Joint Noncoherent Detection and Channel Decoding for UWB Impulse Radio by Belief Propagation

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Abstract—This paper proposes a belief propagation (BP) algorithm based joint noncoherent detection and channel decoding scheme for ultra-wideband impulse radio (UWB-IR) systems. Multiple symbol differential detection (MSDD) can enhance the performance of noncoherent differential UWB-IR systems. Channel codes are usually employed to protect wireless transmissions over various impairments. Thus, it is naturally required to incorporate channel decoding with MSDD for noncoherent UWB-IR systems. In this paper, we propose a new auto-correlation receiver (AcR) architecture to sample the received UWB-IR signal. The statistical model of the signal samples has a trellis structure. Then, we apply BP algorithm on this trellis to derive a soft-in soft-out (SISO) MSDD, which is easy to be incorporated with SISO channel decoding. Simulation results indicate the advantage of the proposed joint noncoherent detection and channel decoding scheme.

Index Terms—Ultra-wideband (UWB), multiple symbol differential detection (MSDD), channel decoding, belief propagation (BP).

I. INTRODUCTION

ULTRA-wideband impulse radio (UWB-IR) is served as a promising candidate for location-aware indoor communications, wireless sensor networks and wireless personal area networks. UWB-IR has earned significant attentions in both academia and industry [1]. However, the implementation of optimal coherent receiver for UWB-IR systems faces many challenges. UWB channels usually contain hundreds of multipath, due to the rich scattering indoor environments. The optimal coherent receiver required to capture multipath energy is the famous Rake receiver [2]. Since the UWB channel is characterized by the dense multipath, we need a large number of Rake fingers to capture a significant part of the signal energy [3]. The implementation of so many Rake fingers and the associated channel estimation on the corresponding multipaths involve intensive complexities [4]. Moreover, such Rake receiver is very sensitive to timing-jitter [5]. These challenges make it difficult and costly to realize the optimal coherent receiver for UWB-IR systems.

In order to bypass these challenges, the suboptimal noncoherent receivers are proposed to obviate the complicated treatments on UWB channels [6]. The typical noncoherent UWB-IR schemes are differential [7] and transmitted-reference [8] UWB-IR systems, both deployed with analog autocorrelation receiver (AcR) that does not require Rake receiver and explicit channel estimation. Due to their good performance-complexity tradeoff, noncoherent receivers now are more popularly used in UWB-IR systems. However, they suffer from performance degradations compared with coherent receivers.

Multiple symbol differential detection (MSDD) is an effective means of improving performance for noncoherent differential UWB-IR systems. The theoretical framework of MSDD is the maximum-likelihood (ML) sequence detection, which is firstly introduced to detect a block of differential MPSK symbols over additive white Gaussian noise (AWGN) channel [9]. Applying MSDD to differential UWB-IR systems is considered in [10]–[12] firstly. Works [12], [13] consider the application of sphere decoding algorithm to fulfill a low complexity MSDD for differential UWB-IR systems. With the same purpose, work [12] proposed a Viterbi algorithm based MSDD and works [14]–[16] proposed decision-feedback MSDD.

Wireless communication systems are susceptible to various impairments, such as noises, interferences and channel fading. We usually employ channel codes to protect the transmitted symbols over possible errors. The decoding of most powerful channel codes that can approach the Shanon capacity depends on iterative algorithm, where iterations are performed between soft-in soft-out (SISO) modules [17]. These MSDD schemes mentioned earlier, however, are all about to detect the hard decisions of the differential modulated UWB-IR signals, which is not compatible with SISO channel decoding. Recently, the work [18] investigates SISO MSDD for UWB-IR systems and incorporate it with SISO channel decoding.

In this paper, we propose a new SISO MSDD scheme for noncoherent differential UWB-IR systems. Even without considering channel encoding, there are memories introduced by differential modulation to all modulated symbols throughout the transmitted packet. In [18], the SISO MSDD processes signal samples block-by-block and it just ignores the information dependencies among different blocks. This leads to information loss. In this paper, by contrast, the proposed SISO MSDD scheme calculates the soft information of one symbol by exploiting the signal samples from the whole packet. We propose an AcR architecture to enable this scheme. The proposed AcR architecture correlates the received UWB-IR
signals, and does not need explicit channel estimation. Thus, it is a noncoherent detection. Moreover, it can exploit the signal dependencies among the whole packet. We use a trellis graph to describe the statistical model of signal samples. We derive the SISO MSDD scheme using the belief propagation (BP) message passing which implements sum-product rule on a factor graph \cite{19}. The proposed MSDD scheme is termed as BP-MSDD. We also consider SISO channel decoding. The outputs of the BP-MSDD are fed to the inputs of the BP algorithm for SISO channel decoding, and vice versa, in an iterative manner. The main contributions of this paper are summarized as the follows.

1) New AcR architecture for SISO MSDD scheme. We propose a new AcR architecture to sample the received UWB-IR signal. The AcR architecture results in a trellis statistical model for the signal samples of the whole transmitted packet. Compared with existing method, the proposed AcR can exploit more signal dependencies imposed by the differential modulation. This also enables us to apply BP message passing approach to noncoherent UWB-IR systems.

2) Message passing approach for joint noncoherent detection and channel decoding scheme. We apply BP message passing to the trellis-type signal model for deriving SISO MSDD scheme. The proposed BP-MSDD scheme is a bidirectional algorithm that consists of a forward and a backward message passing. Since BP message passing is employed as the decoding algorithm for many channel codes, we integrate the proposed BP-MSDD with BP algorithm for SISO channel decoding, and we achieve an iterative algorithm for the joint noncoherent detection and channel decoding scheme. We think this is the first time that applies BP message passing to noncoherent UWB-IR systems.

3) Performance evaluations by simulations. Simulations are performed to validate and evaluate the proposed scheme. The performances of uncoded and coded system under the environments of UWB multipath channel are evaluated. The results indicate the performance advantage of the proposed scheme over other existing schemes.

The rest of this paper is organized as follows. The system model of differential UWB-IR system is described in Section II. Section III introduces the joint noncoherent detection and channel decoding scheme. Section IV is about the parameter estimation in our system. Section V shows simulation results. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

In this section, we establish the system model for UWB-IR communications. A block schematic diagram of the system model is shown in Fig. 1. Adopting binary antipodal pulse amplitude modulation (BPAM), the transmitted signal waveform is given by

$$s(t) = \sum_{i=0}^{N} d_i \omega_s(t - iT_s), \quad (1)$$

where \(d_i \in \{ \pm 1 \}\) is the channel symbol, \(\omega_s(t)\) is the symbol waveform with duration \(T_s\) and \(N\) is the packet size. We denote the original information bits by \(b_i \in \{0, 1\}\), \(i = 1, \cdots, K\). Through channel encoding, interleaving and modulation, these information bits are mapped to the coded data symbols \(a_i \in \{\pm 1\}\), \(i = 1, \cdots, N\). The coding rate is \(R = K/N\). Finally, the channel symbol \(d_i\) is obtained by differential modulation: \(d_i = d_{i-1} a_i\), \(i = 1, \cdots, N\), where \(d_0 = 1\) is the reference symbol. UWB-IR transmissions usually employ \(N_f\) frames to transmit one channel symbol, and each frame includes one very short pulse. According to this unique aspect of UWB-IR, the unmodulated symbol waveform used in (1) is expressed as

$$\omega_s(t) = \sum_{j=0}^{N_f-1} \omega(t - jT_f - c_j T_c), \quad (2)$$

where \(\omega(t)\) is the ultra-short pulse with the duration \(T_o\) (referred to as the monocycle in literatures), \(T_f\) is the frame duration and we have \(T_s = N_f T_f\). The sequence \(\{c_j\}\) in (2) is a user specific time-hopping (TH) code used for the purpose of multiple access. Its elements are integers in the range \(0 \leq c_j \leq N_c - 1\), satisfying \(T_f \geq T_c \geq T_c\). \(T_c\) is the duration of an addressable time chip. Since \(\omega(t)\) has a very short duration, \(T_o\) is typically on the order of nanoseconds, the transmitted signal occupies a huge bandwidth. The frame duration \(T_f\) is usually hundred or thousands times longer than \(T_o\), resulting in a low duty transmission.

We consider dense multi-path environments, such as the industrial and indoor office \cite{20}. The channel impulse response (CIR) between the transmitter and the receiver is modeled as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l),$$

where \(\alpha_l\) is the Dirac delta function, \(L\) is the number of resolvable multipath components (MPCs), \(\alpha_l\) and \(\tau_l\) is the gain and the delay of the \(l\)th MPC, respectively.

We define the received pulse waveform as: \(g(t) = \otimes \omega(t) \otimes h(t)\), where \(\otimes\) denotes the convolution operator. Then, the received noisy signal waveform is given by

$$r(t) = s(t) \otimes h(t) + n(t) = \sum_{i=0}^{N} \sum_{j=0}^{N_f-1} g(t - iT_s - jT_f - c_j T_c) + n(t), \quad (3)$$

where \(n(t)\) is the additive white Gaussian noise process with zero mean and a flat two-sided power spectral density \(N_0/2\). With \(T_g\) denoting the maximum delay spread of the received pulse waveform \(g(t)\), the inter-frame interference (IFI) is avoided in the received signal (3) by letting \(T_f > T_g + (N_c - 1) T_c\).
The \( i \)-th observation window
Symbol \( i+1 \)
Symbol \( i \)
Symbol \( i-1 \)
\ldots
Symbol \( i-M \)
The \( i+1 \)-th observation window

Fig. 2. The illustration for the sampling mechanism of the proposed AcR.

III. JOINT NONCOHERENT DETECTION AND CHANNEL DECODING

A. The Noncoherent Autocorrelation Receiver

The optimal coherent detection of UWB-IR signals requires a implementation of the filter matched to the received pulse waveform \( g(t) \). However, the complexities of the implementation of match filtering and the explicit channel estimation constitute obstacles for the practical use of coherent detection in UWB-IR systems. Therefore, we focus on noncoherent detection that does not involve the explicit channel estimation and the implementation of match filtering. To improve the performance of noncoherent detection, we apply the MSDD scheme to the system. UWB channels are quasi-static in typical indoor environments [20]. This means the channel remains invariant over several symbol durations. Relying on this feature, MSDD jointly detects a block of \( M \) symbols from the received signal in the observation window of size \( M+1 \) symbol durations [10], [12], [18].

In this section, based on the concept of MSDD, we develop an AcR architecture for noncoherent detection of UWB-IR signals. We modify the sampling mechanism of the MSDD in [10], [12], [18]. Essentially, we still employ the correlation principle derived from GLRT criteria in [12] to sample the received signal; however, we change its sliding mode of the observation window. In [12], each time, the observation window of size \( M+1 \) will be slid down \( M \) symbol durations after the current \( M \) symbols have been detected. In a different mode, we slide the \( M+1 \) size observation window down one symbol duration each time. The sampling mechanism of the proposed AcR is illustrated in Fig. 2. In the following, we mathematically formulate the proposed sampling mechanism, and then explain its implications to noncoherent UWB-IR systems.

From the received signal \( r(t) \) in the \( i\text{-th} \) observation window \( (i-M) T_s \leq t \leq (i+1) T_s \), we obtain the \( i\text{-th} \) sample vector \( Y_i \triangleq [Y_{i,1}, Y_{i,2}, \ldots, Y_{i,M}]^T \), where \( Y_{i,m} \) is the correlation sample between the \( i\text{-th} \) and the \( (i-m)\text{-th} \) symbols

\[
Y_{i,m} = \int_0^{T_s} y(t + iT_s) y(t + (i-m)T_s) \, dt \tag{4}
\]

with the de-spreading signal

\[
y(t) = \sum_{j=0}^{N_f-1} r(t + jT_f + c_jT_c). \tag{5}
\]

After we finish the computation of \( Y_i \), the observation window is slid down one symbol duration to \((i+1-M)T_s \leq t \leq (i+1)T_s\). Since there is no transmission occurring \((r(t) = 0 \text{ for } t < 0)\), we pad some zeros at the rear of the first \( M \)-1 sample vectors: \( Y_{i,m} = 0 \) for \( i = 1, \ldots, M-1 \) and \( m = i+1, \ldots, M \).

3) The sampling mechanism of the proposed AcR is on a block-by-block basis. The correlation operations try to exploit the dependencies (imposed by the differential modulation) among symbols within a block of \( M \) symbols. However, the symbol dependencies between different blocks are ignored. This is a kind of information loss. Depending upon the proposed sampling mechanism where blocks overlap some others, the detection of one symbol is able to make use of the information of all the symbols throughout the packet. Since more information are collected, it is expected that the proposed scheme could have better performance.

B. The BP Message Passing Algorithm for SISO MSDD

In what follows, we derive the BP message passing algorithm for SISO MSDD using the samples delivered from the proposed AcR. Substituting (5), (3) into (4) and using the result of differential demodulation \( d_i d_{i-m} = \prod_{z=m+1}^{z+1} a_z \), we can express the sample \( Y_{i,m} \) as

\[
Y_{i,m} = \left( \prod_{z=m+1}^{z+1} a_z \right) N_T^2 E_g + n_{i,m}, \tag{6}
\]

where \( E_g \triangleq \int_0^{T_s} g^2(t) \, dt \) is the captured energy of the received pulse and \( n_{i,m} \) is the discrete noise component. It has been shown in [21] that \( Y_{i,m} \) for all \( i \) and \( m \) can be approximated to mutually independent Gaussian random variables with mean \( \left( \prod_{z=m+1}^{z+1} a_z \right) N_T^2 E_g \) and variance \( \sigma_n^2 = \ldots \)
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Let $Y = \{Y_i\}$ be the set containing all the sample vectors and $a = [a_1, a_2, \ldots, a_N]^T$ be the vector of all the data symbols. The constraint on $a$ by channel encoding will be discussed in the next subsection, and we ignore it here. The target of the BP-MSDD is to calculate the a posteriori probability (APP) of data symbol $a_i$ given $Y$:

$$p(a_i | Y) \propto \sum_{a_i \sim a} p(Y | a) p(a) \quad (7)$$

for all $i$, where the notation $\sum_{a_i \sim a}$ means summation over all data symbols in a except $a_i$. The straightforward calculation of (7) will involve complexity $O(2^N)$, which disastrously increases with $N$. We will develop the trellis representation for the system and employ BP message passing to it for an efficient calculation of (7). To derive the BP message passing, we need to factorize the globe probability function $p(Y | a) p(a)$ into many small local functions and model the system using a factor graph. Specified by (6), we meet an efficient calculation of (7). To derive the BP message passing algorithm that implements the sum-product principal [19]. To visualize the BP message passing for SISO MSDD, we employ a factor graph to model the system. The factor graph of the system is shown in Fig. 4, where circles are variable nodes for inputs and outputs, double circles are variable nodes for state and squares are the factor nodes for check functions.

The resultant BP message passing algorithm consists of a forward and backward message passing, which is similar to the BCJR algorithm [22]. The forward message passing recursively calculates the message $\alpha(S_i)$ which is already defined in (12):

$$\alpha(S_i) \propto \sum_{S_i} \alpha(S_{i-1}) p(Y_i | x_i) T_i(a_i, x_i, S_{i-1}, S_i) \quad (13)$$

for each $i = 1, 2, \ldots, N$, where $T_i(a_i, x_i, S_{i-1}, S_i)$ is the previously defined local check function for the trellis transition.
and $p(Y_i | x_i)$ is the information from observation $Y_i$ (shown in (9)). Similarly, the backward message passing recursively calculates the message $\beta(S_i)$ which is already defined in (12):

$$\beta(S_i) \propto \sum_{S_{i+1}} \beta(S_{i+1}) p(Y_{i+1} | x_{i+1}) T_{i+1} (a_{i+1}, x_{i+1}, S_i, S_{i+1})$$

(14)

for each $i = 1, 2, \cdots, N$. After the forward and backward message passing once in each direction, the APPs of $a_i$ for each $i = 1, 2, \cdots, N$ are given by

$$p(a_i | Y) \propto \sum_{a_{i-1}} \alpha(S_{i-1}) \beta(S_i) p(Y_i | x_i) p(a_i) T_i (a_i, x_i, S_{i-1}, S_i),$$

(15)

where $p(a_i)$ is the priori information of $a_i$, which is a constant. We now finish the derivations on the BP-MSDD scheme.

### C. Joint Noncoherent Detection and Channel Decoding

BP message passing algorithm is also widely used as the decoding algorithm for many advanced channel codes, such as LDPC code, Turbo code and RA code [17], [19]. It is straightforward to integrate BP-MSDD with BP channel decoding under the message passing framework, resulting in a BP message passing algorithm for joint noncoherent detection and channel decoding. In this section, we consider channel encoding part. We denote the valid set of codeword by $C$, and all related probability functions should be conditioned on $C$ hereafter. The factor graph of the overall system includes channel encoding constraint is shown in Fig. 4.

The presence of the constraint on $a$ by channel encoding introduces loops onto the factor graph. As a consequence, the BP message passing cannot exactly calculate these APPs of interest, and it is an iterative algorithm: the message will be passed multiple times on some given edges of the factor graph.

Given the considered factor graph, we can design many different message-passing schedules. In this work, we adopt a serial schedule [19] for iterative BP message passing between the BP-MSDD and channel decoder. The messages exchanged between the BP-MSDD and channel decoder are known as the extrinsic information. In particular, given the messages from observations $Y$ and the extrinsic information from channel decoding, the BP-MSDD performs the message passing algorithm derived in Section III.B to calculate the APPs of all $a_i$; the computation is still according to (15) with the only difference that we replace the priori information $a_i$ with the intrinsic information of $a_i$ sent the from channel decoder. These APPs of $a_i$ are treated as extrinsic information (denoted by red arrows in Fig. 4) which will be delivered to channel decoder. Then, given these extrinsic information from the BP-MSDD, the channel decoder runs several rounds of BP message passing within the subgraph of channel encoding constraint. After that, the channel decoder sends back its extrinsic information (denoted by blue arrows in Fig. 4) to the BP-MSDD for the next iteration. After $K_{BP}$ iterations between the BP-MSDD and channel decoder, we terminate the algorithm, and obtain the final decoding results about information bits.

Finally, we remark that the above iterative processing is implemented in digital domain as long as we have obtained the correlation samples from the AcR receiver, which can be realized using analog components to avoid the ultra high sampling rate in UWB-IR systems. A block schematic diagram about this receiver structure is also shown in Fig. 1.
IV. NUMERICAL RESULTS

In this section, simulations are conducted to validate the proposed scheme. In all simulations, the channel are generated according to IEEE 802.15.3a CM2 model [23], and the channel impulse responses are truncated at $T_c = 100$ ns. The used impulse shape $\omega(t)$ is the second derivative of a Gaussian function. The duration of $\omega(t)$ is set as $T_\omega = 0.5$ ns. The frame and chip duration are set to $T_f = 200$ ns and $T_c = 1.0$ ns, respectively. Each symbol consists of $N_f = 10$ frames. The TH codes are randomly picked up in the interval $[0, N_c - 1]$ where $N_c = 100$. Since now $T_f > T_g + (N_c - 1)T_c$ is satisfied, there is no IFI in our system. The integration interval of AcR is $T_i = T_g = 100$ ns. The bandwidth of the baseband filter employed at the receiver is 2 GHz. The energy used to transmit one information bit is denoted by $E_b$, and the signal-to-noise ratio (SNR) is defined as $E_b/N_0$.

A. The performance of uncoded system

We first investigate the performance of the proposed BP-MSDD scheme for uncoded differential UWB-IR systems. Without considering channel codes, we employ the BP-MSDD to detect the data symbols $a_i$ for $i = 1, 2, \cdots, N$. After the bidirectional message passing, the BP algorithm outputs the APP of $a_i$ as in (15). Then, the hard decision about $a_i$ is made based upon (15). Each packet consists of $N = 1024$ data symbols. We evaluate the BER performance of the proposed BP-MSDD scheme with perfect $E_g$ and estimated $E_g$. As benchmarks, we also evaluate the BER performances of the DD [7] scheme and MSDD [10, 12] scheme for differential UWB-IR systems.

Fig. 5 presents the simulation results. The first point we want to study is the impact of $E_g$ on the system performance. We can observe from Fig. 5 that the BP-MSDD schemes with perfect $E_g$ and estimated $E_g$ nearly have the same performance. Thus, we can conclude that the estimate of $E_g$ by the simple energy estimation method is sufficiently effective for the implementation of BP-MSDD. Then, compared with DD scheme, the proposed BP-MSDD scheme can further improve the uncoded performance by offering an additional detection gain which increases with $M$. This performance trend of BP-MSDD is similar to that of MSDD. Moreover, we see that BP-MSDD has a better performance than MSDD, e.g., 0.7 dB gain with $M = 2$ and 1 dB gain with $M = 5$ at the BER of $10^{-5}$.

B. The performance of coded system

We then investigate the performance of the proposed joint BP-MSDD and channel decoding for coded differential UWB-IR systems. The regular RA code [24] with coding rate 1/3 is employed. Each packet has 1024 information bits (thus 3072 channel-coded data symbols). The energy estimation method is used to obtain the estimate of $E_g$. The performances of the joint MSDD and channel decoding proposed in [18] will be presented as the benchmarks. For all simulation results, we perform 8 iterations between the BP-MSDD and the BP for RA channel decoding, and 20 iterations within the RA channel decoder.

Fig. 6 presents the simulation results. We can see that the proposed joint BP-MSDD and channel decoding scheme has a better performance than the joint MSDD and channel decoding scheme. And, the gain is increased with $M$, e.g., 0.3 dB gain with $M = 2$ and 0.6 dB gain with $M = 5$ at the BER of $10^{-6}$. We believe that these gains are due to the more beliefs collected by the BP message passing for BP-MSDD.

V. CONCLUSION

In this paper, we apply BP algorithm to propose a joint noncoherent detection and channel decoding scheme for UWB-IR systems. Specifically, we propose a new AcR architecture to transform the received UWB-IR signal into discrete samples, whose statistical model has a trellis structure. Using this trellis model and BP algorithm, we derive a new SISO MSDD for computing the APPs of the data symbols. The proposed BP-MSDD is a bidirectional message passing algorithm, which can makes use of all the signal dependences throughout the whole packet. Thus, it has better performance than the block independent MSDD. Then, we feed the outputs of BP-MSDD to the inputs of BP channel decoding, and vice versa, in an
iterative manner. Simulations illustrate the superiority of the proposed scheme over other existing schemes.

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