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

P. Hanpinitsak[*1], **C. Charoenlarpnopparut**[*2], and **P. Suksompong**[*3], Non-members

ABSTRACT

This paper proposes to further design the sub-optimal two-dimensional (2D) interleavers while taking the best interleaver from the previous work into consideration. The newly proposed interleavers are 2D Golden interleavers (Gold), uniformly distributed interleavers (Uniform) and Block and bit wise interleavers (Block&bit). The performances of these interleavers were compared and evaluated by comparing the average (Mean) and standard deviation (SD) of the bit error rate (BER) under the environments with different amounts of burst errors. Moreover, the average computation time (Time) of the interleaver and average distance between adjacent bits after deinterleaving (Dist) were also utilized as the criteria for performance evaluation. Time could also be used to analyze the computational complexity of the interleavers where Time of the proposed 2D interleaver was compared with Time of original 1D block interleaver to test the suitability for hardware accomplishment. The transmission scheme for 2D system is based on previously proposed 2D linear block code and 2D syndrome decoder. The performances of these 2D interleavers were compared with traditional one-dimensional (1D) interleavers with comparably the same complexity. The buffer sizes for 2D channel that were considered in this paper are 256×256, 128×128, 64×64, 32×32 and 16×16 which is equivalent to 65536, 16384, 4096, 1024 and 256 buffer sizes for 1D respectively as they have the same number of elements. Simulation results suggest that 2D interleavers have relatively lower computation time than their 1D equivalent interleavers and reducing the buffer size can dramatically increase the BER. The optimal buffer sizes for 2D interleavers are 256×256 and 128×128. For low error rate error, the best interleaver would be Uniform and Gold for 256×256 and 128×128 buffer size respectively. For the other environment, the finest ones are Block&bit and Uniform for 256×256 and 128×128 buffer size respectively. Comparison results between the computation time of the proposed 2D interleavers and 1D block interleaver also indicate that 2D interleavers are suitable for hardware implementation since they have less computational complexity.

Keywords: BER, Block Code, Channel Coding, Interleaver.

Manuscript received on October 15, 2014 ; revised on October 28, 2014.

1. INTRODUCTION

Originally, the transmission of two-dimensional (2D) data is done by first scanning row-by-row or column-by-column to make the data become one-dimensional (1D) and then send it through a 1D channel. This type of transmission is not optimal since the relationship among nearby bits in 2D is disregarded which leads to un-optimal error correction capability as discussed in [14]. Therefore, the novel 2D block code has been designed in [14] and the performance evaluation of some types of interleavers with 2D transmission system in Figure 1 has been done in [15]-[16].

As 2D transmission system with 2D block code and interleaver are proposed, the comparison with their 1D counterparts is necessary to prove that introducing the 2D transmission system with proposed 2D interleavers can actually improve the performance of the conventional transmission system. To the authors' knowledge, there is no comparison of these two systems in the open literature. Therefore, this paper aims to verify this important point as well as proposing the new optimal interleavers.

Three new interleavers have been proposed and evaluated namely 2D Golden interleavers (Gold), Uniformly distributed interleavers(Uniform) and Block and bit wise interleaver (Block&bit).

2. LITERATURE REVIEW

The ideas of existing 1D interleavers were used to design the new 2D interleavers which are done similarly in [16]. Firstly, the general concept of conventional 1D interleavers must be studied so that the concept can be utilized in 2D interleavers. The concept of interleaving and coding of wireless 1D channel has been studied in [3].

The two most common interleavers for 1D channel are block interleaver and convolutional interleaver. In a block interleaver, codewords are row-wisely read into the interleaver and column-wisely read out of the interleaver. In contrast, codewords are column-wisely read into the deinterleaver and row-wisely read out of

* The authors are with Department of School of Information, Computer, and Communication Technology Sirindhorn International Institute of Technology, Thammasat University, Thailand Email: panawit.hanpinitsak@gmail.com[1], chalie@siit.tu.ac.th[2], and prapun@siit.tu.ac.th[3].

the deinterleaver. Thus, the interleaver is configured as a matrix with each row corresponding to a single codeword and it is considered as memoryless coding scheme. In a convolutional interleaver, the output from the encoder is multiplexed into buffers with different sizes where the sizes of buffers increase from zero to N-1, where N is the size of the codeword. The opposite operator is done at the decoder where the sizes of buffers decrease from N-1 to zero. This interleaver is commonly used with convolutional coding which is a coding scheme with memory. In our study, we focus on 2D block code with 2D interleavers that are suitable for 2D block code because learning of its concepts could lead to an effective 2D convolutional code and 2D interleaver design that is suitable for convolutional code in the future.

The 2D block code design with 2D decoding concepts has been previously proposed in [14]. As opposed to 1D encoder which is comprised of one generator matrix, the definition of 2D encoder is comprised of two generator matrices:

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

where u is the input message; v is the codeword; G_1 and G_2 are row-wise and column-wise systematic generator matrices. H_1 and H_2 are row-wise and column-wise parity check matrices respectively. The relationship between them and their corresponding generator matrices is

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

Row-wise (S_r) and column-wise (S_c) syndromes are used in 2D decoder which can be defined by

$$S_r = EH_2^t = vH_2^t, \qquad S_c = H_1^t E = H_1^t v \tag{3}$$

where E is the error matrix. 2D decoders can be constructed from these syndromes by first finding all possible correctable error patterns and constructing error-syndrome table from these error patterns. After that, this table is used to map the syndromes obtained from output codeword(v) back to get the error matrix. Maximum minimum Hamming distance (d_{min}) of a code describes the capability of error correction of the code which can be found by finding the smallest Hamming distance between distinct codewords [14]. A code that can correct at most t errors can be expressed in term of d_{min} as:

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

The maximum minimum distance is found to be four in [14] when a 2×2 message is encoded into a 4×4 codeword. Therefore, this code can correct at most one error per one codeword.

The 2D transmission system concept has been proposed in [15]. The block diagram of this transmission system is shown in Figure 1.

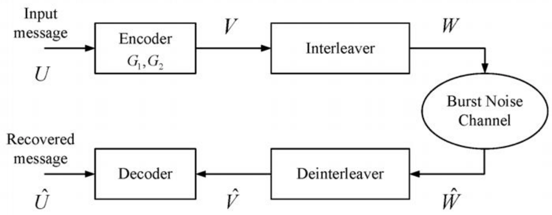

Fig.1: *2D Image Transmission System*[15].

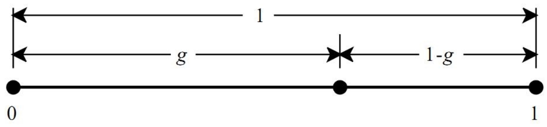

Fig.2: *Illustration of golden section principle*[5].

In [16], the concept of 2D prime interleaver is proposed which utilizes 1D prime interleaver concept in [4]. This interleaver was used to compare the performance with the newly proposed interleavers because it is shown in [16] that this interleaver has the best performance. The position of bits after interleaving can be calculated 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+3p_{row})mod n_r	4→(1+3p_{col})mod n_c
...	...
n_r →(1+(n_r-1)p_{row})mod n_r	n_c →(1+(n_c-1)p_{col})mod n_c

After the new location of bits after interleaving in both row-wise and column-wise are obtained, the new locations are mapped back into 2D interleavers [16].

In [5], the concept of Dithered Golden Interleavers is proposed. This concept arises from the golden section (g) as shown in Figure 2.

Given the line segment of length 1, this line segment can be divided into longer segment g and shorter segment 1-g. The ratio of longer segment to the whole segment is desired to be the same as the ratio of shorter segment to longer segment which can be expressed as:

$$\frac{g}{1} = \frac{1-g}{g} \tag{5}$$

Solving this equation gives the golden section value

$$g = \frac{\sqrt{5}-1}{2} \approx 0.618 \tag{6}$$

The Dithered Golden Interleaver is defined by the golden vector v in which its elements can be calculated by

$$v(n) = [s + nc + d(n)] mod N \tag{7}$$

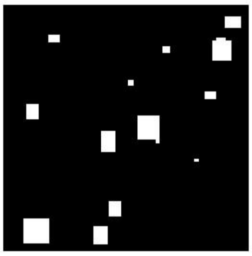

Fig.3: *Burst error with 5% rate of 256×256 channel*[16].

Where N is the interleaver size, $d(n)$ is the nth dither component which is uniformly distributed between 0 and ND, where D is the normalized width of the dither distribution, c is the value which can be stated by

$$\begin{aligned} &c = N(g^m + j)/r \\ &p_{row}, p_{col} \\ &p_{row}^2 + p_{col}^2 \leq 256 \end{aligned} \tag{8}$$

Where m and j is any positive integer greater than zero, r is the index spacing between nearby elements. In a typical implementation, j is set to 0 and r is set to 1. Therefore, c becomes

$$c = N(g^m) \tag{9}$$

3. 2D BURST ERROR CHANNEL MODEL

This model of burst error channel is firstly defined by Gilbert-Elliot [10,11]. This fading channel model usually occurs when the cluster or group of data is lost i.e. "when the line of sight (LOS) is lost" [16]. Figure 3 shows one example of a binary burst error with 256×256 size and 5% error rate.

The error-correcting code cannot efficiently correct these codewords that contain too many error bits because of the limitation of error correction capability. Therefore, an effective 2D interleaver is needed. The previously proposed Prime interleaver [16] is used in this example. The row-wise seed (p_{row}) equals to 13 and the column wise seed (p_{col}) equals to 9. The error pattern after deinterleaving will be as shown in Figure 4.

Considering figure 4 on the left, the error bits are more distributed apart which leads to a more effective error correction [16]. The effect of applying this interleaver to the system is that the error rate will be dramatically reduced from 4.76% to 1.71%. Therefore, the interleaver is the essential component in the transmission system which could significantly reduce the BER of the channel.

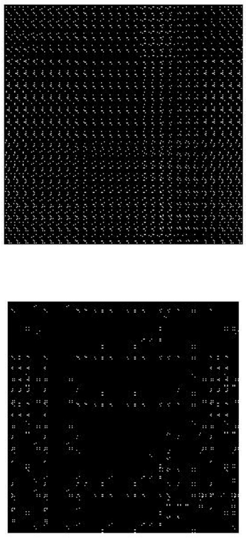

Fig.4: *Error pattern after deinterleaving (left) and error pattern after error correction (right)*[16].

4. PROPOSED INTERLEAVERS

The main difference between the proposed interleaving techniques here and the existing interleaving techniques in the literature is that the proposed interleaving techniques are designed to be suitable with 2D channel where the encoding, decoding and interleaving were done in 2D as oppose to 1D channel where these procedures are done in 1D. Some interleaving techniques utilized 1D interleaving concepts such as 2D Golden interleaving where 1D Golden interleaving is performed row-wisely and column-wisely. After that, these row and column-wise interleaving are combined to create 2D interleavers. The interleaving technique in block and bit wise interleaver is a completely new technique which did not come from 1D interleaving.

4.1 Two dimensional Golden Interleaver

The idea of extending from 1D Golden interleaver [5] into two dimensional was utilized. The concept of proposed golden interleaver is as follows.

Firstly, we calculated golden vector v as in (7) which its elements can be calculated by

$$v(n) = [s + nc + d(n)] mod N \tag{10}$$

After that, the next step was sorting golden vector v in ascending order and finding the sort vector **z** such that $a(n) = v(z(n)),\ n = 0, ..., N-1$ where **a**= sort(v). The golden interleaver index is given by $i(z(n)) = n,\ n = 0, ..., N-1$. Lastly, row wise and column wise interleaver were assigned to be sort vector **z** and golden interleaver index vector **i** respectively. Using the same concept as previously proposed Prime interleaver, the new location of bits was de-

Column-wise

Row-wise	1	2	3	4	5	6	7	8	9
1	a	a	a	b	b	b	c	c	c
2	a	a	a	b	b	b	c	c	c
3	a	a	a	b	b	b	c	c	c
4	e	e	e	f	f	f	g	g	g
5	e	e	e	f	f	f	g	g	g
6	e	e	e	f	f	f	g	g	g
7	h	h	h	i	i	i	j	j	j
8	h	h	h	i	i	i	j	j	j
9	h	h	h	i	i	i	j	j	j

(a)

Column-wise

Row-wise	1	4	7	2	5	8	3	6	9
1	a	b	c	a	b	c	a	b	c
4	e	f	g	e	f	g	e	f	g
7	h	i	j	h	i	j	h	i	j
2	a	b	c	a	b	c	a	b	c
5	e	f	g	e	f	g	e	f	g
8	h	i	j	h	i	j	h	i	j
3	a	b	c	a	b	c	a	b	c
6	e	f	g	e	f	g	e	f	g
9	h	i	j	h	i	j	h	i	j

(b)

Fig.5: *Arrangement of bits of 9×9 channel: (a) before interleaving, (b) after interleaving.*

termined by mapping the row-wise and column-wise interleaving back into 2D interleavers.

4.2 Two dimensional Uniformly Distributed Interleaver

The idea of creating this type of interleaver is similar to the idea of prime interleaver and golden interleaver. It was also divided into 1D row-wise and 1D column-wise interleaving. This interleaver exploits the concept that the adjacent bits will be separated by the size of codeword after interleaving so that every pair of adjacent bits of the channel are located in different codewords in a uniformly distributed way. For example, if a codeword after encoding has the size of 4×5, the adjacent bits will be separated by 4 bits vertically and 5 bits horizontally.

Example 1: Consider the 2D interleaving scheme of 9×9 matrix with the codeword size 3×3. From the codeword size, the adjacent bits will be separated by 3 bits both vertically and horizontally. The arrangement of bits before and after interleaving is as shown in Figure 5.

From this figure, the row wise and column wise interleavers are determined by the algorithm as shown below the figure, where d is the size of the codeword and n is the size of the channel (row or column size)

Step 1: let starting point = 1, i=1
Step 2: p=starting point

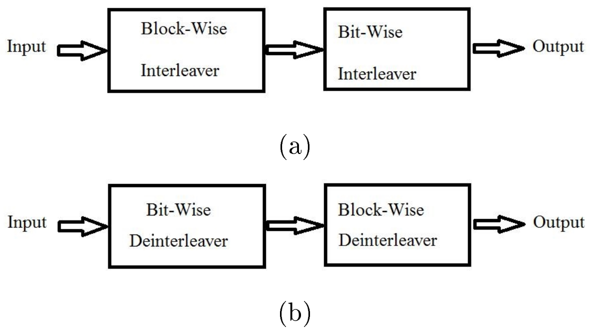

Fig.6: *Block diagram of Block and Bit wise Interleaver: (a) Interleaver, (b) Deinterleaver.*

Step 3: assign the element at the i_{th} position of interleaver to be p
Step 4: $p = p + d$, $i = i + 1$
Step 5: if $p > n$, increment starting point by 1 and go back to step 2. Otherwise go back to step 3. Repeat the iteration until $i > n$

In this example, d is equal to 3 and n is equal to 9 for both row-wise and column-wise interleavers. Thus, both interleavers are the same . Every bit is uniformly distributed such that every 3×3 matrix in this channel will have the bits from all codewords before interleaving. In other words, every 3×3 matrix contains all bits from a to j.

4.3 Block and Bit Wise Interleaver

This interleaver utilized two steps of interleaving namely block wise interleaving and bit wise interleaving. In the first step, the encoded image was divided into many sub-blocks and these sub-blocks were block wise interleaved. Then, every bits inside each sub-block were interleaved within that sub-block. The arrangement of bits inside every sub-block was exactly the same. Deinterleaving is the reverse process of interleaving which means the image was block wise deinterleaved before bit wise deinterleaved. The block diagram of this interleaver is shown in figure 6.

Example 2: Consider the 2D interleaving scheme of 4×4 matrix with block size equal to 2 which is grouped in bold square as shown in figure 7(a). Thus, the number of sub-blocks will be four and the number of bits inside each sub-block will be four. Firstly, the block-wise interleaver will interleave the image in blocks and then the bit-wise interleaver will interleave the bits inside each block with the same arrangement as the other blocks as shown in figure 7(b) and 7(c) respectively

5. SIMULATION RESULTS AND DISCUSSION

In this simulation, the input image of size 128×128 pixels was divided into sub-blocks of size 2×2 before interleaving. The 2D transmission system that we

Table 1: *Specification of 2D interleavers.*

Buffer size	Interleaver	Specification
256×256	Prime	p_{row},p_{col} is with in constraint $p_{row}^2 + p_{col}^2 \leq 256$
	Golden	m=1, D is form 0 to 0.05 with 0.005 increment
	Uniform	d=4
	Block & bit	divide into 4 sub-blocks of 128×128 size and use Uniform interleaver with d=4 for bit-wise interleaver
128×128 64×64,32×32, 16×16	Uniform	d=4
	Golden	m=1, D is form 0 to 0.05 with 0.005 increment

Table 2: *Mean table of 2D interleavers with different buffer sizes.*

Mean table					
Buffer size	interleaver s	Error rate			
		Low	Med	High	Total
256×256	Prime	0.0041	0.1599	3.8885	1.3508
	Golden	0.0017	0.1158	3.6556	1.2579
	Uniform	0	0.0787	3.5376	1.2054
	Block & bit	0.022	0.069	3.4174	1.1694
128×128	Uniform	0.022	0.069	3.4174	1.1694
	Golden	0.0068	0.2436	4.0304	1.4269
64×64	Uniform	0.097	0.9305	5.6308	2.2194
	Golden	0.0543	0.8025	5.3662	2.0743
32×32	Uniform	0.1904	1.2473	6.8207	2.7528
	Golden	0.1678	1.1813	6.767	2.7054
16×16	Uniform	0.2518	1.4001	7.3288	2.9936
	Golden	0.2124	1.3971	7.2488	2.9528

Table 3: *SD table of 2D interleavers with different buffer sizes.*

SD table					
Buffer size	interleaver s	Error rate			
		Low	Med	High	Total
256×256	Prime	0.0041	0.2	2.4152	2.2761
	Golden	0.0059	0.1099	2.1344	2.0974
	Uniform	0	0.239	2.6088	2.2308
	Block & bit	0.0963	0.2203	2.9387	2.3268
128×128	Uniform	0.0963	0.2203	2.9387	2.3268
	Golden	0.0142	0.1954	2.2314	2.2519
64×64	Uniform	0.1167	0.4716	2.3581	2.811
	Golden	0.0769	0.4548	2.1799	2.6776
32×32	Uniform	0.1681	0.549	2.4365	3.259
	Golden	0.1888	0.4475	2.562	3.2699
16×16	Uniform	0.1896	0.5083	2.4753	3.4421
	Golden	0.1881	0.4981	2.4146	3.3924

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

(a)

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

(b)

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

(c)

Fig.7: *Arrangement of bits: (a) before interleaving, (b) after block-wise interleaving, (c) after bit-wise interleaving .*

Table 4: *Average computation time and average distance table for 2D interleavers.*

Time and Dist table			
Buffer size	Interleaver	Time	Dist
256×256	Prime	0.0088	20.16
	Golden	0.0078	123.49
	Uniform	0.0073	6.9058
	Block & bit	0.0063	7.5431
128×128	Uniform	0.0052	-
	Golden	0.0053	-
64×64	Uniform	0.0049	-
	Golden	0.0047	-
32×32	Uniform	0.0052	-
	Golden	0.0059	-
16×16	Uniform	0.0082	-
	Golden	0.0088	-

Table 5: *Specification table of 1D transmission system.*

Message Size	4
Codeword Size	16
Image Size	1×16384
size	1×65536
Buffer size	65536, 16384, 4096, 1024, 256
Error rate	Low(0.1% and 0.5%)
	Medium(1% and 2%)
	High(5% and 10%)

were considering is the same as in Figure 1. We would encoded the input into 4×4 codewords. Therefore, the channel row and column sizes would be 128×4/2 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.

Table 6: *Specification of 1D interleavers.*

Interleaver	Specification
prime	seed(p) are 5,7,9,11,13,15,17
gold	m=1, D is from 0 to 0.05 with 0.005 increment
uniform	d=16

To enhance the capability of error correction with considerable speed, the error-syndrome table was extended from only one possible bit error patterns into all three possible bit errors excluding the ambiguous error pattern. Burst errors were randomly generated by MATLAB®. Error rates used in this simulation were 0.1% and 0.5% for low error rate, 1% and 2% for medium error rate, and 5% and 10% for high error rate. 10 samples were generated for each error rate.

In [16], the size of interleaving or the buffer size used for simulation is 256×256 which is equal to the channel size. This means that every bit must be encoded before they are inputted into the interleaver. The disadvantage of this scheme is that the transmission time is not efficient since the interleaver will have to wait until the last bits of image are encoded. Therefore, smaller buffer sizes are considered so that every encoded bit in each buffer can proceed to the interleaver without having to wait for other bits inside the other buffers. The buffer sizes considered in this simulation are 256×256, 128×128, 64×64, 32×32 and 16×16.

Since prime interleaver has the best performance compared with the others in [16], it was also taken into consideration. Four interleavers used in the simulation have the specifications as shown in Table1. To evaluate the performance of the interleavers, the average (Mean), standard deviation (SD) of bit error rate (BER), computation time (Time) and average distance of adjacent bits after deinterleaving (Dist) of each interleaver were taken into consideration. The desired interleaver would have low Mean, low SD and low computation time so that most of the errors will be clustered in the low BER region with small computational complexity. The average distance (Dist) value in this simulation is not very important since every 4×4 codewords have only one correction capability. However, it is useful for image transmission with larger codewords. The simulation result is shown in Table II and III, where the numbers highlighted by dark grey color are the lowest error rates followed by the numbers highlighted by light grey color.

The performances of 1D conventional interleavers had also been simulated to compare their performances with equivalent 2D interleavers. In order for 1D coding to have the same complexity as 2D counterparts, the codeword was designed to have the same number of data bits and parity check bits which are 4 and 12 respectively. The minimum distance is found

Table 7: *Mean table of 1D interleavers with different buffer sizes.*

Mean table					
Buffer size	interleavers	Error rate			
		Low	Med	High	Total
65536	Prime	0.1969	1.1544	6.8536	2.7349
	Golden	0.0806	0.5859	5.8005	2.1557
	Uniform	0.0809	0.7257	5.3687	2.0584
16384	Golden	0.0653	0.5045	5.7465	2.1054
	Uniform	0.4471	1.2555	7.8033	3.1686
4096	Golden	0.1385	1.0327	6.5585	2.5766
	Uniform	0.2731	1.4594	7.3898	3.0408
1024	Golden	0.105	0.8694	6.2885	2.421
	Uniform	0.2823	1.4502	7.3178	3.0168
16×16	Golden	0.1251	1.0666	6.3992	2.5303
	Uniform	0.0818	0.549	7.3264	2.6524

Table 8: *SD table of 1D interleavers with different buffer sizes.*

SD table					
Buffer size	interleavers	Error rate			
		Low	Med	High	Total
65536	Prime	0.1721	0.5817	2.6133	3.323
	Golden	0.0625	0.2835	2.6855	3.0245
	Uniform	0.1686	1.2332	4.0426	3.377
16384	Golden	0.0547	0.2255	2.8224	3.0588
	Uniform	0.5337	0.9748	2.7522	3.7243
4096	Golden	0.1354	0.4617	2.5732	3.2256
	Uniform	0.1891	0.6132	2.4425	3.4511
1024	Golden	0.0931	0.4347	2.6023	3.1542
	Uniform	0.2023	0.5024	2.5778	3.4455
16×16	Golden	0.1426	0.5549	2.4311	3.1258
	Uniform	0.1573	1.102	4.5568	4.2698

to be 8 [17] so the maximum of three error bits can be corrected inside a codeword. The best encoder (size 4×16) is expressed as in (10). The channel was also divided into different buffer sizes as well which were 65536, 16384, 4096, 1024 and 256. These buffer sizes were compared with 256×256, 128×128, 64×64, 32×32 and 16×16 buffer sizes in 2D channel respectively since the numbers of bits inside the buffers are equal.

The specification of the transmission system and interleaver are as shown in table V and VI. The error rates used in this simulation were exactly the same as the simulation for 2D interleavers so that the comparison is unbiased. The average BER, SD of BER average computation time table for 1D is as shown in table VII-IX respectively.

From the simulation results, 2D interleavers are apparently better than their 1D counterparts because of two main reasons.

Firstly, the performances of 2D interleavers in terms of BER reduction are much better than their 1D counterparts when the buffer sizes are 256×256, 128×128 and 64×64. Moreover, the average computation time for 2D interleavers are also less than their 1D counterparts. Therefore, 2D transmission system with 2D interleaver in these cases is much more preferable over the traditional 1D transmission

Table 9: *Average computation time of 1D interleavers.*

Time table		
Buffer size	Interleavers	Time(s)
65536	Prime	28.222
	Golden	9.0956
	Uniform	0.0344
16384	Golden	0.0057
	Uniform	0.0057
4096	Golden	0.0054
	Uniform	0.0065
1024	Golden	0.0068
	Uniform	0.006
256	Golden	0.008
	Uniform	0.0093

system.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}^T \tag{11}$$

Secondly, even though the Means of 1D transmission system are slightly lower than the 2D counterparts for smaller buffer size which are 32×32 and 16×16, these buffer sizes are not practical since the Mean and Time are too high compared with the values obtained from the channel using higher buffer sizes.

Simulation results of 2D interleavers indicate that reducing the buffer size of the channel can reduce the computation time at some point in which 64×64 buffer size utilize the least computation time. However, the tradeoff is that further reducing the buffer size can severely reduce the error correction capability since the distances between adjacent bits are smaller. Thus, it is necessary to find the optimal buffer size. From this simulation, the optimal buffer size is 128×128. In the medium and high error rate environments, the best 2D interleaver for 256×256 buffer size would be the Block & bit since it creates the least average BER. When the buffer size is 128×128, the best interleaver would be Uniform interleaver. In the low error rate environment, the best interleavers would be Uniform and Golden interleavers for buffer size of 256×256 and 128×128 respectively.

Surprisingly, the BER of Block & bit interleaver and Uniform interleaver with buffer size of 128×128 have exactly the same average BER. It is because the Block & bit interleaver use Uniform interleaver as bit-wise interleaver and it is divided into 128×128 sub-blocks which is the same as buffer size. However, Uniform interleaver consume less time than the Block & bit interleaver.

Computational complexity of the proposed interleavers is an important issue when considering the practical applications. Therefore, the computation time of the proposed interleavers were compared with the original block interleaver [3] by varying the image size. The reason that we selected block interleaver to compare is because it is the most fundamental and common interleaver in practical applications. The codeword for block interleaver has 4 information bits and 12 parity bits. The matrix configuration of block interleaver has the same element as the image size for fair comparison and buffer sizes were not considered in block interleaver. Table X shows the comparison results. Please note that the computer that run this simulation is the different one with the computer that generates the result from the previous tables which has the effect only on the computation time of the interleavers.

The comparison results clearly indicate that the computation time of the proposed 2D interleavers is less than their 1D block interleaver counterparts. The computation time difference between the proposed and block interleaver seems to get smaller as the image size gets larger. Thus, these results also indicate that the proposed 2D interleavers have significantly lower computational complexity and they are suitable for hardware implementation especially when the image size is small.

6. CONCLUSION AND FUTURE WORK

The performance evaluation of different types of proposed 2D interleavers and conventional 1D interleavers were carried out. The conclusion was made from the simulation results that proposed 2D interleavers have higher performance than their 1D counterparts and they also have less computational complexity than original 1D block interleavers which suggest that they are suitable for hardware accomplishment. Further developments of this project include enhancing the performance of optimal 2D interleavers, possibly creating a new type of optimal interleavers and extending the work to 2D convolutional interleavers and hardware implementation. Another approach is to use different kinds of channels or using a colored image instead of a binary image to improve the practicality of this transmission system.

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Table 10: *Average computation time of 1D interleavers.*

Image size before interleaving	buffer size	2D interleavers		1D block interleaver
		Golden	Uniform	
64×64	64×64	2.63E-04	2.20E-04	3.30E-03
	32×32	1.70E-04	1.52E-04	-
128×128	128×128	9.82E-04	8.67E-04	3.60E-03
	64×64	5.67E-04	5.23E-04	-
256×256	256×256	6.20E-03	6.90E-03	1.12E-02
	128×128	2.20E-03	2.00E-03	-
512×512	512×512	2.33E-02	2.92E-02	3.89E-02
	256×256	1.07E-02	1.12E-02	-

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Panawit Hanpinitsak was born in Khonkaen Thailand in 1991. In 2013, he graduated Bachelor's degree in Electronics and Communication Engineering Program from Sirindhorn International Institute of Technology, Thammasat University, Thailand with first class honors. He is currently studying Master's degree in wireless communication at Tokyo Institute of Technology, Japan. His research interests include channel coding and modeling in wireless communication system, MIMO wireless communication system.

Chalie Charoenlarpnopparaut graduated his MSc. (in 1995) and Ph.D. (in 2000) in Electrical Engineering from Pennsylvania State University, USA. He is currently an associate professor in Electronics and Communication Program at Sirindhorn International Institute of Technology, Thammasat University, Thailand. His research area includes multidimensional signal processing, coding theory and their applications in wireless communication.

Prapun Suksompong received his B.Sc., M.Sc., and Ph.D. degrees in electrical and computer engineering from Cornell University, Ithaca, NY, USA in 2002, 2006, and 2008, respectively. He is currently an Assistant Professor at Sirindhorn International Institute of Technology, Thammasat University, Thailand. His research interests include wireless communications, digital communication theory, neuro-informational theory, computational neuroscience, and Poisson convergence.