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Joint Reconstruction of Reed-Solomon Encoder and Convolutional Interleaver in a Noisy Environment

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Abstract—Blind estimation of code and interleaver parameters plays a vital role in various applications such as non-cooperative systems, adaptive modulation and coding, signal intelligence, etc. The present paper proposes novel algorithms to jointly estimate code and interleaver parameters from Reed-Solomon (RS) coded and convolutionally interleaved data stream based on the rank ratio and non-zero-mean-ratio values for noiseless and noisy environments, respectively. Simulation results validating the proposed algorithms are given for various test cases and the accuracy of estimation of convolutional interleaver and RS code parameters is investigated for different values of interleaver width and modulation schemes. It is inferred that the accuracy of parameter estimation improves with decrease in modulation order and interleaver width of convolutional interleaver.

I. INTRODUCTION

Forward error correcting (FEC) codes and interleavers play an important role in counteracting random and burst errors, respectively, in digital communication and storage systems. Blind estimation of FEC code and interleaver parameters is primarily useful in non-cooperative communications, which exist particularly in military, spectrum surveillance, SIGINT (signals intelligence), and COMINT (communications intelligence) systems. In addition, it is also useful in applications such as adaptive modulation and coding (AMC), cognitive radio or reconfigurable receivers, etc [1]. It is always mandatory to identify FEC code and interleaver parameters in non-cooperative scenarios, since complete information about the same may not be available at the receiving end. Reed-Solomon (RS) code followed by convolutional interleaver plays a vital role in serial concatenated codes, which are widely used in space communications, Digital video broadcasting-Terrestrial (DVB-T) systems, etc. In the case of serial concatenated codes, two levels of coding (i.e. inner and outer code) is used. The input data is first encoded by outer code followed by interleaver. After that the interleaved data is further encoded by inner code. The main reason for using serial concatenated codes is to achieve good error performance compared to single coding operation.

Various algorithms had been proposed in the recent literature for the blind estimation of FEC code and interleaver parameters. The blind estimation algorithms for convolutional codes with and without puncturing were reported in [1] and [2] and the parameter estimation was restricted to Galois Field GF(2) or binary field. Further, the algorithms were proposed in [3] for the blind estimation of codeword length of various non-binary error correcting codes. The blind reconstruction of RS

encoder without interleaver was reported in [4] for erroneous scenario. In [5] and [6], the blind reconstruction of RS and low-density parity-check (LDPC) encoders, respectively, based on the average log-likelihood ratio (LLR) of syndrome a posteriori probability (SPP) was proposed. In [7], algorithm for estimating interleaver period of block interleaver was given for non-binary RS encoded data. The algorithms for parameter estimation of convolutional interleaver were proposed in [8] and [9] for noiseless and noisy scenarios, respectively.

The main motivations of the proposed work are given as follows: In non-cooperative communications, it is always essential to estimate the code and interleaver parameters at the receiver for decoding and de-interleaving, respectively. Previously proposed algorithms in [3], [4], and [5] for blind reconstruction of RS encoder can recognize only code parameters. In the prior works, the proposed algorithms for estimating the convolutional interleaver parameters were restricted to non-erroneous scenario [8] and binary field [9]. To the extent of our knowledge, algorithms are not proposed for the joint estimation of code and interleaver parameters from RS encoded and convolutionally interleaved noisy data symbols. Further, it is also essential to propose algorithms for the blind reconstruction of convolutional interleaver and RS outer encoder to complete the parameter estimation process of serial concatenated codes.

A. Contributions

The major contributions of this paper are given as follows:

- Algorithms are proposed for joint recognition of convolutional interleaver and RS code parameters considering non-erroneous (noiseless) and erroneous (noisy) scenarios.
- The estimated convolutional interleaver parameters are interleaver depth B and interleaver width M . Further, codeword length n , code dimension k , number of bits per symbol m , primitive polynomial $p(x)$, and generator polynomial $g(x)$ are the estimated RS code parameters.
- Accuracy of estimation of code and interleaver parameters is investigated to show the robustness of the proposed algorithms.
- The proposed algorithms can be integrated with the convolutional inner code parameter estimation algorithms to complete the parameter estimation process of serial concatenated codes.

II. RS CODE AND CONVOLUTIONAL INTERLEAVER

Let α be a primitive element in $\text{GF}(2^m)$, where $\alpha^{2^m-1}=1$ and m denotes the number of bits per symbol. For a t error correcting (n, k) RS code, $\alpha, \alpha^2, \dots, \alpha^{2t}$ are the roots of the generator polynomial $g(x)$ with degree $n-k$ and $g(x)$ is given by $g(x) = (x - \alpha)(x - \alpha^2) \cdots (x - \alpha^{2t})$. It is noticed that $g(x)$ has $2t+1$ non-zero terms. As $g(x)$ is a polynomial of degree $n-k$, it can be written as $n-k=2t$. In summary, t error correcting (n, k) RS code has the following parameters: Codeword length $n=2^m-1$, Number of parity check symbols $n-k=2t$, Code dimension $k=2^m-1-2t$, and Minimum Hamming distance $d_{\min}=2t+1$. We denote RS encoded data symbols as $\text{RS}(n, k, m, p)$, where p denotes the integer representation of primitive polynomial $p(x)$.

Convolutional interleaver stores the data symbols into a bank of B registers, where B denotes the interleaver depth, and the i^{th} register consists of $(i-1) \cdot M$ delay units, where M denotes the interleaver width. With each new incoming code symbol, the commutator switches to a new register. When a new code symbol enters the shift register, the commutator, which is attached to a particular shift register, shifts out the oldest code symbol for transmission. After that the commutator switches to the next register and repeat the same process. The structure of convolutional interleaver with detailed explanation is given in [9]. It is to be noted that the delay and memory requirements are lesser for a (B, M) convolutional interleaver compared to a $(B, B \cdot M)$ block interleaver.

III. JOINT PARAMETER ESTIMATION PROCESS

It is to be noted that algorithms were proposed in [1] and [2] to estimate the parameters of convolutional inner code. Therefore, the current work focuses on the estimation of RS outer code and convolutional interleaver parameters alone. The RS encoded and convolutionally interleaved data symbols are converted into binary data and then transmitted using a suitable M -ary phase-shift keying (M -PSK) scheme. After demodulation at the receiver, rank deficiency difference parameter [9] along with RS code parameters $m, p(x)$, and n will be estimated. The rank deficiency difference is an intermediate parameter which is to be estimated in order to estimate B and M . Subsequently, individual convolutional interleaver parameters B and M will be estimated by de-interleaving with limited possible combinations of interleaver parameters. After de-interleaving using the estimated convolutional interleaver parameters, code dimension k and $g(x)$ will be identified. The receiver only knows that the incoming data is RS coded and convolutionally interleaved without knowing the code and interleaver parameters.

A. Parameter estimation over non-erroneous scenario

In this section, the parameter estimation process considering non-erroneous scenario is explained using Algorithm 1. Note that $p = \text{primpoly}(m, 'all')$ in Algorithm 1 returns all primitive polynomials $p(x)$ corresponding to m in an integer form. The rank of a matrix is the number of linearly independent rows/columns of a matrix and is obtained by transforming the

Algorithm 1: Estimation of code and interleaver parameters: non-erroneous scenario

Notations: b and a denote the number of columns and rows of data matrix S , respectively. m_{est} , n_{est} , and p_{est} denote the estimate of m , n , and p , respectively;

Assumptions: $a=2 \cdot b$;

Output: Rank deficiency difference ζ'_{est} , m_{est} , n_{est} , and p_{est} ;

```

1: for  $m = m_{\min} : m_{\max}$  do
2:    $p = \text{primpoly}(m, 'all')$ ;
3:   for  $b = b_{\min} : b_{\max}$  do
4:     The incoming RS coded and convolutionally
       interleaved binary data symbols are converted
       into the respective elements of  $\text{GF}(2^m)$  using  $p$ ;
5:     RS encoded GF array elements is reshaped
       into a data matrix  $S$  of size  $a \times b$ ;
6:     Using finite-field Gauss elimination process,  $S$ 
       is converted into column echelon form  $F$ ;
7:     By evaluating the number of non-zero columns
       in  $F$ , rank  $\rho(m, p, b)$  is computed;
8:     Compute rank ratio  $\rho'(m, p, b) = \rho(m, p, b)/b$ ;
   end
end
9: Obtain  $[m_{\text{est}}, p_{\text{est}}] = \underset{m, p}{\text{argmin}}(\rho'(m, p, b))$  and
    $n_{\text{est}} = 2^{m_{\text{est}}} - 1$ ;
10: Observe the difference between successive number of
     columns with deficient rank values and it gives  $\zeta'_{\text{est}}$ ;

```

given matrix into its row/column echelon form using finite-field Gauss elimination method [7]. The number of non-zero rows/columns of row/column echelon form also gives the rank. Rank deficiency difference parameter indicates the difference between the successive number of columns of data matrix S with deficient rank values.

The correct combination of $[m, p]$, which minimizes the rank ratio $\rho'(m, p, b)$, has been chosen as the estimated RS code parameters m_{est} and p_{est} as mentioned in step 9 of Algorithm 1. In addition, the codeword length is estimated as follows: $n_{\text{est}} = 2^{m_{\text{est}}} - 1$. From Algorithm 1, it is also observed that the estimated rank deficiency difference is equal to $\text{lcm}(n, B)$ i.e. $\zeta'_{\text{est}} = \text{lcm}(n, B)$. This is because, the deficient rank values will be obtained for the case when b is a multiple of $\text{lcm}(n, B)$. Let $b = \alpha' \times \text{lcm}(n, B)$ and $b' = (\alpha' + 1) \times \text{lcm}(n, B)$ denote two successive columns with deficient rank values, where α' is a positive integer. From $b' - b$, the rank deficiency difference $\zeta'_{\text{est}} = \text{lcm}(n, B)$ is identified. The reason for rank deficiency when b is a multiple of $\text{lcm}(n, B)$ for $m=m_{\text{est}}$ and $p=p_{\text{est}}$ is given as follows:

Due to inherent property of RS codes, n coded output data symbols depend on k uncoded input data symbols or each parity symbol is a linear combination of information symbols as mentioned in [4] and [7]. Similarly, $\chi \cdot n$ coded output data symbols, where χ denotes the number of codewords in a particular row of data matrix S , depend on $\chi \cdot k$ uncoded input data symbols. If the message and parity symbols of χ

codewords in all the rows of S are aligned properly in the same column, the linear relation is satisfied in all the rows. Therefore, there will exist linear relations between the columns of S . Hence, after converting S into F using finite field Gauss elimination process, at least $\chi \cdot (n - k)$ dependent columns out of b columns will be eliminated and the rank deficiency will be obtained.

This linear relations between the columns of S hold good only when the number of columns of the data matrix is a multiple of $\text{lcm}(n, B)$ i.e. $b = \alpha' \cdot \text{lcm}(n, B)$. Note that if $b = \alpha' \cdot \text{lcm}(n, B) = \gamma \cdot n$, where γ is a positive integer, then the data matrix S will contain less than γ complete codewords within b columns in each of its row due to the structural properties of convolutional interleaver [9]. If the data and parity symbols of a particular codeword are in the same row of S , then it is called a complete codeword. We assume that there are $\chi < \gamma$ complete codewords in each row of S . The finite field Gauss elimination process also eliminates few more parity symbols of incomplete codewords in all the rows of S . If the data and parity symbols of a particular codeword are segregated in different rows of S , then it is called an incomplete codeword. If the alignment of data and parity symbols of incomplete codewords is proper in all the rows of S , there will exist linear relations between the columns of S and few more dependent columns will be eliminated eventually through finite field Gauss elimination process. The number of complete and incomplete codewords in a particular row of S depend on the interleaver and code parameters.

In a nutshell, the upper bound on the rank of S , which is the maximum number of independent columns of S , considering b columns and χ complete codewords in all the rows of S is given by

$$\rho(m_{\text{est}}, p_{\text{est}}, b_{\text{est}}) \leq b - \chi \cdot (n_{\text{est}} - k_{\text{est}}), \quad (1)$$

where $b = \alpha' \cdot \text{lcm}(n, B) = \gamma \cdot n$, n_{est} and k_{est} denote the estimate of n and k , respectively. In Algorithm 1, the data and parity symbols of χ complete codewords and few more incomplete codewords in all the rows of S with b columns will be aligned properly in the same column only for the correct combination of $[m, p, b]$, which in turn will lead to deficient rank.

If $b \neq \alpha' \cdot \text{lcm}(n, B)$, then the data and parity symbols of χ complete codewords and few more incomplete codewords in all the rows of S will not be aligned properly in the same column. Due to this the linear relations between the columns in S will be affected and full rank will be obtained i.e. $\rho(m_{\text{est}}, p_{\text{est}}, b_{\text{est}}) = b$. Thus, the incorrect combination of $[m, p, b]$, where $b \neq \alpha' \cdot \text{lcm}(n, B)$, in Algorithm 1 will lead to full rank. As only the correct combination of $[m, p, b]$ gives deficient rank, we obtain RS code parameters m_{est} , p_{est} , and n_{est} , which minimize $\rho'(m, p, b)$. Now by varying b , the deficient rank values will be obtained for the case when b is a multiple of $\text{lcm}(n, B)$ i.e. $b = \alpha' \cdot \text{lcm}(n, B)$. Thus, by observing the difference between the successive number of columns with deficient rank values, we estimate rank deficiency difference ζ'_{est} .

B. Parameter estimation over erroneous scenario

In the case of non-erroneous scenario, the dependent columns in S will be eliminated using finite-field Gauss elimination process and the number of non-zero columns in F gives the deficient rank value. However, Algorithm 1 fails in case of noisy scenario. The presence of transmission errors or additive white noise increases the linear independence among rows/columns of a deficient rank matrix [3]. Hence, the data matrix S exhibits full rank feature irrespective of the number of columns b in an erroneous environment. However, note that the dependent columns in S will have less number of non-zero elements in F compared to independent columns for noisy or erroneous scenario. Therefore, it is intuitive that the column echelon form of deficient rank matrix will have less number of non-zero elements compared to the full rank matrix. Each element in the finite field will occur with equally likely probability for full rank matrix [7]. Hence, the rank deficient matrix for erroneous scenario is recognized based on the number of non-zero elements in F instead of number of non-zero columns. We modify Algorithm 1 for erroneous scenario and the rank deficiency difference ζ'_{est} together with RS code parameters are estimated based on the normalized non-zero-mean-ratio of F using Algorithm 2. The normalized non-zero-mean-ratio, which is denoted by $\mu'(m, p, b)$ in Algorithm 2, is the ratio of the sum of normalized non-zero-ratio values in each column to the total number of columns of F . It is to be noted that the normalization is done with respect to maximum value.

Most of the steps (i.e. steps 1 to 6) in Algorithm 2 are similar to Algorithm 1. The only difference is the correct combination of $[m, p, b]$, which minimizes normalized non-zero-mean-ratio $\mu'(m, p, b)$, has been chosen as the estimated RS code parameters m_{est} and p_{est} . Similarly, the difference between successive number of columns with lower values of $\mu'(m, p, b)$ has been chosen as the estimated rank deficiency difference parameter ζ'_{est} . From Algorithm 2, it is observed that $\zeta'_{\text{est}} = \text{lcm}(n, B)$. After estimating ζ'_{est} and $n_{\text{est}} = 2^{m_{\text{est}}} - 1$, the individual convolutional interleaver parameters B and M along with code dimension k are estimated. The normalized non-zero-mean-ratio of F , which is denoted by $\mu'(B_0, M_0)$, is calculated for limited possible combinations of interleaver parameters $[B_0, M_0]$ as given in step 16. The corresponding interleaver parameters for which the normalized non-zero-mean-ratio reaches global minimum gives the estimate of B and M as shown in step 17. It is to be noted that by fixing b as a multiple of n_{est} i.e. $b = \alpha' \cdot n_{\text{est}}$ will lead to successful estimation of interleaver parameters. The reason is given as follows: If $b = \alpha' \cdot n_{\text{est}}$, then there will be only $\alpha' \cdot k_{\text{est}}$ non-zero columns out of b columns in F (non-erroneous scenario) [4]. Equivalently, the non-zero-mean-ratio of F will be lower in noisy channel conditions. Thus, the correct combination of $[B_0, M_0]$, which minimizes $\mu'(B_0, M_0)$, has been chosen as the estimated interleaver parameters.

Finally, after de-interleaving using the estimated convolutional interleaver parameters B_{est} and M_{est} , the code di-

Algorithm 2: Estimation of code and interleaver parameters: erroneous scenario

Assumptions: $a > 2 \cdot b$ and $M_0 \in [1, M_{\max}]$;

Notations : $M_{\max}$ denotes the maximum value of interleaver width, B_{est} , M_{est} , and k_{est} denote the estimate of interleaver depth B , interleaver width M , and code dimension k ;

Output: Rank deficiency difference ζ'_{est} , m_{est} , n_{est} , k_{est} , p_{est} , B_{est} , and M_{est} ;

```

1: for  $m = m_{\min} : m_{\max}$  do
2:    $p = \text{primpoly}(m, 'all')$ ;
3:   for  $b = b_{\min} : b_{\max}$  do
4:     Convert the incoming RS coded and
       convolutional interleaved binary data symbols
       into the respective elements of  $\text{GF}(2^m)$  using  $p$ ;
5:     Reshape the RS encoded GF array elements
       into a data matrix  $S$  of size  $a \times b$ ;
6:     Convert  $S$  into  $F$  using finite-field Gauss
       elimination process;
7:     Evaluate ratio of non-zero elements i.e.
       non-zero-ratio  $\sigma(c, m, p)$ , where  $c \in \{1, 2, \dots, b\}$ ,
       and normalize the obtained values with respect to
       the maximum value;
8:     Calculate normalized non-zero-mean-ratio
        $\mu'(m, p, b)$ , where  $\mu'(m, p, b) = \frac{\sum_{c=1}^b \sigma'(c, m, p)}{b}$ ;
9:   end
10:  Obtain  $[m_{\text{est}}, p_{\text{est}}] = \underset{m, p}{\text{argmin}}(\mu'(m, p, b))$  and
11:   $n_{\text{est}} = 2^{m_{\text{est}}} - 1$ ;
12:  Observe the difference between successive number of
       columns with lower values of  $\mu'(m, p, b)$  and the same
       gives  $\zeta'_{\text{est}}$ ;
13:  Convert the incoming RS coded and convolutionally
       interleaved binary data symbols into the respective
       elements of  $\text{GF}(2^{m_{\text{est}}})$  using  $p_{\text{est}}$ ;
14:  Get all possible values of  $B_0$  that satisfy
        $\text{lcm}(n_{\text{est}}, B_0) = \zeta'_{\text{est}}$ ;
15:  De-interleave using  $B_0$  and  $M_0$ ;
16:  Reshape the GF array elements into a data matrix  $S$ 
       of size  $a \times b$  and fix  $b$  as a multiple of  $n_{\text{est}}$ ;
17:  Convert  $S$  into  $F$  using finite-field Gauss elimination
       process;
18:  Evaluate normalized non-zero-mean-ratio  $\mu'(B_0, M_0)$ 
       of  $F$  considering all possible values of  $B_0$  and  $M_0$ ;
19:  Find  $[B_{\text{est}}, M_{\text{est}}] = \underset{B_0, M_0}{\text{argmin}}(\mu'(B_0, M_0))$ ;
20:  De-interleave using  $B_{\text{est}}$  and  $M_{\text{est}}$ ;
21:  Identify the number of roots of generator polynomial
       and estimate  $n - k$ ;
22:  Obtain  $k_{\text{est}}$  from  $n - k$  and generator polynomial
        $g(x)$ ;

```

Fig. 1. Variation of $\mu'(m, p, b)$ with $[m, p, b]$ for RS(7, 3, 3, 11) assuming $B = 5$, $M = 3$, 8-PSK constellation, and $\text{SER} = 10^{-2}$

Fig. 2. Variation of $\mu'(B_0, M_0)$ with $[B_0, M_0]$ for RS(7, 3, 3, 11) assuming $B = 5$, $M = 3$, 8-PSK constellation, and $\text{SER} = 10^{-2}$

mension is estimated from the number of roots of generator polynomial. Note that the code polynomials share the roots of generator polynomial. Therefore, we evaluate the number of roots of more than 100 code polynomials. In most of the cases, it has been observed that the number of roots for code polynomials and generator polynomial are the same though there exists few cases with different number of roots. Thus, we adopt a maximum likelihood approach to identify the number of roots of the generator polynomial. By identifying the number of roots, $2t$ is estimated, where t is the error correcting capability of RS code, and for RS codes $n - k = 2t$. Since n_{est} is already estimated using Algorithm 2, k_{est} is recognized from $n - k$. After estimating the number of roots, the generator polynomial $g(x)$ is obtained.

IV. SIMULATION RESULTS AND DISCUSSIONS

The simulation results are shown only for erroneous case due to space constraint. In Fig. 1, the variation of $\mu'(m, p, b)$ with respect to $[m, p, b]$ for RS(7, 3, 3, 11) assuming $B = 5$, $M = 3$, 8-PSK constellation, and $\text{SER} = 10^{-2}$ is shown. Here, we assume binary symmetric channel (BSC) model to validate the proposed algorithm. From the figure, it is observed that $\mu'(m, p, b)$ achieves minimum at $[m, p, b] = [3, 11, 105]$.

Fig. 3. Accuracy of estimation of code and interleaver parameters considering RS(7, 3, 3, 11), $B=5$, and $M=3$ for different M -PSK modulation schemes

Fig. 4. Accuracy of estimation of code and interleaver parameters considering RS(15, 7, 4, 19), $B=5$, and QPSK scheme for different values of interleaver width

Therefore, RS code parameters $m_{\text{est}} = 3$, $p_{\text{est}} = 11$, and $n_{\text{est}} = 2^3 - 1 = 7$ are successfully estimated using Algorithm 2. Further, by noticing the difference between successive number of columns with lower values of $\mu'(m, p, b)$, $\zeta'_{\text{est}} = \text{lcm}(n, B) = 35$ is also identified successfully using Algorithm 2. In Fig. 2, it is noticed from the variation of $\mu'(B_0, M_0)$ with respect to $[B_0, M_0]$ that at $B_0 = 5$ and $M_0 = 3$, the normalized non-zero-mean-ratio curve attains minimum and hence, the individual convolutional interleaver parameters are correctly estimated using Algorithm 2. After de-interleaving the data symbols using $[B_{\text{est}}, M_{\text{est}}] = [5, 3]$, the number of roots of generator polynomial i.e. $n_{\text{est}} - k_{\text{est}} = 4$ is estimated successfully. From the number of roots, $k_{\text{est}} = 3$ and $g(x) = (x - \alpha)(x - \alpha^2)(x - \alpha^3)(x - \alpha^4)$ are obtained.

In Fig. 3, the accuracy of estimation of interleaver and code parameters for RS(7, 3, 3, 11) is shown for different M -PSK modulation schemes assuming $B=5$ and $M=3$ by varying the average SNR. Note that additive white Gaussian noise (AWGN) channel model is considered to evaluate the performance of the proposed algorithm. It is inferred that the accuracy of estimation improves with decrease in modulation order, as expected. The accuracy of estimation is 100% for

average SNR values greater than 6 dB, 9 dB, and 14 dB, for BPSK, QPSK, and 8-PSK schemes, respectively. In Fig. 4, the accuracy of estimation of RS(15, 7, 4, 19) assuming $B=5$ and QPSK modulation scheme is given for different values of interleaver width M . It is observed that the accuracy of estimation is 100% for average SNR greater than 10 dB. In addition, the accuracy of estimation deteriorates with increase in the value of M . This is mainly due to increase in the deficient rank value for the case when $b = \alpha' \cdot \text{lcm}(n, B)$, when M increases. Further, the number of complete codewords in a particular row aligned properly in the same column decreases, as M increases. This will decrease the number of dependent columns or increase rank $\rho(m, p, b)$ and rank ratio $\rho'(m, p, b)$. As $\rho'(m, p, b)$ increases, it is always difficult to classify deficient rank and full rank data matrices based on normalized non-zero-mean-ratio for erroneous case.

To the best of our knowledge, there exists no other blind RS code and convolutional interleaver parameter estimation algorithms. The existing algorithms for estimating the convolutional interleaver parameters were restricted to noiseless scenario [8] and binary field [9]. Hence, we cannot compare with other existing method(s) in literature.

V. CONCLUSIONS

In this paper, the parameter estimation of RS code and convolutional interleaver is investigated in a noisy environment. Innovative algorithms for the joint estimation of RS code and convolutional interleaver parameters are proposed for noiseless and noisy scenarios based on the rank ratio and non-zero-mean-ratio values, respectively. Detailed simulation studies are conducted for different test cases and successful parameter estimation of RS code and convolutional interleaver is reported. It has been inferred that the accuracy of estimation improves with decrease in modulation order and interleaver width of convolutional interleaver.

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