 18$ will result in 10 non-zero columns. Already 2 independent columns (i.e., $b - \chi n$) are observed in $S$ due to misalignment of codewords for both the cases. Therefore, the column echelon form of $S$ will comprise of 9 and 12 non-zero columns for $b = 12$ and $b = 18$ cases, respectively or $\chi k + m + b - \chi n$ non-zero columns in general as mentioned in proposition 3. Since the number of non-zero columns in $F$ gives the rank of a matrix, $\rho(S) = \chi k + m + b - \chi n$, which validates (1). It is also noticed from Table 4 that for the case when $b = 15$, all the 15 columns are observed to be independent due to misalignment of codewords and hence, it will result in full rank. Thus, the rank values evaluated from Table 4 assuming $K = 3$ well agree with the values shown in Fig. 16.

Since $\beta = C \times N$ is a multiple of $n$, rank deficiency is observed for the case when $b$ is a multiple of $\beta$. For the case when $b$ is not a multiple of $\beta$, full rank is observed as inferred from Table 4 and Fig. 16. Similar to case study 2, if $b$ is not a multiple of $\beta$, rank deficiency will be observed for the case when $b$ is a multiple of lcm($n, \beta$). Further, full rank will be observed for rest of the cases.

REFERENCES


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