Inter-symbol Interference in High Data Rate UWB Communications Using Energy Detector Receivers

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***Abstract*— Inter-symbol interference (ISI) is known to be a major factor complicating the realization of high data rate ultrawideband (UWB) communications. In the literature, methods for suppressing ISI in UWB systems employing complex receivers exist. In this paper, considering the low cost requirement along with the need for high data rates, we propose a modified, on-off keying (OOK) based low complexity energy detector receiver capable of eliminating ISI. The presented receiver utilizes an ISI cancellation algorithm depending on decision feedback equalization (DFE) and it is advantageous in that it does not suffer from error propagation. The results obtained demonstrate a considerable gain in the symbol detection performance of the UWB system.** [1]

I. Introduction

Ultrawideband (UWB) is one of the latest wireless technologies and it promises extremely high data rates with considerably low cost circuitry. Because of these tempting features, UWB is considered a candidate for the wireless personal area networks (WPAN), whose range is up to 10 meters. For the channel models CM1 and CM2 in [1], which are appropriate for this range, the maximum excess delays (MED) are around 80 ns and 115 ns, respectively. Hence, at high data rates, some portion of the transmitted symbol energy unavoidably leaks into the following symbols, a fact which is known as inter-symbol interference (ISI). ISI is one of the major factors degrading the detection performance of UWB systems. Therefore, for a successful implementation of high data rate UWB communications, it is compulsory to suppress ISI.

In order to meet the requirement for high data rate, the UWB system has to employ a receiver that is also capable of handling ISI. Although RAKE receivers can provide a satisfying solution to this problem [2], [3], [4], their high complexity increases the cost dramatically. Hence, alternative transceiver designs are needed that have low computational and hardware complexity, while providing high data rates. Possible candidates are the non-coherent receivers such as the energy detector or the transmitted reference (TR) receiver.

Energy detector is a non-coherent approach for ultrawideband signal reception, where low complexity is achieved at the expense of partially degraded performance [5], [6]. As opposed to more complex RAKE receivers, estimation of individual pulse shapes, path amplitudes, and delays at each multipath component is not necessary for energy detectors. Moreover, energy detectors are less sensitive against synchronization errors [7], and are capable of collecting the energy from all the multipath components.

In this paper, we address the ISI issue in impulse radio UWB systems. We propose an energy detector based receiver that has high data rate capability through ISI cancellation. The ISI suppression algorithm of the receiver depends on the usage of a simplified decision feedback equalizer (DFE), which does not employ feed-forward filters, but only feedback filters. In spite of the fact that decision feedback equalizers are known to cause error propagation, an important feature of the proposed DFE equalizer along with the transceiver is that it does not have error propagation. The DFE equalizer requires some parameters to be measured. We will address the parameter estimation in energy detector receivers and develop a simple algorithm to estimate the signal energy leaking from one symbol into the following symbol. For this purpose, we propose to transmit a sequence of training symbols, which is generated in such a way that it enables measuring the signal energy contribution from the previous symbol. In section III, the amount of ISI effect is quantified and a performance evaluation of the UWB system in the presence of ISI is provided. Then, in section IV, the ISI cancellation algorithm is explained in detail and resulting gains are presented.

II. System Model

The impulse radio (IR) based UWB signal received for bit i in a multipath environment can be represented as

$$r_i(t) = \sum_{l=1}^{L} \gamma_l \omega_l(t) + n(t) \ , \tag{1}$$

where

$$\omega_l(t) = \begin{cases} b_i v_l\big(t-\tau_l-T_d\big) + r_i v_l\big(t-\tau_l\big), & \text{for } PAM \\ v_l\big(t-\tau_l-T_d-b_i\delta\big) + r_i v_l\big(t-\tau_l\big), & \text{for } PPM \end{cases}$$

L is the number of multipath components arriving at the receiver, l is the tap index, b_i is the ith transmitted bit, γ_l, $v_l(t)$ and τ_l are the fading coefficient, the received pulse shape, and the delay of the lth multipath component, respectively, δ is the duration between the two possible positions in pulse

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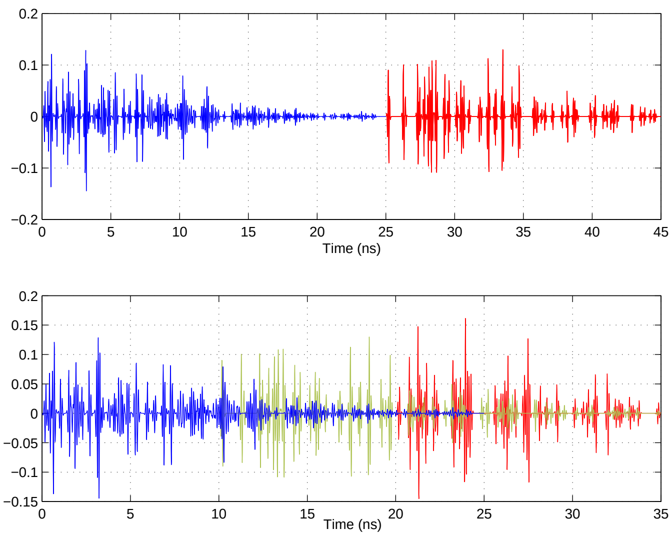

Fig. 1. a. The pulse repetition period (κ) greater than the maximum excess delay (D). b. $D > \kappa$, energy leaks from one symbol to the subsequent symbol.

position modulation (PPM), r_i has a binary value determining the existence of a reference pulse, and T_d is the delay between the reference and data in TR systems. In the case of an energy detector, both r_i and T_d become zero. The additive white Gaussian noise (AWGN) with double-sided noise spectral density $N_0/2$ is denoted by $n(t)$.

III. Effect of ISI and Receiver Model

In the impulse radio based ultrawideband communications, the transmitted UWB pulses go through a highly frequency selective channel and become dispersed in time. Let the maximum excess delay of the channel be denoted by D and the pulse repetition period by κ. In many works dealing with UWB, κ is assumed to be longer than D (illustrated in Fig. 1-a). However, in practical high data rate communications, the pulse repetition period is much shorter than the maximum excess delay (Fig. 1-b), i.e. $\kappa \ll D$, and this fact is going to be taken into account throughout this paper.

The time dispersiveness of the UWB pulse causes a considerable portion of the symbol energy to appear as a part of the following symbol, leading to inter-symbol interference. This problem is valid for all kind of transmission schemes, however, in this paper the focus is going to be on the energy detector using on-off keying (OOK), which is a specific case of pulse amplitude modulation (PAM).

To visualize the ISI effect, simulations are performed considering the different channel models in [1]. In the simulations, a fifth order derivative of the Gaussian pulse , which satisfies the FCC limitations regarding the transmission bandwidth, is used. The results obtained reveal that at a data rate of 100 Mbps, the average ratio of ISI to the symbol energy is 11.8% for CM1 and as high as 25.89% for CM2. In Fig. 2 and Fig. 3, the effect of ISI in both channel models for data rates up to 200 Mbps is demonstrated. The E_b/N_0 values used are 15 dB and 20 dB, respectively. At relatively low data rates such as 10 Mbps, the ISI effect is almost unnoticeable. However, as the data rate increases, ISI grows considerably. Towards 200 Mbps, the curves for 15 dB and 20 dB converge to the same level. The reason for this fact is that at high data rates, the effect of ISI almost totally dominates the noise effect.

In an energy detector, the following decision statistic is used to make a symbol detection by sensing if there is energy or not within the symbol interval

$$h_i = \int_{T_i} \Big[\sum_{l=1}^{L} \gamma_l b_i v(t-\tau_l) + n(t) \Big]^2 dt \ , \qquad (2)$$

where T_i is the integration window defined by synchronization and dump points (u,v). The symbol decision is performed by

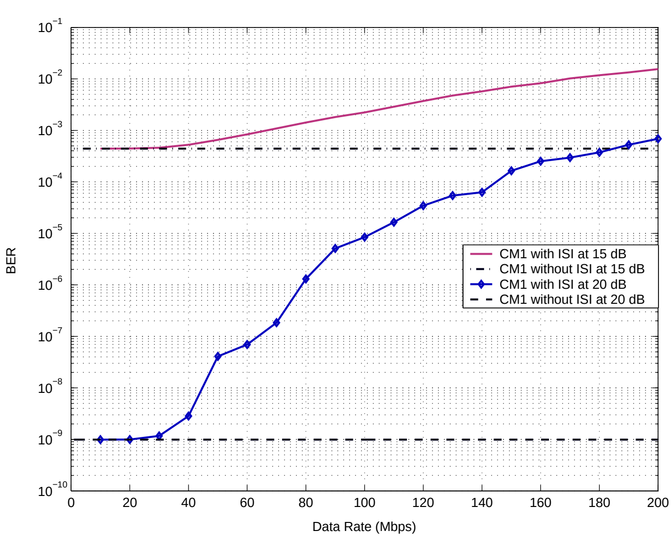

Fig. 2. BER vs. data rate for channel model CM1 at E_b/N_0 values of 15 dB and 20 dB.

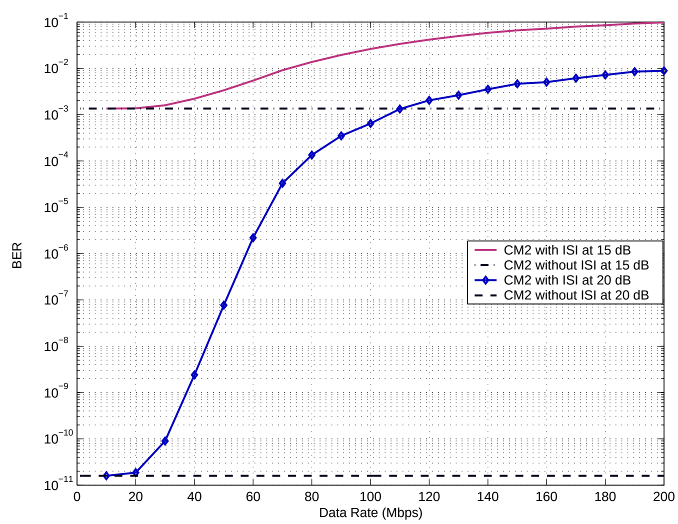

Fig. 3. BER vs. data rate for channel model CM2 at E_b/N_0 values of 15 dB and 20 dB.

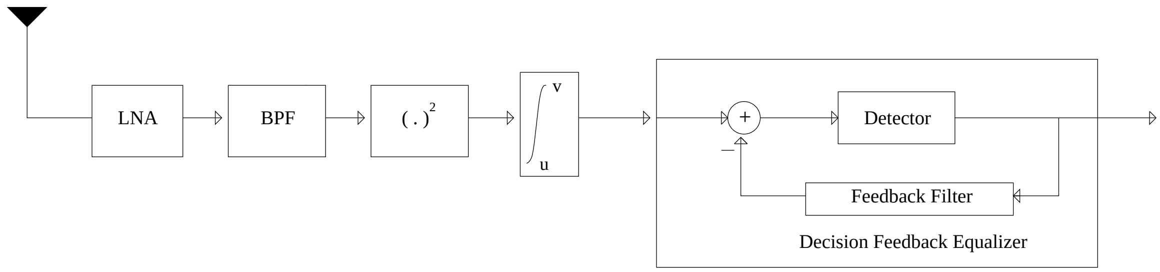

Fig. 4. Decision feedback equalization based ISI cancelling energy detector.

comparing h_i with a threshold ξ, $h_i \underset{0}{\overset{1}{\gtrless}} \xi$.

The proposed ISI cancelling energy detector (shown in Fig. 4) is implemented by taking the square of the received signal (by means of a square law device such as a Schottky diode operating in square-region), integrating it and passing it to a decision mechanism, where the symbol is determined. Inside the decision mechanism, the signal is processed in such a way that the effect of the leaking energy from the previous symbol is suppressed and the decision is made by comparing the remaining energy to a threshold.

IV. ISI Cancellation

In order to improve the detection performance of the UWB system, the effect of ISI has to be cancelled before a bit decision is made. In communication systems, decision feedback equalizers are commonly employed for this purpose [8]. The main idea behind decision feedback equalization is that once a data symbol has been detected, the interference it induces on the following symbols is estimated and subtracted out before the detection of these subsequent symbols [9].

The proposed energy detector makes use of a simplified DFE algorithm, which employs only feedback filters but no feed-forward filters. With the purpose that the current symbol is not affected by the following symbols (so that there is no need for feed-forward filters), the integration interval of the energy detector is adjusted in such a way that it does not capture any portion of the subsequent symbol. However, this fact brings about a limitation on the highest possible data rate. At very high data rates, the pulse repetition period falls far below the optimum integration interval, a fact, which substantially decreases the amount of energy obtained for a particular symbol. According to [10], where a detailed analysis about the optimum integration intervals is given, at 20 dB E_b/N_0, integrating the received signal for 10 ns in CM1 and for 20 ns in CM2 yields the highest detection performance. As a result, the data rates for these channel models can not be increased far beyond 100 Mbps and 50 Mbps, respectively.

In this section, we will assume that the received symbol energy has the form

$$E(i) = b_i E_d(i) + \sum_{j=1}^{n} b_{i-j} E_l(i-j) \ , \qquad (3)$$

where b_i and b_{i-j} are the symbol values, $E_d(i)$ is the energy of the current symbol, and $E_l(i-j)$ is the amount of leaking energy from the j^{th} previous symbol to the i^{th} symbol. From (3), it is obvious that for determining b_i correctly, the DFE requires the estimation of $E_l(i-j)$, which are the equalizer coefficients. In this paper, only the energy leaking from the immediately previous symbol $\big(E_l(i-1)\big)$ is considered, because this has the strongest effect on the current symbol, as long as the channel is not highly dispersive.

In order to estimate the DFE filter coefficients, which are positive real values, we propose to transmit sequences of training symbols between the packets of data symbols. During the training sequences, the channel is assumed to be non-varying, hence the filter coefficients are considered constant. To make these sequences mostly efficient, the inherent structure of OOK, which enables estimation of the filter coefficients, is utilized. A reasonable approach is transmitting a ’1’ followed by an array of ’0’s (shown in Fig. 5). After sending the ’1’, the energy obtained during the first ’0’ following ’1’ is measured. Since no signal is transmitted for a ’0’ in OOK, the detected energy is composed of the leaking energy from the previous symbol $\big(E_l(i-1)\big)$ and the AWGN energy induced by the channel. The amount of the leaking energy, which constitutes

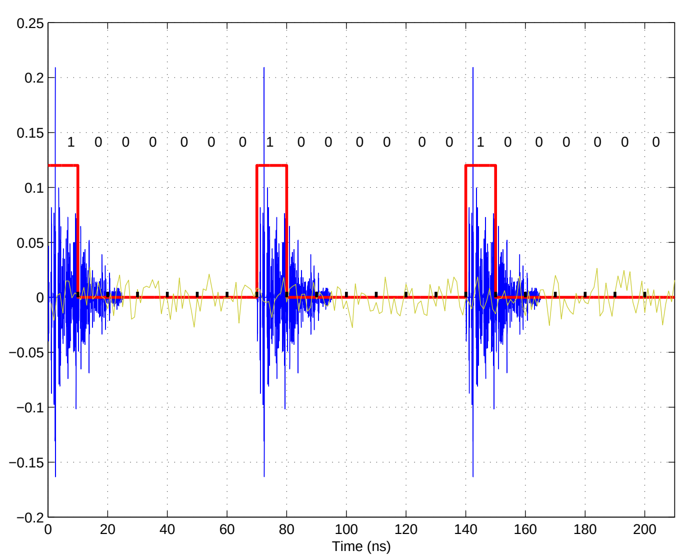

Fig. 5. Successive training sequences used for estimating the feedback filter coefficients.

ISI, can be found by subtracting the previously estimated noise energy from this composite energy. Since at high data rates it is possible that the energy of a symbol leaks even beyond the immediately following symbol, it is necessary to put a guard band of ’0’s following the first ’0’, on which the ISI is measured. It is also reasonable to transmit extra ’0’s for noise estimation. Using multiple training sequences successively, an average value for the leaking energy from the previous symbol, which yields the DFE coefficient, can be found. Then, during the data processing, every time when a ’1’ is detected, the DFE mechanism subtracts this DFE coefficient from the immediately following symbol energy and thus cancels the ISI effect.

The decision feedback equalizers are known to cause error propagation when processing the received data [11], [12]. In the case of OOK modulated UWB signals, however, due to the structure of on-off keying, this problem does not occur. Keeping in mind that after each ’1’ the leaking energy has to be removed from the next symbol, if b_i is ’0’ and it is mistakenly detected as ’1’, then the DFE coefficient is unnecessarily subtracted from the following symbol (b_{i+1}). If b_{i+1} is ’1’, this subtraction may cause it to be detected as ’0’. So, the error is propagated by one symbol in this case. If b_{i+1} is already ’0’, the error in b_i does not cause it to change. If, on the other hand, b_i is ’1’ and it is mistakenly detected as ’0’, no subtraction is done on b_{i+1}, therefore, no error related to DFE occurs. Obviously, the proposed algorithm has the advantage that an error arisen due to any reason is not forwarded by more than one subsequent symbol, hence there is no error propagation.

Simulations implementing ISI cancellation based on decision feedback equalization reveal that an important gain can be achieved with the proposed energy detector receiver. In Fig. 6, the bit error rates obtained at a data rate of 100 Mbps, with and without implementing the proposed ISI cancellation algorithm are compared for all four channel models.

V. Conclusion

In this paper, the inter-symbol interference problem in high data rate UWB systems employing OOK based energy detectors is investigated. The increasing negative effect of ISI on the system performance with increasing data rate is demonstrated. In order to overcome the ISI problem, a modified energy detector that has a built-in symbol decision mechanism based on decision feedback equalization is proposed. A simple but clever way of using training symbols with the purpose of estimating the decision feedback filter coefficients is introduced. It has been proven that the error propagation problem, which is generally observed in decision feedback equalizers, does not exist in the proposed approach. In the final section, the gains achievable with the proposed energy detector are exhibited. These gains turned out to be considerably high, verifying the necessity of ISI cancellation and showing the effectiveness of the proposed detector.

Although the focus of this paper is on cancelling ISI in UWB systems employing an energy detector, the proposed approach can easily be carried over to the other non-coherent UWB receivers such as the transmitted reference receiver.

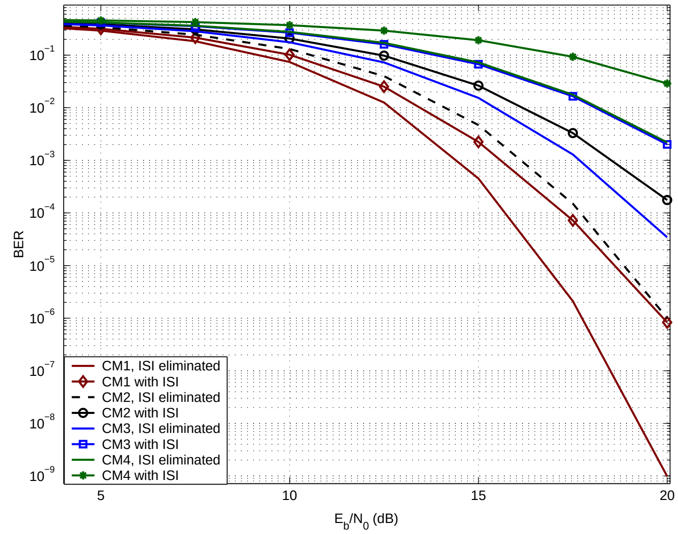

Fig. 6. Bit error rate vs. E_b/N_0 for different channel models before and after the ISI suppression.

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