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Anti-Interference Design Based on Prime Interleaving for a Combined FH and DS Spreading Spectrum System

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Abstract: A combined prime interleaving design is proposed for a spreading spectrum system with frequency hopping (FH), direct sequence (DS), and coherent detection. Obtaining a lower bit error rate (BER) is the object of classical anti-jamming communication systems. By employing combined prime interleaving, we get lower BER results compared with conventional block interleaving under the same signal-to-noise ratio (SNR) level by merit of superior storage and interleaving effects. Prime interleaving requires only one row to interleave while both block and random interleaving require the whole interleaving matrix, which results in lower latency time. Simulations reveal that the proposed combined interleaving design has comparative performance with random interleaving, and has advantages in transmission reliability and system delay. Moreover, the prime interleaving outputs slightly worse BER compared with random interleaving over the same SNR. Compared with random interleaving, the proposed combined interleaving has 0.25 dB worse SNR over the same average BER.

Key words: frequency hopping-direct sequence spread spectrum system; combined prime interleaving; block interleaving; random leaving; bit error rate

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Spread spectrum (SS) techniques are applied to spread narrow-band signal power onto a much larger bandwidth. Direct sequence (DS) and frequency hopping (FH) are two classical spreading frequency schemes[1]. DSSS modulates the message signal with a pseudo-noise sequence (PN) while FHSS is a frequency-shift keying (FSK) scheme using multiple carriers controlled by a pseudo-random sequence. A recently proposed spread spectrum generalized frequency division multiplexing (SS-GFDM) scheme has been proven to be effective over a typical satellite channel with lower complexity[2]. Generally, a DS system is designed to combat various interferences. DSSS has been proven to be able to overcome multipath fading and can achieve an approximately 6 dB SNR improvement[3].

To further improve anti-jamming effects and lower bit error rate (BER) performances, interleaving and scrambling are employed. Interleaving improves system performance by scattering the sending bits or symbols, turning burst errors into sparse ones which lower the BER. To further lower BER performances, various interleavers have been widely applied[4-10]. Interleaving mainly fall into two categories: random interleav-

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ers or ones with known rules and parameters. Both categories of interleavers reshape the input data with a given mapping. An optical satellite system with LDPC codes and interleaving has been proven to have a 3 dB SNR enhancement in burst error environments[4]. Multiple interleaving methods are also used to reduce peak-to-average power ratio (PAPR) in OFDM signals and have a reduction of 4.5 dB under the BER of 10^{-3}[5]. A quadratic polynomial permutation (QPP) interleaving along with turbo coding is used for the long time evolution (LTE) system[6]. New interleaving methods are also being fitted into the oncoming generation of communication systems, 5G[7-9]. Due to the scattering nature of interleaving, it can also be used as a method of safekeeping instead of anti-interference[10]. In addition, random interleaving can provide a high level of security[10].

The paper is organized as follows: the combined anti-interference design based on prime interleaving for a combined FH and DS is stated in Section 1; performance analysis of different interleaving Methods are stated in Section 2; simulations are given in Section 3; finally, Section 4 concludes the proposed combined interleaving design.

1 System Model

We introduce a prime interleaving design to combat interference in a combined FH-DS system. Fig. 1 demonstrates the system model of anti-interference design based on prime interleaving for a FH-DS system.

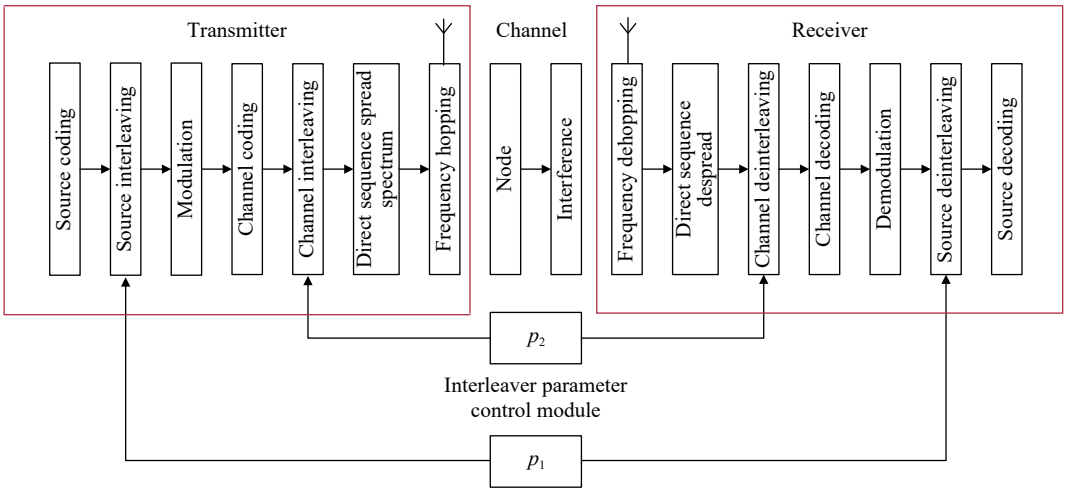

Fig. 1 Anti-interference design based on prime interleaving for a FH-DS system

As shown in Fig. 1, two suitable prime numbers p_1 and p_2 are chosen to generate the address matrix for interleaving of the source and the channel, respectively. The source data is source coded before it undergoes the source interleaving. The interleaved symbols are modulated and channel coded before they experience the channel interleaving. Then, the interleaved channel symbols go through the combined DS-FH process, the output of which is transmitted under the channel with noise and interference. The receiver undergoes the whole transmitted procedure in reverse, where the received signal is dehopped and despreaded first. Then, the despreaded symbols are channel deinterleaved and decoded in the channel decoding section. After the demodulation, the source deinterleaving, and decoding processes, the restored source data are acquired.

The interleaving parameter control module outputs prime parameters based primarily on the signal-to-noise ratio of the transceiver. We label the two parameters as p_1 and p_2, where p_1 would be given to the source interleaving unit and

source deinterleaving unit while p_2 would be given to the channel interleaving unit and channel deinterleaving unit. It should be noted that both p_1 and p_2 are prime numbers of the prime code and quadratic prime code. Fig. 2 shows in detail the procedures of the combined prime interleaving.

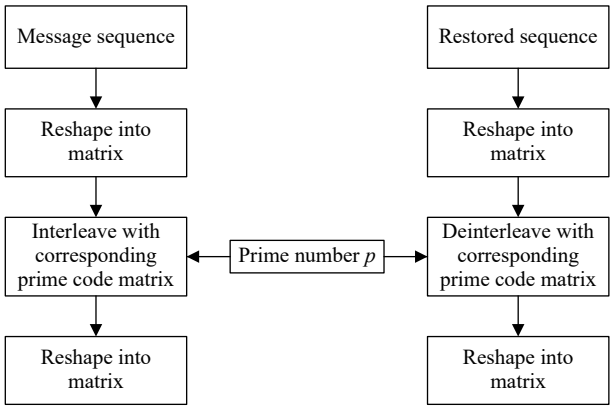

Fig. 2 Detailed procedures of the prime interleaving

In Fig. 2, the message sequence is reshaped into a matrix and interleaved with a prime code matrix generated by a corresponding prime number to the message matrix. It is then transmitted and received where it goes through a reverse deinterleaving procedure using the same prime matrix. The prime code matrix is generated by the following equation as

$$\mathrm{GF}(n+1, m+1) = nm \bmod p \qquad (1)$$

Where p is the chosen prime number and m and n are integers from 0 to $p-1$. The following Tab. 1 displays the prime code matrix where $p=13$. From Tab. 1, we observe that the scrambled numbers (bolded) from row 3 and column 2 to both the ends could be used as the row address of prime interleaving, where the zeros and natural ordered numbers are disposed.

During interleaving, the last column of the message data normally cannot make up a full column. In this case, the interleaver only needs to pick out element amounts that are no more than the remaining data sequence from the relevant column to form the address sequence.

Tab. 1 Prime interleaving address matrix

$\mathrm{GF}(n+1, m+1) = nm \bmod p$, where $p=13$, $0 \le n, m \le p-1$												
0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	2	3	4	5	6	7	8	9	10	11	12
0	**2**	**4**	**6**	**8**	**10**	**12**	**1**	**3**	**5**	**7**	**9**	**11**
0	**3**	**6**	**9**	**12**	**2**	**5**	**8**	**11**	**1**	**4**	**7**	**10**
0	**4**	**8**	**12**	**3**	**7**	**11**	**2**	**6**	**10**	**1**	**5**	**9**
0	**5**	**10**	**2**	**7**	**12**	**4**	**9**	**1**	**6**	**11**	**3**	**8**
0	**6**	**12**	**5**	**11**	**4**	**10**	**3**	**9**	**2**	**8**	**1**	**7**
0	**7**	**1**	**8**	**2**	**9**	**3**	**10**	**4**	**11**	**5**	**12**	**6**
0	**8**	**3**	**11**	**6**	**1**	**9**	**4**	**12**	**7**	**2**	**10**	**5**
0	**9**	**5**	**1**	**10**	**6**	**2**	**11**	**7**	**3**	**12**	**8**	**4**
0	**10**	**7**	**4**	**1**	**11**	**8**	**5**	**2**	**12**	**9**	**6**	**3**
0	**11**	**9**	**7**	**5**	**3**	**1**	**12**	**10**	**8**	**6**	**4**	**2**
0	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**

2 Performance of Different Interleaving Methods

We measure the effects of interleaving with computation overload, interleaving delay, and storage requirements in Tab. 2. Interleaving delay indicates the maximum delay a symbol experiences before it is output into the transmission sequence. As shown in Tab. 2, block interleaving has a matrix size of (M, N), and its address sequence inputs by column and outputs by row. This method, however, leaves the first and last bits unchanged. In random interleaving, for a message sequence of "N" length, it marks down every bit position then generates a corresponding "N" amount of random numbers between $[0, 1]$ and lines them in order of generation into a sequence, defined as sequence X. It reshapes sequence X by a given method into a new sequence, defined as sequence Y. The order of the elements in sequence Y would be the address sequence for the random interleaving. For random interleaving, an interleaver with length N has $N * N$ ways of interleaving.

Storage requirements relate to the dimensions of the interleaving and deinterleaving matrices; normally, a larger matrix leads to longer delay and worse instantaneity in communication with better performance. Random interleaving and block interleaving both require storage of the whole address matrix; prime interleaving and quadratic prime interleaving prove to be

much more flexible. For lowest storage, the latter can choose not to store any of the address matrices at all as they can be computed by the mode operation based on the prime number parameter. Computational overload indicates the arithmetic steps of different interleavers. If the address storage needs "zero", then the corresponding computation load is "multiply and mod". If the address storage needs "N" or "$M*N$", then the corresponding computation load is zero, which means there is no need for computation operations.

Tab. 2 Storage requirements of different interleaving methods for interleaving of a $M*N$ matrix

Interleaving method	Interleaving delay	Address storage	Computation overload
Block interleaving	$M*N$	$M*N$	No need
Prime interleaving	N	**0** $N\sim M*N$	**Multiply and mod** No need
Quadratic prime interleaving	N	**0** $N\sim M*N$	**Multiply and mod** No need
Random interleaving	$M*N$	$M*N$	No need

3 Simulation Results

First, we simulate the BER performance of a combined FH and DSSS system with only source interleaving by using separate interleavers shown in the plots in Fig. 3. The signal goes through an AWGN channel with one-tone jamming of a 30 dB jamming-to-signal ratio (JSR). The interleavers in Fig. 3a and Fig. 3b apply the prime number $p = 23$ and $p = 31$, respectively. The block interleaver interleaves 20 elements per row.

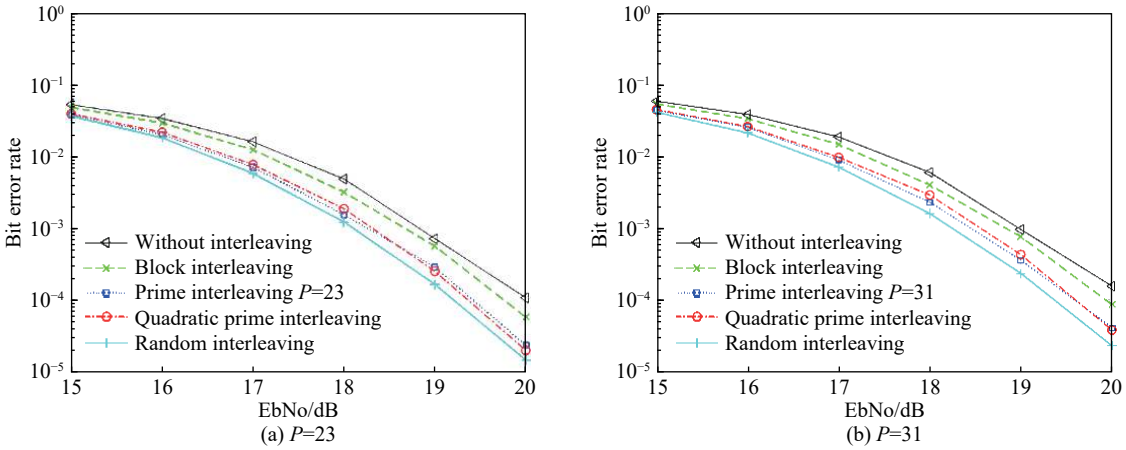

Fig. 3 BER performances of source interleavings with different prime number over JSR=30 dB

From the plots of Fig. 3, the prime interleaver achieves 0.45 dB (P=23) and 0.3 dB (P=31) SNR improvements compared with block interleaving over the same BER(10^{-4}). Moreover, the prime interleaving have 0.2 dB (P=23) and 0.25 dB (P=31) worse SNRs compared with random interleaving over the same BER(10^{-4}). Then, we combine source interleaving and channel interleaving to obtain the BERs in Fig. 4, where $p_1 = 11$ and $p_2 = 41$.

Compared with no interleaving and block interleaving, it has 0.2 dB and 0.4 dB SNR improvements over the same BER(10^{-4}), respectively. Moreover, the prime and quadratic prime interleaving have 0.25 dB and 0.26 dB worse SNRs compared with random interleaving over the same BER(10^{-4}). It can be seen from plots in Fig. 3 and Fig. 4 that in all cases, the method without interleaving has the highest BER and declines slowly with the increase of SNR. Block interleaving has a slight SNR increase in BER compared to no interleaving. Random interleaving has the lowest BER performance. Prime interleaving and quadratic prime interleaving have similar performances compared to a random interleaver, which has the highest efficiency among

all interleavers. As a trade-off in between, it can perform interleaving with zero storage or only one row at a time, which shows much lower complexity.

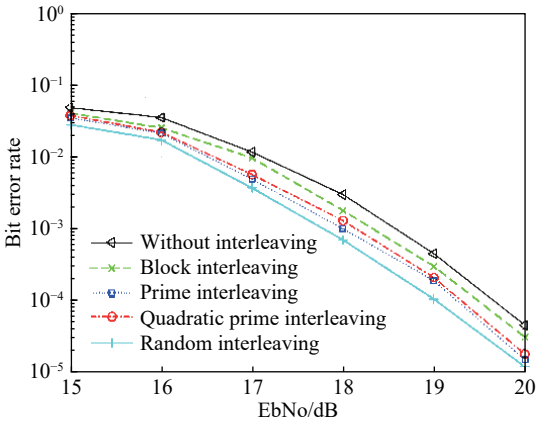

Fig. 4 BER performances of combined interleaving with JSR=30 dB

4 Conclusion

In this paper, we proposed a combined prime interleaving design for a FH-DS system with coherent detection. The demonstrated simulation results show that the proposed design has a significantly lower BER. Compared no interleaving or block interleaving, the BER performance has improved the same SNR. It has an equal or better performance compared to quadratic prime interleaving. Combined prime interleaving also exerts a slight 0.17 dB with only source interleaving, 0.1 dB with only channel interleaving, and 0.3 dB with source interleaving and channel leaving, a worse but similar performance compared to random interleaving. However, this should be a reasonable trade-off when considering the two methods' complexities and corresponding latencies. By only requiring the prime parameters p_1 and p_2 along with the message signal, the proposed anti-interference design based on prime interleaving dramatically increases the effectiveness of the communication process for random interleaving and would only need to send the random interleave matrix along with the message for deinterleaving, which is the same size of the message sequence. Furthermore, prime interleaving requires only one row at a time to do the interleaving while both block interleaving and random interleaving require the whole interleaving matrix.

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