Spinal-Polar Concatenated Codes in Non-coherent UWB Communication Systems

Qianwen Luo, Zhonghua Liang(✉), and Yue Xin

School of Information Engineering, Chang'an University,
Xi'an 710064, People's Republic of China
`956829305@qq.com`, `lzhxjd@hotmail.com`, `342996436@qq.com`

Abstract. Non-coherent ultra-wideband (UWB) systems have attracted great attention due to their low complexity, and without the need of channel estimation. In order to improve the transmission reliability, polar codes were recently introduced into non-coherent UWB systems because of their capability of approaching the Shannon channel capacity, and their low complexity in both coding and decoding. In the case of polar codes with medium and short length, the bit error rate (BER) performance of coded incoherent UWB systems is limited to incompletely channel polarization, poor Hamming distance and the sensitivity of successive cancellation (SC) decoding resulting in error propagation. In order to improve the performance of coded systems using polar codes with medium and short length, Spinal-Polar codes were recently presented, in which inner codes and outer codes are complementary, and the outer codes have good pseudo-random characteristics and error correction performance in the case of short length. Therefore, in this paper, the interleaved Spinal-Polar codes are introduced into the non-coherent UWB systems. Simulation results show that the interleaved Spinal-Polar codes can effectively improve the BER performance of the coded non-coherent UWB systems using polar codes with medium and short code length.

Keywords: UWB · Non-coherent reception · Spinal coding · Polar coding · Concatenated coding

1 Introduction

Ultra-wideband (UWB) is a short-range wireless communication technology that uses spectrum overlap technology to make full use of spectrum resources. UWB technology has good coexistence and confidentiality characteristics, strong multipath resolution and fine positioning accuracy. The incoherent UWB systems

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have been widely studied for its low cost, low complexity and without the need of precise synchronization while achieving suboptimal bit error rate (BER) performance. However, many key technologies need to be developed for UWB communication systems, and these key technologies are of great significance to improve the performance of systems. Among them, channel coding is investigated to guarantee reliability.

At present, some forward error correction FEC codes have been introduced into incoherent UWB systems to improve the BER performance of the systems [1–4]. Polar codes were also recently introduced into non-coherent UWB systems due to their capability of approaching the Shannon channel capacity, and complexity in both coding and decoding [5]. In the case of polar codes with medium and short length, the performance is inferior to that of Turbo codes and low density parity check (LDPC) codes. Several typical concatenated polar coding schemes were studied to improve the performance of polar codes with medium and short length at present. The traditional Reed Solomon (RS)-Polar codes can reduce the frame error rate (FER), however, it is hard to implement because the length of outer codes increases exponentially with the increase of the length of inner codes [6]. In the interleaved RS-Polar codes, the efficiency of the concatenated codes is higher as the coding length increases [7]. The LDPC-Polar codes was proposed to overcome the incompletely polarization of polar codes with medium and short length [8]. The BCH-Polar codes and the Convolutional-Polar codes were proposed, in which the decoding scheme of outer codes is relatively complex [9]. In order to solve the problem of pairwise bit error resulted from SC decoding, interleaved LDPC-Polar codes were proposed [10]. However, LDPC codes can obtain better error correcting ability only when the coding length is long enough. Moreover, it has high encoding complexity, therefore, the encoding complexity of the concatenated codes will increase. Each of these concatenated codes improves the performance of polar codes, but also suffers from the problem that the error correction capability of outer codes is affected by the coding length. The interleaved Spinal-Polar codes were proposed in [11], and it can significantly improve the performance of polar codes in acceptable complexity [11]. In the interleaved Spinal-Polar codes, the information sequence is divided into many data streams before interleaving operation. Therefore, we can make full use of the performance of Spinal codes with short code length. The joint iterative decoding corresponding to interleaved coding can alleviate the problem of error derivation in SC decoding [12].

Based on the discussions above, in this paper, the interleaved Spinal-Polar codes are used to improve the BER performance of the coded incoherent UWB systems using polar codes with medium and short length. The information sequence is coded by Spinal coding scheme firstly, and then the second layer of protection is obtained by polar coding.

The rest of this paper is organized as follows. Section 2 introduces the signal and channel models for the coded non-coherent UWB systems. Section 3 introduces interleaved Spinal-Polar codes and joint iterative decoding. Section 4 gives some simulation results. Finally, Sect. 5 provides the concluding remarks.

2 Signal and Channel Model

2.1 NC-PPM Signaling

PPM is a modulation method that uses data signal to change the pulse position in one symbol period. According to the IEEE 802.15.4a standard, PPM-UWB signal is formed by evenly spaced double pulses to meet the FCC mask requirements. The PPM-UWB signal is [4]

$$s\left(t\right)=\sqrt{\frac{E_b}{2N_s}}\sum_{i=0}^{N-1}v_i\left(t-iT_s\right) \tag{1}$$

where $v_i\left(t\right)\triangleq\left[1-c_n\left(i\right)\right]s\left(t\right)+c_n\left(i\right)s\left(t-\frac{T_s}{2}\right)$, information bit $c_n(i)$ determines the location of $s(t)$ throughout the symbol period, N indicates the length of the original information transmitted, E_b represents the average energy of each symbol, N_s represents the pulse pairs in each symbol, and T_s represents the symbol period.

2.2 TR Signaling

Assuming the information bit stream is $c_n\in\{0,1\}$, it is expressed as symbol sequence $b_n\in\{-1,1\}$ after BPSK modulation. In the TR transmission scheme, the basic unit of the transmitted signal is a pulse pair containing a data pulse and a reference pulse, and the reference pulse is transmitted before the modulated data pulse. The TR signaling is [13]

$$\hat{s}_{TR}\left(t\right)=\sum_{n=-\infty}^{\infty}\sum_{i=0}^{N_s-1}g\left(t-nT_s-iT_f\right)+b_ng\left(t-nT_s-iT_f-T_d\right) \tag{2}$$

where $g\left(t\right)$ represents the UWB pulse, T_f represents the duration of each frame, T_d represents the interval between two pulses in a pulse pair, $T_s=N_sT_f$ is the bit period, and b_n is the n information bit. $\tau_{\max}$ and T_p represent maximum channel spread time and pulse width respectively, to avoid inter-pulse interference (IPI), taking $T_d\geq\tau_{\max}+T_p$, and taking $T_f\geq 2T_d$ to avoid inter-frame interference (IFI). Compares to TR-UWB systems, the TRPC-UWB systems have smaller interval between the data pulse and the reference pulse. In this paper, the simulation of the BER performance of TRPC-UWB systems, assuming $T_d=T_p$.

2.3 Channel Model

The channel impulse response of the UWB multipath channel model given by the IEEE 802.15.4a standard is [14]

$$h\left(t\right)=\sum_{l=1}^{L}\alpha_l\delta\left(t-\tau_l\right) \tag{3}$$

where L represents the total number of multipaths, α_l and τ_l represent complex amplitude and spread delay of the l-th path.

3 Interleaved Spinal-Polar Coding Scheme for Non-coherent UWB Systems

3.1 Interleaved Spinal-Polar Coding Scheme

The coding process of coded non-coherent UWB systems using interleaved Spinal-Polar codes is described as follows. Firstly, the information sequence is coded by Spinal codes, next the interleaving process is operated, and then polar coding is parallel implemented. The specific Spinal coding process is referred to in reference [15]. Polar coding is represented by four parameters (N, k, A, u_{A^c}), the specific coding process is referred to reference [16]. Two important steps in polar coding are generating matrix and selecting bit sub-channel index of transmission information. When selecting the bit sub-channel index of transmission information, the channel noise is obtained by training sequence in non-coherent UWB systems, the specific process is referred to reference [5]. When the interleaved Spinal-Polar coding is performed, it is assumed that the number of channels is P, and each row of the matrix W has P Spinal code-words. Table 1 shows the specific procedure of the interleaved Spinal-Polar coding, where the channel number is P [11], m represents the length of each Spinal code-word and n represents the length of each polar code-word.

Algorithm 1. Interleaved Spinal-Polar coding procedure

```
Initialization:
  Divide the information sequence $M$ into $r$ block data streams, each block contains $m'$ bits, $m'$bits are divided into $m'/k$ part;
  Set the channel number parameter $P$ in the outer Spinal coding;
  Define the concatenated encoding matrix $X$ with size $mP \times n$.
  for $i \leftarrow 1$ to $m'/k$ do
      for $j \leftarrow 1$ to $r$ do
          $W\left(j, (i-1)\, mk/m'p + 1 : imk/m'p\right) = Spinalencoder(\bar{m}_i, P)$;
      end for
      $W' = W^t$;
      $X\left((i-1)\, mk/m' + 1, imk/m'\right) = Polarencoder\left(W', n\right)$;
  end for
End Obtain the interleaving Spinal-Polar coding matrix $X_{mP\times n}$.
```

3.2 Joint Iterative Decoding for Interleaved Spinal-Polar Codes

The coded NC-PPM, TR and TRPC signaling using interleaved Spinal-Polar codes pass through the channel firstly, then the channel transmission sequence pass through the receiving filters. The signals are expressed as follows [5]

$$r\left(t\right) = \tilde{s}\left(t\right) * h\left(t\right) + n\left(t\right) \tag{4}$$

where $*$ denotes a linear convolution, $n(t)$ represents a complex additive white Gaussian noise.

The autocorrelation operation is performed on the filtered TR and TRPC signaling, and the output decision variable by the receiver is [4]

$$D = \int_{mT_s+T_1}^{mT_s+T_2} \tilde{r}\,(t)\tilde{r}\,(t-T_d)\,dt \tag{5}$$

where $T_1 = T_d + T_l$, $T_2 = T_d + 2\,(N_f - 1)\,T_d + T_h + T_p = (2N_f - 1)\,T_d + T_h + T_p$, T_l and T_h represent the starting and ending points of the integral respectively, T_l usually approaches the arrival time of the first path, integral interval $[T_1, T_2]$ will affect the detection effect, so the choice of T_1 and T_2 should make the autocorrelation operation cover as many meaningful multipath channels as possible. The specific determination algorithm can be referred to reference [17], and finally the receiver output information [17]

$$\tilde{b} = \frac{\operatorname{sgn}(D - d_0) + 1}{2} \tag{6}$$

In TR-UWB systems, d_0 in (6) is taked as 0. However, in TRPC-UWB systems, it is generally assumed that the pulse interval is approximately equal to the pulse width. This will inevitably lead to inter-pulse interference, so it results in the deviation of the decision threshold. Therefore, "0" isn't the appropriate decision threshold for TRPC-UWB systems any more. In the process of simulating the BER performance of the coded TRPC-UWB systems, we assume that $T_d = T_p$ and use the optimized decision threshold d_0, and the specific acquisition method is referred to reference [17].

The coded NC-PPM signaling passing through the filter is detected by a square-law detector firstly, and then the signal passing through the square-law detector is fed into the energy integrator with different integration windows. The decision variable is from the different energy value of the energy integrator with different integration windows. The signal energy collected corresponding to different integration length is [4]

$$D_0 = \int_{T_1}^{T_2} \tilde{r}(t)^2 dt \tag{7}$$

$$D_1 = \int_{T_1+\frac{T_s}{2}}^{T_2+\frac{T_s}{2}} \tilde{r}(t)^2 dt \tag{8}$$

Among them, the starting and ending moments of the integral T_1 and T_2 are determined in reference [4]. The final decision variable $D = D_1 - D_0$. The receiver output decision information [4]

$$\tilde{b} = \frac{\operatorname{sgn}(D) + 1}{2} \tag{9}$$

where $\operatorname{sgn}(x) = \begin{cases} +1, & x > 0 \\ -1, & x < 0 \end{cases}.$

In the coded non-coherent UWB systems, the decision variable is used as the output of the receiver, to obtain the decoded decision variable. In this paper, the joint iterative decoding algorithm [12] is applied, where, SC decoding for inner codes [16] and FSD decoding for outer codes [18] are used, respectively. Algorithm 2 shows the process of the joint iterative decoding algorithm.

Algorithm 2. Joint iterative decoding algorithm

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Initialization:
  Define the decoding auxiliary matrix $y^t$ and decoding matrix $\hat{W}$;
  for $i \leftarrow 1$ to $r$ do
      for $j \leftarrow 1$ to $mP$ do
          $y^t\left(1:mP,i\right) = Polardecoder(n, A, y\left(1:mP,i\right))$;
      end for
      $\hat{W}\left(1:m,i\right) = FSDdecoder\left(P, y^t\left(1:m,i\right), B, k\right)$;
      //update information obtained from Spinal decoder back to the SC decoder
      $y'\left(1:mP,i\right) = Spinalencoder\left(\hat{W}\left(1:m,i\right), P\right)$;
  end for
End the decoding matrix $\hat{W}_{m\times r}$ is get.
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4 Simulation Results and Discussions

4.1 Parameter Setting for Outer Codes

In order to realize the complementary advantages between inner and outer codes in interleaved Spinal-Polar codes, it is necessary to reasonably design the code length of Spinal codes and polar codes, that is, to reasonably set the values of k and r of Spinal codes and the values n of polar codes. In simulation, the parameter setting of the outer codes mainly includes the Hash function and the number of channel. In addition, the outer codes are applied at a fixed coding rate, so it is also necessary to set the coding form.

A. Hash Function

In order to reduce the collision probability of different information segments through hash function and ensure the efficiency of identifying the original information sequence correctly, it is needed to adopt hash function with a long state length as much possible. However, in order to balance hardware requirements and the performance of concatenated codes, the one-at-a-time hash function with 32 bits length is adopted in this paper.

B. Coding Form

Due to the sequential nature of Spinal coding, the information data stream m_i has nothing to do with the coding symbol according to the information data stream $m_{i-1}, m_{i-2}, \cdots, m_1$, so the information data stream in former coded by

Spinal codes can be better protected. That is, the error correction performance of Spinal codes cannot be improved by increasing the coding length [19]. Therefore, the BER of the coding form $S\left(n,k,P\right)$ (where $n \neq k$) is greater than that of the coding form $S\left(k,k,P\right)$, that is $P_e > \varepsilon_D$, where ε_D is the BER of the coding form $S\left(k,k,P\right)$ of spinal codes.

C. Channel Number Settings

The BER calculation formula for the Spinal codes in the AWGN channel is given in [20]

$$P_e\left(i\right) = 2^{-\Theta\left(iPC^2/k\right)} \tag{10}$$

In the formula (10), i represents the index of the block information, P represents the number of channels, and C represents the channel capacity. It can be seen that the error correction performance of the Spinal codes increases with the increase of the number of channels. Therefore, a number of channels greater than 1 is set in the simulation process.

4.2 Simulation Results

In this paper, simulation is carried out under CM1 and CM8 channel models, and the final BER data are obtained from an average of 100 channels, including coded NC-PPM, TR and TRPC systems using interleaved Spinal-Polar codes. CM1 is the channel environment of residential line-of-sight and CM8 channel is the channel environment of factory non-line-of-sight. The uncoded TRPC systems have better BER performance compared to uncoded TR systems. The NC-PPM systems are one kind of non-coherent UWB systems, which have different modulation modes at the transmitter and detection methods at receiving end. In the case of outer codes with single channel, there are two cases of concatenated coding rate, 1/4 and 1/8, and the corresponding coding length are 512, 1024.

Figure 1 shows the BER performance of the coded TR-UWB systems using interleaved Spinal-Polar codes in the CM1 channel model. The results show that the coded systems have better performance. When the coding rate is the same, the interleaved Spinal-Polar codes can improve the BER performance of the coded systems using polar codes with medium and short length. For example, when the code length is 512 and $BER = 1 \times 10^{-3}$, the coded TR-UWB systems using interleaved Spinal-Polar codes achieve a performance gain of 0.5 dB compared to the coded TR-UWB systems using polar codes. When the code length is 1024 and $BER = 1 \times 10^{-4}$, the coded TR-UWB systems using interleaved Spinal-Polar codes achieve a performance gain of 1.3 dB compared to the coded TR-UWB systems using polar codes.

Figure 2 shows the BER performance of the coded TRPC-UWB systems using interleaved Spinal-Polar codes in the CM1 channel model.

As can be seen from Fig. 2, the coded systems have better performance as the coding rate decreases. For example, when $BER = 1 \times 10^{-4}$, compared to the coded systems with the coding rate 1/4, the coded systems with coding rate 1/8

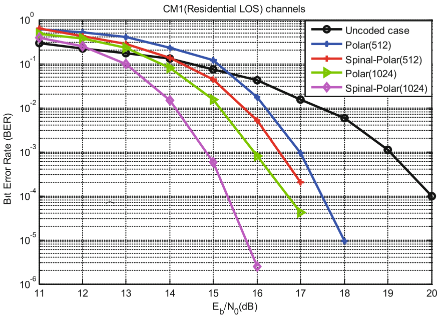

Fig. 1. BER performance of the coded TR-UWB systems using interleaved spinal-polar codes in CM1 channels.

achieves a performance gain of approximately 1.5 dB. When the coding rate is the same, the coded TRPC-UWB systems using interleaved Spinal-Polar codes improve the BER performance of the coded TRPC-UWB systems using polar codes. For example, when the code length is 512 and $BER = 1 \times 10^{-5}$, the coded TRPC-UWB systems using concatenated codes achieves a performance gain of approximately 0.9 dB.

Figure 3 gives the BER simulation of the coded TRPC-UWB systems interleaved Spinal-Polar coding scheme in the CM8 channel model.

The simulation result in Fig. 3 shows that the interleaved Spinal-Polar coded systems under this channel model have better BER performance as the coding rate decreases. For example, when $BER = 1 \times 10^{-5}$, the concatenated coding systems with a coding rate 1/8 obtain a performance gain of nearly 2.0 dB compared with the concatenated coding systems with a coding rate 1/4. At the same coding rate, the BER performance of the coded TRPC-UWB systems using interleaved Spinal-Polar coding scheme is better than that of the coded TRPC-UWB systems using polar coding scheme. For example, when the codes

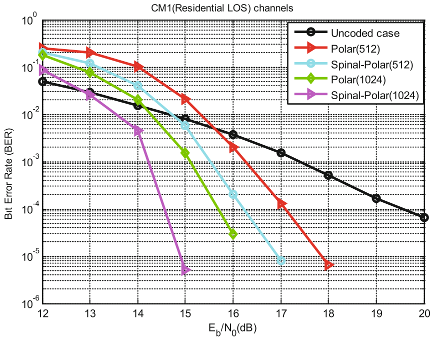

Fig. 2. BER performance of the coded TRPC-UWB systems using interleaved spinal-polar codes in CM1 channels.

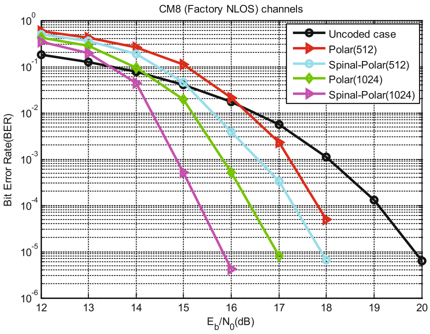

Fig. 3. BER performance of the coded TRPC-UWB systems using interleaved spinal-polar codes in CM8 channels.

length is 1024, the coded systems using the concatenated coding scheme obtain a performance gain of 1.1 dB.

Figure 4 shows the BER performance simulation of the coded NC-PPM system using interleaved Spinal-Polar codes in the CM1 channel model. As can be seen from Fig. 4, the Spinal-Polar interleaved coded systems achieve better performance gain than polar coded systems at the same coding rate. For example, when $BER = 1 \times 10^{-4}$, the concatenated coding systems with the coding rate 1/4 and 1/8 obtain the performance gains of 0.4 dB and 0.6 dB compared with the coded systems using polar codes alone. The BER performance of the coded systems using concatenated codes get better as the coding rate decreases. For example, when $BER = 1 \times 10^{-4}$, the concatenated coding systems with the coding rate 1/8 obtain a performance gain of nearly 1 dB compared with the concatenated coding systems with the coding rate 1/4.

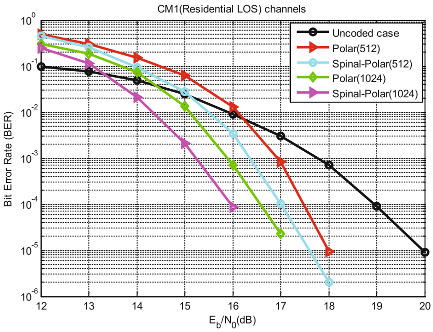

Fig. 4. BER performance of the coded NC-PPM systems using interleaved spinal-polar codes in CM1 channels.

4.3 Complexity Comparison

Table 1. Complexity comparison

	Interleaved Spinal-Polar concatenated codes	Polar codes
Coding	$O\left\{\frac{m'}{k}P\left[r\left(v+k\right)+n\right]\right\}$	$O\left(N\right)$
Decoding	$O\left(rmB\cdot 2^k\left(v+k+\log B\right)+N\log n\right)$	$O\left(N\log N\right)$

Table 1 shows the time complexity of the interleaved Spinal-Polar codes and the polar codes. Where the massage sequence is divided into r blocks, the state length of Hash function for Spinal coding is v, the number of channels is P, each of information blocks is divided into m'/k parts, the length of spinal code-word is m. The length of polar code-word is n. The main time cost is the Hash function acts on the information in Spinal coding, that is $O\left(v+k\right)$.

5 Conclusions

In this paper, the coded non-coherent UWB systems using interleaved Spinal-Polar codes are evaluated under CM1 and CM8 channels. Theoretical analysis and simulation results show the interleaved Spinal-Polar coding scheme can effectively improve the BER performance of the coded non-coherent UWB systems using polar codes with the medium and short length.

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