2D Interleaver Design for Image Transmission over Severe Burst-Error Environment

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Abstract—**The aim of this paper is to design sub-optimal 2D interleavers and compare the bit error rate (BER) of different kinds of 2D interleavers in different randomly generatedburst error environment which are low, medium and high burst error environment. Typically, low burst error occurs in indoor environment and high burst error occurs in outdoor environment since transmission scheme in indoor use less distance and it is less likely that the line of sight (LOS) is blocked by external objects. This transmission scheme is based on 2D channel model with 2D linear block codeand 2D syndrome decoderpreviously proposed.The proposed interleavers that we use to compare their performance are block interleavers, prime interleavers, random interleavers and set partitioning concept interleavers. From the simulation results, prime interleavers are preferred over their counterparts since they have relatively lower average (Mean) and standard deviation (SD) of BER.**

Index Terms—**BER, block code, channel coding, interleaver**

I. Introduction

For many years, the digital transmission of two-dimensional (2D) data array or image is preferred to be performed by first converting the 2D data into one-dimensional(1D) by scanning row-by-row or column by column and send them through 1D channel. As the result, the 2D correlation of neighboring bits is overlooked and the correctable error bits per codeword is not optimal. Therefore, the concept of 2D channel is created. One of the important applications of 2D channel is the wireless transmission systems by employing Multiple-Input Multiple-Output (MIMO) and Orthogonal Frequency Division Multiplexing techniques (OFDM). 2D channels can employ OFDM and MIMO by having one spatial dimension and one dimension as the orthogonal carrier frequency of OFDM.The MIMO-OFDM systems have received a great deal of attention because it can improve channel spectral efficiency and channel capacity .The concept of 2D linear block encoder, syndrome decoder and performance evaluation of block interleavers have been previously proposedin [14].

Four new interleavers have been proposed and evaluated namely proposednew version block interleaver, 2D prime interleaver, 2D random interleaver and set partitioning concept interleavers.

The organization of this paper is as follows. Firstly, the Literature review of this research is described in Section II. The 2D burst channel model is explained in Section III.Fourproposed interleavers are defined in Section IV. The simulation and performance evaluation of these interleavers are carried out anddiscussed in Section V. Lastly, conclusion and future work is presented in Section VI.

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II. Literature Review

To design optimal 2D interleavers, the idea of extending 1D interleavers into 2D is utilized. Firstly, the concept of general 1D block coding and interleaving must be studied. Secondly, apply the idea into 2D block coding and interleaving. Thirdly, design the new 2D interleavers using the idea from existing 1D interleavers.

In [3], the concept of coding and interleaving of wireless 1D channel has been studied.

Prior to this paper, the concept of 2D block code design with 2D decoding has been proposedin [14].The 2D encoder is defined by two generator matrixes:

$$v = G_1 u G_2, \tag{1}$$

where u is the inputmessage; v is the codeword;$G_1$and G_2 are row-wise and column-wise systematic generator matrices. The parity check matrices (H_1 andH_2) are defined and the relationship between the generator matrix and parity check matrix is

$$H_1^t G_1 = G_2 H_2^t = 0. \tag{2}$$

The decoding process use row-wise (S_r) and column-wise (S_c) syndromes which are defined by

$$S_r = E H_2^t = v H_2^t, \quad S_C = H_1^t E = H_1^t v \tag{3}$$

where E is the error matrix. These syndromes will be used to create decoder by first constructing error-syndrome table from all possible correctable error patterns and then use this table to map the decoded syndromes back to error matrix. The correct ability of the code is defined by using the maximum minimum Hamming distance(d_{min}) of a code. It is defined as the smallest Hamming distance between distinct codewords. If a code can correct at most t errors, then it can be expressed as:

$$t = \left\lfloor \frac{d_{\min} - 1}{2} \right\rfloor \tag{4}$$

For size 2x2 messages and 4x4 codeword, the maximum minimum distance is found to be fourin [14]. Therefore, this code can correct at most one error.

Moreover, the concept of 2D channel system and idea of

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block interleavers are proposedin [15]. The proposed transmission system is as shown in Fig. 1.

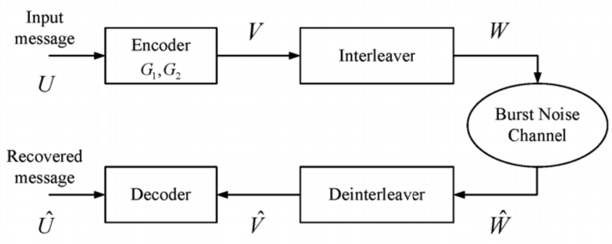

Fig. 1. Proposed image transmission system

In [4], the concept of 1D prime interleavers is attained. The model of 2D prime interleavers extended from its 1D model isthen proposed. In 1D prime interleavers, the location of interleaved bits of size *n*array with seed *p*can be calculated as follows.

1 → 1
2 → (1+p) mod n
3→ (1+2p) mod n
…
n→ (1+(n-1)p) mod n

In [5], the idea of set partitioning technique for interleaving and the concept of optimal distance between adjacent bits after interleaving is found. These concepts will be explained in detail in Section IV. This technique of interleaving would be taken into comparison in Section V.

III. 2D Burst Channel Model

In the fading channel such as high-mobility mobile communication, the bit error pattern usually occurs in patch or cluster i.e. when the line of sight (LOS) is lost. The modeling of this burst error channel is first described by Gilbert-Elliot [10], [11]. One example of 5% error rate burst error of size 256x256 channel is as shown in Fig. 2.

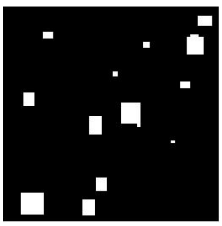

Fig. 2. Burst error with 5% error rate of 256x256 channel

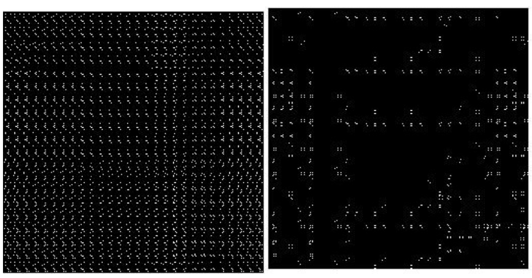

Fig. 3. Error pattern after deinterleaving (left) and error pattern after error correction (right)

Since the error correction capability of a code is limited, the error-correcting code cannot effectively correct these codewords that contain too many erroneousbits. Therefore, an effective 2D interleaver is needed. In this example, we use Prime interleaver with value of row-wise seed (p_{row}) to be 13 and column wise seed (p_{col}) to be 9. The error pattern afterdeinterleaving will be as shown in Fig. 3.

From this figure, the error bits are almost uniformly distributed and the error correction will be more effective. After applying this interleaver to the system, the error rate will be greatly reduced from 4.76% without interleaver to 1.71%. Therefore, interleavers play a very significant role in reducing the error of the channel.

IV. Proposed Interleaves

A. Newly Proposed Block Interleaves

Originally, the bits in sub-block before and after block interleaving are as shown in Fig. 4(a) and 4(b). This originally proposed interleave still has some drawback. The adjacent bits at the edge of the mask are still not separated after interleaving such as A2 and B1 bits, A4 and B3 bits and so on.

The idea of newly proposed block interleaved comes from this issue. The new arrangement of bits for this type of interleave is as shown in Figure 4(c).From this figure, the problem of adjacent bits in the original type of block interleaves is solved.

B. Two dimensional Prime Interleaves

In this type of interleaves, the idea of extending from 1D prime interleaved [4] into two dimensional is utilized. The concept of proposed prime interleaved is as follows.

A1	A2	B1	B2
A3	A4	B3	B4
C1	C2	D1	D2
C3	C4	D3	D4

(a)

A1	B1	A2	B2
C1	D1	C2	D2
A3	B3	A4	B4
C3	D3	C4	D4

(b)

A1	C1	A2	C2
D1	B1	D2	B2
A3	C3	A4	C4
D3	B3	D4	B4

(c)

Fig. 4. Arrangement of bits in a sub-block: (a) before interleaving, (b) after originally proposed block interleaving, (c) after newly proposed block interleaving

Consider the case of two-dimensional interleaving ofn_r by n_c matrix. Firstly, we divide the interleaving scheme into row-wise interleaving and column-wise interleaving. Secondly, we assign the value of seed as row-wise seed and column-wise seed to row-wise and column-wise interleavers respectively. Therefore, the location of bits after interleaving will be as follows.

Row-wise	Column-wise
1 → 1	1 → 1
2 → (1+p_{row}) mod n_r	2 → (1+p_{col}) mod n_c
3 → (1+2p_{row}) mod n_r	3 → (1+2p_{col}) mod n_c
4 → (1+p_{row}) mod n_r	4 → (1+p_{col}) mod n_c
…	…
n_r→ (1+ (n_r-1) p_{row})	n_c→ (1+(n_c -1)p_{col})

mod n_r mod n_c

where p_{row} and p_{col} are row-wise and column-wise seeds.

After we get the new location of bits after interleaving in both row-wise and column-wise, the new locations are mapped back into 2D interleavers to get the resulted interleaved bits in 2D.

Example 1: Consider the 2D prime interleaving scheme of128×128 matrix with p_{row}=3 and p_{col}=5. The new location of bits will be as follows.

Row-wise	Column-wise
1 → 1	1 → 1
2 → (1+1×3) mod 8=4	2 → (1+1×5) mod 8=6
3 → (1+2×3) mod 8=7	3 → (1+2×5) mod 8=3
4 → (1+3×3) mod 8=2	4 → (1+3×5) mod 8=8
5 → (1+4×3) mod 8=5	5 → (1+4×5) mod 8=5
6 → (1+5×3) mod 8=8	6 → (1+5×5) mod 8=2
7 → (1+6×3) mod 8=3	7 → (1+6×5) mod 8=7
8 → (1+7×3) mod 8=6	8 → (1+7×5) mod 8=4

Consider the arrangement of bits before and after interleaving. From Fig. 5(a) arrangement, apply the new order of column-wise and row-wise interleaved bits obtained from the above calculation and map the positions to get Figure 5(b). For example, the bit 20 of the matrix corresponds to the 3rd position row-wise and 4th position column-wise. This position will correspond to the 7th position row-wise and 8th position column-wise after interleaving.

Column-wise

Row-wise	1	2	3	4	5	6	7	8
1	1	2	3	4	5	6	7	8
2	9	10	11	12	13	14	15	16
3	17	18	19	20	21	22	23	24
4	25	26	27	28	29	30	31	32
5	33	34	35	36	37	38	39	40
6	41	42	43	44	45	46	47	48
7	49	50	51	52	53	54	55	56
8	57	58	59	60	61	62	63	64

(a)

Column-wise

Row-wise	1	6	3	8	5	2	7	4
1	1	6	3	8	5	2	7	4
4	25	30	27	32	29	26	31	28
7	49	54	51	56	53	50	55	52
2	9	14	11	16	13	10	15	12
5	33	38	35	40	37	34	39	36
8	57	62	59	64	61	58	63	60
3	17	22	19	24	21	18	23	20
6	41	46	43	48	45	42	47	44

(b)

Fig. 5. Arrangement of bits of 8 ×8 channel: (a) before interleaving, (b) after interleaving

From [5], the efficient distance between adjacent bits after interleaving is given by

$$d^2 \leq n, \tag{5}$$

where n is the size of row or column matrix and d is the maximum distance between adjacent bits after interleaving

Since the distance between adjacent bits of prime interleavers can be expressed as

$$d = \sqrt{{p_{row}}^2 + {p_{col}}^2} \tag{6}$$

Therefore, the optimal distance between adjacent bits of prime interleavers with channel size 256 × 256should be constrained by the constraint

$${p_{row}}^2 + {p_{col}}^2 \leq 256 \tag{7}$$

C. Two dimensional Random Interleavers

The idea of creating this type of interleavers is similar to the idea of prime interleavers. It is also divided into 1D row-wise and 1D column-wise interleaving. However, it uses random permutation for interleaving instead of using row-wise seed and column-wise seed.

D. Set Partitioning concept Interleavers

This kind of interleavers uses the same technique as proposed in [5] but originally they are used for 1D interleaving with quasi circular of clusters of error bits. These interleavers can also be used in 2D channel with burst error as well because they can spread the adjacent bits farther apart in both horizontal and vertical direction. The proposed concept of set partitioning concept interleaver in [5] is as follows.

Consider the 5 × 5 channel before and after interleaving as shown in Fig. 6.

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

(a)

1	20	9	23	12
24	13	2	16	10
17	6	25	14	3
15	4	18	7	21
8	22	11	5	19

(b)

Fig. 6. Arrangement of bits: (a) before interleaving, (b) after interleaving

Two parameters need to be defined which are the distance of adjacent bits in one direction ($dist_1$) and distance of bits in another direction ($dist_2$). If we assign $dist_1 = 2$ and $dist_2 = 1$, the arrangement of bits after interleaving will be as in Figure 6(b).

From Figure 6(b), every horizontal adjacent bits before interleaving will be separated by two units horizontally and one unit vertically. Similarly, every vertical adjacent bits will be separated by one units horizontally and two unit vertically. For instance, bit 1 which is at position (1,1) has bit 2 as horizontal adjacent bit and bit 6 as vertical adjacent bits. Therefore, after interleaving, bit 2 and 6 must be located at position (2,3) and (3,2) respectively.

To employ the constraint in equation (5), we can use the Euclidean distance of adjacent bits. Therefore, constraint equation (5) with channel size 256×256 can be expressed as

$${dist_1}^2 + {dist_2}^2 \leq 256 \tag{8}$$

V. Simulation Results and Discussion

In this simulation, the input image of size 128×128 pixels is divided into sub-blocks of size 2×2 before interleaving. The transmission system that we are considering is the same as in Figure 1. We would like to encode the input into 4×4 codewords. Therefore, the channel row and column size would be $128 \times 4/2$ which is 256. The best encoders, column-wise and row-wise, are

$$G_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 1 & 1 \end{bmatrix}, G_2 = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \end{bmatrix}$$

The minimum distance is found to be four. Therefore, the maximum of one error bit can be corrected. Beyond the maximum correctable bits, some of error pattern will have ambiguity, i.e., more than one error patterns account for the same column-wise and row-wise syndrome. These error patterns could lead to incorrectly corrected codeword and should be excluded from error-syndrome table. To enhance the capability of error correction with considerable speed, the error-syndrome table is extended from only one possible bit errorpatterns into all three possible bit errors excluding the ambiguous error pattern. Burst errors are randomly generatedby MATLAB®. Error rates used in this simulationare 0.1% and 0.5% for low error rate, 1% and 2% for medium error rate, and 5% and 10% for high error rate. Each percentage of error rates has 10 samples.

We group five categories of interleavers in this simulation which are two Block Interleavers (originally proposed and newly proposed version), 10 Prime Interleavers with p_{row} and p_{col} between 30 and 50, 10 Random Interleavers, 8 Prime Interleavers (Prime*) employing the constraint in (7) and four Set Partitioning Concept Interleavers(SP) employing the constraint in (8).

To evaluate the performance of proposed interleavers, the average (Mean) and standard deviation (SD) of bit error rate (BER) obtained from five categories of interleavers mentioned above are taken into consideration. The desired interleaver would have low Mean and low SD so that most of the errors will be clustered in the low BER region. The simulation result is shown in Table I and II, where the number highlighted is the lowest error rate.

TABLE I: AVERAGE BER TABLE (%) FOR DIFFERENT ERROR RATES AND CATEGORIES OF INTERLEAVERS

Error rate	Mean table				
	Block	Prime	Rand	Prime*	SP
Low	0.0388	0.0082	0.0449	0.0041	0.0363
Med	0.2173	0.234	0.4897	0.1599	0.6929
High	5.5661	3.8663	4.6757	3.8885	5.6229
Total	1.9407	1.3695	1.7368	1.3508	2.1174

TABLE II: STANDARD DEVIATION TABLE OF BER TABLE FOR DIFFERENT ERROR RATES AND CATEGORIES OF INTERLEAVERS

Error rate	SD table				
	Block	Prime	Rand	Prime*	SP
Low	0.0904	0.0457	0.0642	0.0144	0.0582
Med	0.2098	0.2692	0.3037	0.2000	0.4097
High	2.9282	2.3989	2.2707	2.4152	2.4416
Total	3.0756	2.2511	2.4706	2.2761	2.8756

From the results, Prime* interleavers are preferred over their counterparts in low burst error environment since they have considerably the lowest Mean and SD of BER. Prime* and Block interleavers are preferred in medium burst error environment. The performances of Prime and Prime* interleavers in high burst error environment are almost equal. In high burst error environment, the group of errors can sometimes very large so that the constraint in (7) makes Prime*interleavers not optimal because the separation between adjacent bits after interleaving is not enough. Therefore, there is no difference between Prime and Prime* interleavers and both of them are preferable in this case. In total, combining all errors together, Prime and Prime* interleavers have a very close average and standard deviation of BER.Thus, both of them are preferable over their counterparts.The concluded result of priority of interleavers for each error rate is as shown in Table III.

TABLE III: PRIORITY TABLE OF INTERLEAVERS FOR DIFFERENT ERROR RATES

Error rate	Priority table				
	1st	2nd	3rd	4th	5th
Low	Prime*	Prime	SP	Rand	Block
Med	Prime*	Block	Prime	Rand	SP
High	Prime, Prime*		Rand	SP	Block
Total	Prime, Prime*		Rand	Block	SP

Therefore, to ensure the best transmission performance, Prime* interleavers should be selected.

A. VI. CONCLUSION AND FUTURE WORK

The performance of the image transmission with different types of proposed 2Dinterleavers is compared. The aim here is to find optimal interleavers that are suitable for different transmission environment, which has different percentage of errors. The further development of this project is to enhance the performance of optimal 2D interleavers and the new optimal interleavers may be found.Alternatively, the comparison of performance result of 1D and 2D image transmission systems with comparable complexity may be carried out. An alternative approach for this project is designing new interleavers that specific to a certain application such as MIMO-OFDM wireless communication in which a statistical burst error model of this transmission scheme should be extensively studied. Therefore, this approach is also possible in the future.

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