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CRCSI: A Generic Block Interleaver for the Next Generation Terrestrial Broadcast Systems

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Abstract: In order to combat the impulse noise and channel time-frequency selective fading, it is essential to use channel interleavers. Among them, the block interleaver has been widely used in terrestrial broadcasting systems such as DVB-T2 and ATSC 3.0, since it can better reflect the mapping relationship of data units on time-frequency resources. Due to the limited value of the interleaving structure parameter, the existing block interleavers cannot fully exploit time and frequency diversities, which leads to a loss of partial diversity gains. To address this problem, this paper proposes a generic block interleaver for channel interleaving through jointly considering the time and frequency diversities. First, row crossing is performed according to a certain interval, which will increase the interleaving distance; then, cyclic shift is used to achieve a greater time diversity gain. The proposed method can achieve flexible parameter configuration, which can effectively increase the scalability of the parameters and make the interleaver more versatile. Theoretical analysis shows that a larger interleaving distance is obtained and the multiplicity of minimum distance is significantly reduced. The simulation results of the fixed and mobile reception scenarios in the terrestrial broadcasting systems demonstrate the effectiveness of proposed interleaver compared to existing block interleavers.

Keywords: block interleaver; time and frequency interleaving; terrestrial broadcasting; interleaving distance; cyclic shift

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1. Introduction

In order to improve the reliability of wireless transmission, it is necessary to introduce interleaving technologies into the system, where the transmitted bit or symbol sequence is reordered according to a specific interleaving rule to repair the channel damage caused by burst errors [1].

Bit interleaving can break the inherent correlation in the input bit sequence through certain permutation rules, and the original bit sequence is wisely reordered, enhancing the ability to resist burst errors [2]. Bit interleaving is widely used in the design of Forward Error Correction (FEC) codes such as Turbo code [3] and LDPC code. There are many bit interleavers studied in the literature. Among them, the random interleaver [4] uses a string of randomly generated permutation indexes to permute the input data, and then de-interleaves it with the knowledge of permutation patterns. Although this method is able to achieve good performance, it is time-consuming and requires a lot of storage space to store the large random interleaver. In order to reduce the resources consumed by the interleaving, O.Y.Takeshita et al. studied the use of a Quadratic Polynomial Permutation (QPP) in LTE to produce a regular interleaver with the statistical property of random interleavers [5]. Considering that the length of burst error is random, Crozier et al. [6] proposed the Dithered Golden Interleaver (DGI) which achieves a good spreading property by adding a random

component to golden interleavers. However, the golden section method does not apply to all lengths [7]. To resolve this issue, based on the regular permutation method, Dithered Relative Prime (DRP) interleavers and Almost Regular Permutation (ARP) interleavers [4,7] were also developed, which can achieve excellent interleaving performance with the same Hamming distance.

The above-mentioned bit interleaving methods perform well over memoryless channels, especially when errors are randomly distributed and statistically distributed. However, when transmitted over impulse noise and/or selected fading channels, the error rate performance of the bit sequence will be greatly deteriorated due to the limited error correction capability of FEC. Therefore, it is of great importance to introduce the channel interleaver [8]. By taking advantage of time and frequency diversities of the encountered channel, the codewords belonging to the same frame are distributed as far apart as possible.

In order to combat the impulse noise and the time-frequency selective fading, the block interleaver suitable for processing time-frequency resource mapping has become the predominant choice of researchers in designing channel interleavers. In the Digital Video Broadcasting Terrestrial (DVB-T2) standards [9], the classic row-column interleaver (RCI) is introduced, which has the simple and practical characteristics of writing in columns and reading row-wisely. In the Advanced Television Systems Committee (ATSC) 3.0 [10] system, a twisted block interleaver (TBI) is used, which rotates each row to the left and reads it out column by column. This method can achieve a good time diversity. However, since the row or column reading interval of the above two block interleavers is fixed at 1, the transmitted data cannot fully obtain the time and frequency diversity in a channel with uneven time-frequency selectivity, i.e., clustering errors. Therefore, how to maximize the time and frequency diversity gain is worth studying. To achieve this, Xu, W.Q [11] proposes a two-dimensional interleaver with Latin rectangles based on sphere-packing model [12,13], and then extends the design to correct arbitrary shaped cluster errors in [14,15]. Nevertheless, these schemes can only maximize the time diversity gain, and only consider data blocks with a large number of columns. Therefore, it is not suitable for multi-carrier terrestrial broadcast transmission with more rows [16].

In this paper, a generic block interleaver jointly considering the time and frequency diversity in the fading channels is developed. The basic idea is that by setting the corresponding sorting vectors in the time and frequency domain, the adjacent elements distances are expanded. Specifically, through permuting the row according to a certain spanning rule, and then cyclically shifting the row elements so as to achieve the reordering of columns, the ability of the data block to resist continuous errors is enhanced. Numerical analysis and simulation results for fixed and mobile reception scenarios are provided to validate the effectiveness of the proposed block interleaver schemes.

The remainder of this paper is organized as follows. The system model and problem formulation are introduced in Section 2. Section 3 elaborates the design of the proposed interleaver and the numerical evaluations are shown in Section 4. Finally, conclusions are drawn in Section 5.

2. System Model

2.1. Block Interleaving

In a terrestrial broadcast system, deep fading and impulse noise typically introduce burst errors beyond the capability of forward FEC codes. As a solution, block interleaver is introduced to convert burst errors into random-like ones, spreading burst errors over multiple codewords within the correction capability of the FEC codes.

The interleaving operation π (the mapping rule) [4] can be generally expressed as

$$\pi(i) = (p \cdot i + s(i)) \bmod K, \quad (1)$$

where $i = 0, 1, \dots, K - 1$ is the index of the input data, $\pi(i)$ is the index of the output data, p denotes the increment reading interval and s is the predefined shift vector with a period

of disorder cycle Q . In addition, $\mathbf{s}(l) \in [0, Q - 1]$, $l \in 0, 1, \dots, K - 1$, and mod denotes the modulo operation.

For block interleaving, the input data are divided into blocks of the size MN , and fed into the interleaver sequentially [17]. This operation is given by

$$\Pi(j) = k_1 \cdot \pi_1\left(\left\lfloor \frac{j}{M} \right\rfloor\right) + k_2 \cdot \pi_2(j \bmod M), \quad (2)$$

where $j = 0, 1, \dots, MN - 1$ is the index of one input block, $\Pi(j)$ is the index of the output block, and $\lfloor \cdot \rfloor$ denotes the round down function. Note that $k_1 = 1, k_2 = N$ and $k_1 = M, k_2 = 1$ denote the row-wise and column-wise reading, respectively. Here, π_1 and π_2 follow the mapping rules defined in (1).

In this paper, we consider two types of typical block interleavers: RCI applied in DVB-T2 and TBI also known as diagonal interleaver in ATSC 3.0. For RCI, we have $p = 1, Q = K = N$ and $\mathbf{s}(l) = 0, \forall l$ in π_1 , and $p = 1, Q = K = M$ and $\mathbf{s}(l) = 0$ in π_2 . For TBI, we have $p = 1, Q = K = N$ and $\mathbf{s}(l) = l \bmod Q$ in π_1 , and $p = 1, Q = K = M$ and $\mathbf{s}(l) = 0$ in π_2 .

2.2. Performance Indicator

In general, the interleaving distance [18] is an effective indicator to evaluate the performance of block interleavers, defined as

$$d = |a - b| + |\Pi(a) - \Pi(b)|, \quad (3)$$

where a and b denote the position of entries before interleaving, and $\Pi(a)$ and $\Pi(b)$ denote the addresses after interleaving. Usually, the minimum interleaving distance is utilized to characterize the degree of randomization of the interleavers, which is represented by

$$d_{\min} = \min_{a \neq b} \{|a - b| + |\Pi(a) - \Pi(b)|\}. \quad (4)$$

For RCI, the minimum interleaving distance is $d_{\min}^{\text{RCI}} = 1 + N$, where 1 represents the difference between adjacent elements, and N denotes the interleaving depth. For TBI, the minimum interleaving distance follows the following relationship

$$d_{\min}^{\text{TBI}} = \begin{cases} N + (M \bmod N), & M \geq 2N \\ 2N, & M \leq 2N \end{cases} \quad (5)$$

where the observation is that the upper bound for $d_{\min}^{\text{TBI}}$ is $2N$.

However, if we only calculate the interleaving distance, some essential information about the pattern distribution of an interleaver will be missed, especially in the case that different interleavers share the same interleaving distance. The smaller the number of data cells with the minimum interleaving distance, the wider the distribution range of data cells with a larger interleaving distance. In order to characterize this distribution, here, we define the sum of the minimum interleaving distances as

$$D_{\text{tot}} = \sum \mathbb{1}(d_{\min}), \quad (6)$$

where $\mathbb{1}(\cdot)$ is the indicator function and D_{tot} denotes the sum of the minimum interleaving distances.

2.3. Problem Formulation

Consider an $M \times N$ block interleaver with the reading order k and mapping rule π in Π , which is in accordance with Equation (2). In existing block interleavers, there are only two types of the reading order k , i.e., row by row and column by column. In RCI, the elements in the data block are read row-wisely, which is determined by the row index rule. In TBI, the column reading of elements is attributed to its inherent column sorting rules. Therefore, the reading order k depends on the mapping rule π that maximizes $d_{\min}$.

Thus, the design problem of the block interleaver is transformed into the design of the column and row mapping rules π_1 , π_2 with incremental interval p and predefined shift vector $\mathbf{s}$.

2.3.1. Incremental Interval p

For a given data sequence, the incremental interval p determines the reorder index, and p is usually chosen to be a prime number so as to traverse all possible values. It can be seen from Equation (4) that by assigning an appropriate value of p , the first or second term of the equation is increased, thereby increasing the minimum interleaving distance d_{min} . The common case that $p = 1$ in RCI and TBI results in the under-utilization of the diversity of M and N . Hence, the value range of p should be expanded to make full use of the diversity gain.

2.3.2. Predefined Shift Vector $\mathbf{s}$

To make use of the time diversity, an initial periodic shift is often performed on each data sequence of the length of K , which is given by $s(l), l \in [0, K - 1]$. In existing block interleavers, the cyclic shift operates in the order of natural numbers, so that the distribution of the data elements after interleaving is not sufficiently separated within the period of Q .

In summary, to maximize the interleaving distance d_{min} of the block interleaver, joint optimization of p and $\mathbf{s}$ needs to be considered, which is also the main design goal of this paper.

3. Designing the Block Interleaver

In this section, we will jointly optimize the design of the block interleaver from two dimensions, i.e., the time domain and the frequency domain. Through the joint design of the row and column mapping rules π_1 and π_2 aiming at increasing d_{min} and reducing D_{tot} , a Cross-Row Cyclic Shift Interleaver (CRCSI) is proposed.

3.1. Interleaver Structure

Generally, a transmission data block is mapped to different frequency domain sub-carriers and different time domain Orthogonal Frequency-Division Multiplexing (OFDM) symbols, corresponding to the rows and columns of the data block, respectively.

In the frequency dimension, in order to combat the frequency selective fading caused by the multipath effect, it is necessary to disperse the data units continuously distributed in the frequency domain to obtain the frequency diversity gain. This can be achieved by sorting the rows in π_2 . As for the time dimension, to resist the time-selective fading of OFDM symbols caused by the mobility of the terminal and avoid the continuous error caused by the deep fading of the channel within a period of time, the method of time interleaving is used to disperse this continuous error. This can be achieved by sorting the columns in π_1 .

Based on above analysis, we propose a synthesized block interleaver by jointly designing π_1 and π_2 . The main idea of the proposed block interleaver can be summarized as follows:

- Each sequence is sorted at an appropriate interval to increase the interleaving distance;
- Adjacent sub-carriers in the same OFDM symbol are spaced as evenly as possible;
- The shift period of the OFDM symbol is extended in a two-dimensional manner to obtain the time diversity;
- Reading order is determined by the result of joint processing.

Without loss of generality, assume that the $M \times N$ resource elements to be transmitted are written in columns. The data cells in the $M \times N$ block matrix will decide which mode is used according to the block size.

3.2. CRCSI Design

The block interleaver improves the transmission performance by increasing the interleaving distance between adjacent elements in the same row or column. Based on the mapping rule defined in Equation (2), a generalized block interleaver is developed, which includes a row crossing frequency interleaving method performs on π_2 and a cyclic shift time interleaving method implements on π_1 .

3.2.1. Row Crossing

For fixed reception scenarios, the large scale fading of the wireless channel changes slowly, and the time selectivity of the channel is not obvious. However, the trend of choosing a long cyclic prefix (CP) numerology for rooftop reception has been verified [19], which introduces a larger number of codeblocks. In this case, a large delay spread leads to more evident frequency selectivity. Therefore, the frequency interleaving method can be used to disperse data cells transmitted on adjacent subcarriers, thereby improving the system's ability to resist the frequency selective fading and improving the reliability of transmission.

The traditional row-by-row reading method is to read the data cells of different OFDM symbols on the same subcarrier, thus achieving time interleaving. However, the incremental interval $p = 1$ in this way is relatively small compared with the full range M , and the interleaving distance between different data cells is not large enough. Therefore, expanding the value of p can achieve a larger d_{min} .

For a common $M \times N$ data block, assuming the incremental interval p is a constant and the row index is given by

$$R_i = (p \cdot i + s) \bmod M, \quad (7)$$

where $i \in [0, M - 1]$, and the preshift vector $s = 0$. Typically, the minimum interleaving distance d_{min} is the smaller value of the interleaving distance between two elements of adjacent rows before and after interleaving, which can be expressed as

$$d_{min} = \min\{p + N, 1 + \frac{M}{p} \cdot N\}, \quad (8)$$

where $\frac{M}{p}$ denotes the number of complete periods based on the selected incremental interval p .

We set the two terms on the right side of Formula (8) equal, then, we can derive p_0 as

$$p_0 = \frac{1 - N + \sqrt{(N - 1)^2 + 4MN}}{2}. \quad (9)$$

In Equation (9), the value of p_0 is not necessarily an integer. In order to ensure the normal operation of the row index, the value of p should be $p \geq 1, p \in \mathbb{Z}$, then p_0 should be fixed as:

$$\hat{p} = \left\lceil \frac{M}{\lfloor M/p_0 \rfloor} \right\rceil,$$

where $\lceil \cdot \rceil$ denotes the rounding operation including round up and round down. The fixed incremental interval $\hat{p}$ fluctuates when M/p_0 approximate to an integer less or greater than itself. The fluctuation will result in the deviation on minimum interleaving distance upper bound d_{min} in (8), making the derived value not optimal. Moreover, rounding up or down M/p_0 to an integer will also lead to the same result.

Therefore, derivation beginning with p_0 is not appropriate for the general case. Instead, considering the cyclic groups $z = \frac{M}{p}$, substitute z into Formula (8), then the calculation can be rewritten as

$$M/z + N = 1 + z \cdot N. \quad (10)$$

here we have

$$z_0 = \frac{N - 1 + \sqrt{(1 - N)^2 + 4MN}}{2N}. \quad (11)$$

Since the number of cyclic groups z has to be an integer, the rounding function should be conducted on z_0 , which leads to two possible results, i.e.,

$$z_1 = \lfloor z_0 \rfloor \text{ and } z_2 = \lceil z_0 \rceil,$$

where $\lfloor \cdot \rfloor$ and $\lceil \cdot \rceil$ denotes round up and down operation, respectively.

For the given z_0 , we have an initial incremental interval value $p'_0 = M/z_0$. Comparing the rounding value z_1 and z_2 with p'_0 on d_{min} , we have the following inequation, i.e.,

$$z = \begin{cases} z_1, & (z_0 - z_1) \cdot N < p'_0 - \lfloor M/z_2 \rfloor \\ z_2, & \text{otherwise.} \end{cases} \quad (12)$$

To retain the value p as an integer and maximize d_{min} , the incremental interval p is revised as

$$\tilde{p} = \lfloor M/z \rfloor. \quad (13)$$

The range of values $\tilde{p}$ derives from the Equation (13) expanding to all positive integers, which is different from the prime value in the traditional interleavers. Thus, a new principle is needed to ensure traverse all the row index.

Here, we define the cross principle as: when the value of a cycle exceeds the range, the last digit of the starting value of the previous cycle is selected as the initial value of the next cycle.

Specifically, to ensure d_{min} is maximized, two conditions for p need to be corrected. The first case is that the block is divisible by M and z after adding one element. For example, for an 11×5 data block, according to (11)–(13), we have $z = 3$ and $\tilde{p} = 3$. Considering only the row sorting, the calculation result is shown in Figure 1a, where it is indicated that $d_{min} = p + N = 8$. This kind of block structure layout can be improved with a larger p , as shown in Figure 1b.

Figure 1. $M \bmod z = z - 1$ case: a 11×5 block. (a) $p = 3$, $d_{min} = 8$; (b) $p = 4$, $d_{min} = 9$.

Another case is that the block is divisible by M and z after subtracting one element. For example, for a 17×3 data block, we have $z = 4$ and $\tilde{p} = 4$. Similarly, the comparison of increasing the p value is shown in Figure 2.

Figure 2. $M \bmod z = 1$ case: a 17×3 block. (a) $p = 4, d_{min} = 7$; (b) $p = 5, d_{min} = 8$.

In these two cases, the original rules cannot meet the principle of maximizing the minimum interleaving distance, therefore, the interval value p ought to be rounded up.

Finally, the incremental interval p is developed as

$$p = \begin{cases} \lceil M/z \rceil, & M \bmod z = z - 1 \text{ or } M \bmod z = 1 \\ \lfloor M/z \rfloor, & \text{else.} \end{cases} \quad (14)$$

Based on above derivation, the row mapping rule π_2 is redefined as the row index vector $R_i, i = 0, 1, \dots, M - 1$ following:

1. p is a prime number of M ,

$$R_i = (p \cdot i + s_0) \bmod M, i = 0, 1, \dots, M - 1 \quad (15)$$

2. p is a common divisor of M ,

$$R_{i+1} = \begin{cases} R_i + p, & R_i + p < M \\ s_k + 1, & R_i + p \geq M \end{cases}, i = 0, 1, \dots, M - 1 \quad (16)$$

where $s_k = k, k = 0, 1, \dots, p - 1$. For example, for a 10×6 block, the group size is $z = 3$, and the incremental interval is $p = 4$, hence, the row index is $R = \{0, 4, 8, 1, 5, 9, 2, 6, 3, 5\}$.

Up to now, we have implemented the row mapping rule π_2 by the design of the incremental interval p and the cross value s_i . Next, we consider designing the column mapping rule π_1 in a cyclic shift manner.

3.2.2. Cyclic Shift

For mobile reception scenarios, since the Doppler effect caused by the mobility of user terminals is inevitable, it is necessary to resist continuous error caused by the time-selective fading. Time interleaving is realized by dispersing the neighboring data cells belonging to different OFDM symbols.

The cyclic shift scheme is a simple and effective method to implement time interleaving. As mentioned in TBI, a row-by-row cyclic shift to the left achieves diagonal-wise reading. However, $p = 1$ and $s(i) = i \bmod N$ does not sufficiently break up the relationship between two adjacent elements. The traditional method involves continuously reading different OFDM symbols and subcarriers, which cannot maximize the error correction capability of the codewords.

In order to better characterize the excellent performance of the block interleaver in resisting cluster errors, we adopt the two-dimensional interleaver form in the design

phase [13]. It is worth pointing out that this two-dimensional representation is not only applicable to two-dimensional arrays, but also applicable to one-dimensional data.

The sphere-packing model gives a theoretical resolution for the error correction upper bound in a two-dimensional array with arbitrary shapes. It is indicated that the t -interleaved array is less likely to be corrupted by the interference, where t represents the radius of the sphere associated with the array [20], that is, the interleaving ability. The definition is as follows:

$$\mathcal{S}_{2,t} = \begin{cases} |x_1| + |x_2| \leq (t-1)/2, & \text{if } t \text{ is odd} \\ |x_1| + |x_2 - 1/2| \leq (t-1)/2, & \text{if } t \text{ is even} \end{cases}$$

Let $\mathcal{S}_{2,t}$ be a sufficiently large t -interleaved two-dimensional array. We calculate the elements in $\mathcal{S}_{2,t}$, then the degree of interleaving is bounded by

$$|\mathcal{S}_{2,t}| \geq \lceil \frac{t^2}{2} \rceil, \quad (17)$$

where $t \geq 1$ and t is less than or equal to the minimum value of the row and column in an array.

When the size of the data block is given, the elements in the t -interleaved sphere are bounded by (17). Conversely, when the number of elements is N , the interleaving radius t has the upper bound:

$$t \leq \sqrt{2N}. \quad (18)$$

Correspondingly, the smallest number of elements with the interleaving ability [21] t is

$$N^* = \frac{t^2}{2}. \quad (19)$$

Finally, the upper bound t of the cyclic shift operation and the lower bound N^* of the interleaving degree for a block interleaver have been developed.

As defined in π_1 , the incremental interval p needs to be a prime number so as to iterate over all the columns. We now set the cyclic shift value p_t as

$$p_t = 2 \lceil \frac{t}{2} \rceil - 1. \quad (20)$$

Then, the permuting order C^t in a sphere model becomes $C_i^t = p_t i \bmod N^*$.

Based on above cyclic shift rules, a preshift vector $\mathbf{s}$ following Equation (1) is defined with

$$s(i) = p_t i \bmod Q, i = 0, 1, \dots, M-1, \quad (21)$$

where $Q = N^*$. However, the time diversity cannot be fully utilized, especially when the number of column elements exceeds N^* but is still within N . For example, for a 5×12 block, according to Equations (20) and (21) we have $p_t = 3$, $Q = 8$, and $\mathbf{s} = (0, 3, 6, 1, 4)$ as shown in Figure 3a. Obviously, the last four columns are not contained in the row shift period.

To make full use of time diversity, we need to define a new shift period Q in the range of N with definite incremental interval p_t . The design process is detailed as follows.

Firstly, the preshift vector $\mathbf{s}^t$ for π_1 is expressed as

$$s_i^t = p_t i \bmod N, i = 0, 1, \dots, M-1. \quad (22)$$

Once the sequentially increasing value exceeds the column number N , a return value s_{i+1}^t is needed to serve as the new initial value of the circular shift. To maintain the error correction ability of the sphere, the returned value s_{i+1}^t must be limited to N^* . Additionally, s_{i+1}^t should start with an unused value in p_t to avoid coincidence with previous periods.

Thus, the preshift vector s^t is rewritten as

$$s_{i+1}^t = \begin{cases} s_i^t + p_t, & s_i^t + p_t \leq N \\ [(s_i^t + p_t) \bmod N^*] \bmod p_t, & s_i^t + p_t > N \end{cases} \quad (23)$$

where $i = 0, 1, \dots, M-1$ and $s_0^t = 0$. For the 5×12 block, a new preshift vector s^t is determined according to Equation (23). It is observed in Figure 3b, $p_t = 3, Q = 12$ and $s^t = (0, 3, 5, 8, 1)$ makes spare columns exploited.

(a)

(b)

Figure 3. Cyclic shift design. (a) $p_t = 3, Q = 8$; (b) $p_t = 3, Q = 12$.

Following the above analysis, the proposed CRCSI interleaver design algorithm can be summarized as follows. For a given size of the data block, first rearrange the row data in the data block according to the designed cross-row index method. Then, the cyclic shift operation is performed row-by-row to maximize the time diversity. Finally, the data are read out sequentially according to the reading order. For ease of understanding, a schematic diagram is also illustrated in Figure 4.

After designing the mapping rule, the reading order k shall be determined. Since the Row Crossing performs row permutation and Cyclic Shift achieves column sorting simultaneously, the reading order should be by line in order to satisfy the overall effect.

Figure 4. Schematic diagram of CRCSI.

4. Simulation Results

In this section, parameter settings in accordance with the LTE-based 5G terrestrial broadcasting in 3GPP are given first. Then, the performance of the minimum interleaving distance for CRCSI is evaluated. Numerical results are presented to demonstrate the effectiveness of the proposed interleaver in fixed and mobile reception scenarios.

4.1. Simulation Parameters

The main parameter settings for this paper are listed in Table 1, where the LTE-based 5G terrestrial broadcasting setup is used. Rel-16 introduces two CP lengths of 100 μ s and 300 μ s for car-mounted and fixed reception, respectively. The new CP of length 300 μ s adopted in the middle power middle tower (MPMT) scenario supports coverage radius up to 100 km, while the 100 μ s CP length can be used to support the transmission with a maximum speed of 250 km/h in the low power low tower (LPLT) scenario. For the fixed reception, the transmission block size (TBS) is 76208/45352, while for the mobile reception, the TBS is 9912. Tapped delay line (TDL) channel models with 10 MHz bandwidth are utilized to perform the simulation. The channel model TDL-B is adopted for the fixed reception scenarios with a delay spread of 35 μ s for MPMT and the mobile reception with 20 μ s for LPLT, which is obtained according to link-level simulation in [22].

Table 1. Simulation parameters.

Parameters	Fixed Reception	Mobile Reception
Bandwidth	10 M	10 M
Carrier Frequency	700 M	700 M
TBS	76208/45352	9912
Channel Type	TDL-B	TDL-B
Code Rate	1/2	1/3
N_{FFT}	41,472	6144
Constellation	64 QAM	64 QAM
Sub-carrier Spacing	0.37 kHz	2.5 kHz
RS Overhead	1/12	1/4
Delay Spread	35 μ s	20 μ s
Speed	-	30/60/120 kmph

4.2. Theoretical Results

In this subsection, the minimum interleaving distances for CRCSI, RCI and TBI and no interleaving are evaluated, including the interleaving distance d_{min} and multiplicity D_{tot} .

For fixed reception, the minimum interleaving distances and multiplicity for d_{min} of CRCSI, RCI and TBI are calculated, illustrated in Table 2. For TBS 76208, the block size is 1485×15 and 2475×9 for TBS 45352. Obviously, it is shown that CRCSI has the maximum d_{min} for both TBS values. The multiplicity of d_{min} is reduced over 50 times compared with other methods, which implies that more distance values are distributed over a larger range.

Table 2. Comparison of minimum distance and multiplicity for fixed reception.

Method	TBS 76208		TBS 45352	
	d_{min}	D_{tot}	d_{min}	D_{tot}
CRCSI	40	420	104	256
TBI	30	22,050	18	22,194
RCI	16	22,260	10	22,266
NO	2	22,260	2	22,266

For mobile reception, the duration of a subframe is 1 ms. Each subframe corresponding to the 2.5 kHz subcarrier spacing contains two OFDM symbols, where the effective number of subcarriers of the OFDM symbol is 2700, that is, the row number M is equal to 2700. In the calculation, the unit of time interleaving is the number of subframes, and the length (TIL) is 1, 3, 13 and 39, respectively. At this time, the number of columns corresponding to the block interleaver is 2, 6, 26 and 78, respectively. In order to illustrate the impact of time interleaving, we only consider the d_{min} performance over the last three TIL values in the following analysis, shown in Tables 3 and 4. It is observed that CRCSI achieves the maximum d_{min} and smallest D_{tot} in all three TIL cases.

Table 3. Comparison of d_{min} for mobile reception.

Method	TIL = 3	TIL = 13	TIL = 39
CRCSI	106	53	204
TBI	12	52	156
RCI	7	27	79
NO	2	2	2

Table 4. Multiplicity D_{tot} for different depths in mobile reception.

Method	TIL = 3	TIL = 13	TIL = 39
CRCSI	14,970	2704	4056
TBI	16,164	69,524	204,500
RCI	16,194	70,174	210,500

4.3. Link-Level Simulation Results

In this section, the link-level performance of the designed block interleaver is evaluated for fixed and mobility scenarios using Block Error Rate (BLER). Here, the BLER represents the ability of the resource block to resist continuous errors.

The BLER performance of the proposed block interleaver for fixed reception under the MPMT scenario is evaluated in the following, where the occupied bandwidth is 10 MHz, and the used channel model is TDL-B with 35 μ s delay spread. Figure 5 shows the performance comparison among the schemes of CRCSI, RCI, TBI and the scheme without interleaving.

It is observed that for the 45352 TBS, compared to the no-interleaving scheme, RCI can obtain a performance gain of 1 dB @BLER = 10^{-2} , while for CRCSI, this gain is 1.2 dB; when the TBS is 76208, the gain of RCI can exceed 1.5 dB, while the performance gain of CRCSI is increased to 1.7 dB, which demonstrates the effectiveness of the cross-line interleaving effect. Moreover, the gain of TBI for the two TBS sizes is slightly larger than RCI. Notice that the BLER simulation results match the analysis of the minimum interleaving distance shown in Table 2, where the ascending order of d_{min} is RCI, TBI and CRCSI.

Figure 5. Comparison for fixed reception.

Since the wireless channel in the fixed reception scenario has a longer delay spread, the signal is more susceptible to frequency selective fading. Therefore, in the designed scheme, the method of changing the transmission sequence of the subcarriers can effectively combat continuous bit errors. It is worth noting that for the case of TBS equal to 45352, CRCSI only has a smaller gain over TBI and RCI. This is because burst errors are sufficiently dispersed in a relatively small TBS, which makes room for further improvement in randomization more limited. The simulation results illustrate a tendency of the gain being larger for large TBS.

The performance of the proposed block interleaver in the LPLT scenario is also evaluated. In the simulation, the TDL-B channel model with a delay extension of 20 μ s is used, with a bandwidth of 10 MHz, and TBS equal to 9912. Figure 6 shows the BLER performance of different TILs at a middle moving speed of 60 km/h, while Figure 7 compares the system performance of the maximum TIL with the speed varying from 30 km/h to 120 km/h.

Figure 6. Comparison for mobile reception.

It can be seen from Figure 6 that the performance difference of the three interleavers is not obvious when TIL equals 3. This is because the Doppler spread is small at this time

and the channel coherence time is large, and the time selective fading experienced by the channel within 3 ms is still not obvious. When TIL equals 13, the gain of CRCSI compared to RCI and TBI reaches 0.5 dB and 0.1 dB@ $BLER = 10^{-2}$, respectively. Moreover, when TIL equals 39, the performance of the proposed block interleaver outperforms the other two types of interleaver by 0.6 dB and 0.3 dB@ $BLER = 10^{-3}$. It is found that CRCSI performs better when the time selective fading is significant, which can be attributed to the more time diversity gain it obtains in the interleaving operation. In addition, the simulation results are consistent with the theoretical analysis of the minimum interleaving distance in Table 3.

Figure 7 compares the performance of the interleavers at three moving speeds, ranging from handheld terminals to the highway scenario. It can be seen that the system performance improves by at least 0.2 dB at the speed of 30 km/h, 0.35 dB at 60 km/h and up to 0.5 dB at 120 km/h @ $BLER = 10^{-3}$.

Thus result can be explained as follows. As the moving speed increases, the coherence time caused by the Doppler frequency shift gradually decreases. The coherence time at 120 km/h is $T_c = 12.9$ ms, which is less than the duration of one frame of 40 ms. At this time, the data on the time-frequency resource block is more susceptible to time-selective fading than in the low-speed case.

From the above performance evaluations we can conclude that, compared to other classical block interleavers, the proposed CRCSI is able to effectively alleviate the impact of deep fading, providing superior system performance under MPMT and LPLT scenarios. The proposed CRCSI can meet the 5G terrestrial broadcasting system's requirements for wider coverage and faster transmission rates.

Figure 7. Comparison for different speed.

5. Conclusions

In this paper, we considered the design of a generic block interleaver to resist the effect of channel selective fading in terrestrial broadcast system. To tackle this problem, we formulated the block ordering problem into the design of row-column mapping rules, and proposed a generic block interleaver without extra memory space by crossing and cyclically shifting the row in order. Compared to classical block interleavers, the theoretical interleaving distance of the proposed block interleaver is obviously increased. The simulation results showed that the BLER performance in fixed reception is improved with the increasing of TBS. Moreover, the proposed block interleaver can obtain a significant performance improvement against the Doppler shift in different mobile reception scenarios.

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