Energy-Detection Based UWB Demodulator with a Supplementary Integration Block

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Abstract — In this paper it is investigated the non-coherent demodulation of the 2PPM modulated UWB signal, based on energy-detection. This type of demodulation leads to a simple receiver architecture, low power consumption and the benefit of multipath energy capture. However, this technique is very sensitive to noise and channel interference. To minimize this drawback, optimizations have been proposed with respect to the reduction of the integration windows size and bandwidth of input matched filter.

Instead of reducing the integration windows size, the adding of a second integration block is proposed. In this way, a similar effect is obtained by progressive accumulation of energy, the front-side useful signal having a better gain in comparison to later noise signal.

The simulations show an improvement in bit error rate performance relative to the basic method of energy-detection.

Index Terms — ultra-wideband communications, pulseposition modulation; non-coherent detection, ultra-wideband; non-coherent; energy detection; bit-error-rate.

I. INTRODUCTION

The future of wireless technology brings devices with superior efficiency and low cost feasibility. In the realm of UWB communications, the impulse radio technology is considered for applications where power consumption and cost are important constraints [8].

In last years, several works have been reported to develop IR-UWB transceivers. There are two ways of data demodulation schemes for IR-UWB system, coherent and non-coherent ones. The coherent transceiver is highly complex and contains the problem of precise timing synchronization between the transmitter and receiver. The non-coherent demodulation schemes have been proposed to avoid the need for complex synchronization blocks. The non-coherent transceiver is more attractive as a low-power low-complexity solution despite the drawback of being susceptible to noise and interference [2].

The UWB energy detector receiver offers a low cost analog front end and could be considered for medium/high data rate communications. For ultra-wideband (UWB) impulse radios, non-coherent energy detectors are motivated for their simple circuitry and effective capture of multipath energy. A major performance-degrading factor in energy detection is the noise floor, which is aggravated for lowduty-cycle UWB signals with a large time-bandwidth product [3]. For noise suppression, has been developed different techniques, regarding the optimization of the integration window length or weighted energy detection over multiple integration windows.

In this paper, it is proposed a double integration of the signal instant power, however using a single windows

integration time. For a certain multipath channel model, an optimal integration time is found. Simulations show that this supplementary integration of energy enhances the bit-errorperformance of conventional non-coherent energy detector.

II. THE 2PPM NONCOHERENT UWB SYSTEM MODEL

The 2PPM emitted UWB signal with average energy per bit E_b can be written as:

$$s(t) = \sum_{j=-\infty}^{\infty} \sqrt{E_b} w(t - jT_b - b_j T_b / 2)$$
(1)

where w(t) is a unit energy waveform with support in $[0, T_b/2]$ interval such as w(t) and $w(t-T_b/2)$ is time-orthogonal, T_b is the bit duration, split into two subintervals each of length $T_b/2$. Depending on the binary information $b_j \ \epsilon\{0, 1\}$, to be transmitted, the waveform w(t) is generated either at the time $j \cdot T_b$ or at $T_b/2$ seconds later.

The unit energy basis function w(t) needs to be ultra wide band, therefore to have a bandwidth of at least 500 MHz. In this paper, according to the IEEE 802.15.3a [1], we adopt w(t) as a fifth-order Gaussian pulse, with a duration of 0.6 ns, much smaller than T_b , and with a 2 GHz bandwidth.

After the propagation over the channel, the incoming signal at the receiver, if we take into account and the noise of the input LNA, has the expression:

$$r(t) = r_u(t) + n(t) \tag{2}$$

where $r_u(t)$ represent the useful signal and n(t) the unwanted added noise. The basic energy-detection receiver structure for the detection of 2PPM IR-UWB pulses is illustrated in Fig. 1.



Fig. 1. The basic 2PPM energy-detection receiver

The main block, in contrast to coherent demodulator, is the squaring device, which removes any phase/polarity. Follows an integrator that summarized the power of the signal, giving the total energy of the signal over the integration window time. A special feature of this method is the equal gain combining of the multipath arrivals, if the integration time is chosen larger that the delay spread of the channel.

To evaluate the transmitted data bit, the receiver will have

to measure and compare the energy received in two adjacent time periods, namely, in T_{slot1} and in T_{slot2} . The received signal is first applied to a matched filter (for example, a low pass filter) that limits the bandwidth of the noise. Next the output of the channel filter is fed into a square-law circuit and integrated, first over T_{slot1} and then over T_{slot2} . The results of integrations, i.e., the energies received in this two periods are estimated and stored by a sample-and-hold capacitor network for bit slicing. A relative compare is then performed on the voltages of the two capacitors and the decision circuit evaluate the received bit [4].

The decision variables $Z_{i, i \in \{0, 1\}}$ at the outputs of the integrators, for the frame corresponding to transmitted bit b_k have the expressions:

$$Z_{k,i} = \int_{t_0 + kT_b + i\Delta}^{t_0 + kT_b + i\Delta + T_i} r^2(t) dt$$
(3)

The binary decision at the receiver is based on two samples y_0 and y_1 of the variables Z_0 and Z_1 . If $y_0 \ge y_1$, the pulse was probably transmitted at the first position or, if $y_0 < y_1$, the pulse was probably transmitted $T_b/2$ seconds later.

According to the two orthogonal waveforms (or pulse positions), the a_k received bit, corresponding to the b_k transmitted bit, is :

$$a_{k} = \begin{cases} 0, if \ Z_{0} > Z_{1} \\ 1, if \ Z_{1} > Z_{0} \end{cases}$$
(4)

III. OPTIMIZATIONS OF THE ENERGY-DETECTION SCHEMES

Because in IR-UWB systems the duration of the pulses waveform is much less than bit duration T_b , the integration time should be matched to these parts of UWB signal that contains considerable bit energy. This special property of UWB-IR systems has a serious effect on the noise performance, namely, it strongly depends on the product of $B \cdot T_i$. Then, the performance, which is a measure of E_b/N_0 to achieve a certain bit-error-rate (BER), is strongly affected by the size of integration window time T_i [4].

One solution is to make the size of integration window smaller than the slot duration $T_b/2$, but still bigger enough than the spread of the channel, to enable the capture all of multipath arrival energy. The optimal values are then specifically depending of the model of the propagation channel adopted in various situations. But, in principle, the aim is to maximize the energy of the signal captured in left part of the integration period and to minimize the energy of the remaining signal, that is, in fact, only the noise. This optimization of the energy-detection method is known as *Single-Window Combining (SinW-C)*.

A better solution proposed has been based on the analysis of the properties of the propagation channel by its power delay profile. Therefore, the channel is composed by "L" clusters, either having its propagation parameters as the gain and the delay. The transfer function of the channel is then expressed as:

$$\sum_{l=0}^{L-1} |\alpha_l|^2 \delta(t - l/B)$$
(5)

The performance can be improved if the "observation"

window is divided into several weighted sub-windows [5]. To have equally spaced samples of the integrator output, we assume that each interval of size T_i is divided into a number of K sub-intervals, thus the integration time is now $T_{subi} = T_i/K$. Compared to the single-window method, the sampling rate is now increased by a factor K and the decision is based on K suitable values. This solution, named *Weighted Sub-Window Combining (WSubW-C)* may be used in order to avoid the optimization problem of the size of integration windows, but at the expense of a higher sampling rate or usage of several integrators [6].

A low-cost and simple solution proposed in this paper is based on a supplementary added integration block. The principle is to consider the ensemble of two integration blocks as an operator that makes a progressive (weighted) sum of the input values. The values added first are more accentuated, but the end values have a little effect on the final output of the double integrator block. This observations exactly results by applying the integration by parts rule:

$$\int_{0}^{T_{s}} \int_{0}^{t} r^{2}(u) du dt = \int_{0}^{T_{s}} (t - T_{s})' \int_{0}^{t} r^{2}(u) du dt$$

= $(t - T_{s})' \int_{0}^{t} r^{2}(u) du \Big|_{0}^{T_{s}} - \int_{0}^{T_{s}} (t - T_{s}) r^{2}(t) dt$ (6)
= $\int_{0}^{T_{s}} (T_{s} - t) r^{2}(t) dt$

In this way, the energy of the useful pulses of the signal, present at the beginning of the integration window time is added with a bigger gain factor; then, the multipath delayed pulses is taken in account with middle gain; on the last part, the remaining signal, consisting only in the noise, is added with a smaller gain. In fact the equal-gain combining arrival of the *SinW-C* method is substituted with a linear-descending gain combining, according to the gradually less favorable contribution of these arrivals over the noise to a correct estimation of the bit based on total collected energy.

The schematic block of the proposed receiver is presented in Fig. 2.



Fig. 2. The proposed double-integrator ED receiver

Obviously, the performance is improved over the basic demodulation method. But, in comparison of *SinW-C* method, our proposed scheme still has an improved performance. The sample time remains the same, and the optimal size of the window integration time may be bigger in this case, and therefore the integrator easier to implement.

IV. SIMULATIONS

Matlab Simulink was used to construct a simulation model of UWB systems, composed of three components: the UWB 2PPM transmitter, the AWGN or multipath propagation channel models, and non-coherent energy-based demodulator receiver. First, the basic scheme with one integrator was simulated and then, in a similar way, the new proposed demodulator with a supplementary integration block, as an extension of previous schematic.

The Simulink model for analyzing the performance of the proposed model is depicted in Fig. 3.



Fig. 3. Simulink model of UWB transmission system

The system parameters are chosen in order to respect the low-band UWB 3.1-5.1 GHz and to obtain a data rate of 10 Mbps. For simplicity, we don't consider here the effect of channel coding, therefore one information bit is represented by a one PPM modulated pulse, contained into a first or second half-subframe of a frame with a total duration of 100 ns.

The pulse waveform is the fifth derivative of Gaussian pulse with a form factor $\sigma=0.09$ ns, leading to an effective duration of $T_p=0.6$ ns and a center frequency of 4 GHz.

In Fig. 4 are illustrated the waveforms representing two bits of UWB signal in different points over the transmission way, in the case of a multipath propagation channel.



Fig. 4. Waveforms of signals over trasmission system

The first graphic represents the emitted 2PPM signal

corresponding to sequence of bits $\{1,0\}$; the graphics (b) and (c), the received signal after multipath propagation and with added AWGN noise ($E_b/N_o = 15 \ dB$), respectively. The graphics (d) and (e) represent the result of single and double integration blocks, respectively. These outputs are compared by the operation of subtraction and the result, sampled at the end of each frame, gives the decision about received information bit. From this final values, we can be observe that single-integrator demodulator receives the bits $\{0,0\}$, the first bit erroneously, but the double-integrator provides the correct bits $\{1,0\}$.

This pulse may be obtained based on the approximation pulse proposed in for third-order derivative Gaussian generator [9], together with the effect of the emitter and receiver bandpass filter. If we take into account the doublederivative effect of the emission and reception antennas, we can consider that the fifth-order derivative of Gaussian pulse is used in our simulation and it is a candidate to a practical implementation of a UWB transceivers.

The Simulink model is running at a sample time of 0.25 ns in accord to Nyquist sampling frequency for a considered signal with a bandwith of 2 GHz. The integration windows limits are determined by the "mask" blocks, permiting only specific samples of the frame not to be discarded. The tuning parameter T_{int} , can be varied from 0.5 ns (pulse duration) to maximum $T_{smax}=T_s/2=50$ ns (duration of the half-frame allocated for the modulated pulse).

V. PERFORMANCE EVALUATIONS

In order to compare the receiver structures described in the previous sections in terms of BER performance, we resume the theoretical limits for BER in the coherent and non-coherent case. Then, we simulated two variants of 2PPM UWB systems, one implemented with basic single integrator demodulator and another with our proposed double-integration demodulator, operating in an indoor environment. We make a parallel analysis and we find the optimal and specific integration times for both cases. As a result, we conclude that performance is improved in the case of the optimal double-integration demodulator.

A. Theoretical Performance in AWGN channel

We begin to study the performance of non-coherent energy-detection in the ideal case of a well known AWGN propagation channel, because an expression of BER may be deducted.

Compared to a rather hypothetical coherent receiver which employs a channel matched filter, the non-coherent detection is a suboptimal combining, leading to a performance loss, which increases with the product $B \cdot T_{int}$. If we assume that the whole bit energy E_b is contained within the integration interval T_{int} , and if we further assume that $B \cdot Tint$ is an integer N > I, the BER for 2PPM signal detection can now be estimated as [12]:

$$p_{b} = \frac{1}{2^{N}} \exp\left(-\frac{E_{b}}{2N_{0}}\right) \sum_{i=0}^{N-1} \frac{1}{2^{i}} L_{i}^{N-1} \left(-\frac{E_{b}}{2N_{0}}\right)$$

$$\approx Q\left(\frac{E_{b} / N_{0}}{\sqrt{2E_{b} / N_{0} + 2N}}\right)$$
(7)

where L_i is generalized Laguerre polynomial of order *i* and Q(.) is the Q-function.

The equation (7) may be simplified in particular cases, obtaining the results as in Table 1.

ENERGY-DETECTION	
Coherent	$Q\!\!\left(\!\sqrt{rac{E_{b}}{N_{0}}} ight)$
Non-Coherent (AWGN)	$\frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right)$
Non-Coherent (Multipath)	$\mathcal{Q}\!\!\left(\!\frac{E_{_{b}}/N_{_{0}}}{\sqrt{2E_{_{b}}/N_{_{0}}+2N}}\right)$

TABLE I. BER PEFORMANCE OF 2PPM

The exact formula may be used for the ideal AWGN channel, when we have optimal integration window over the pulse duration only. Therefore N=1 (may be neglected) and the formula becomes more simple.

The approximation formula may be used for large integration windows, needed to collect multiple timedispersed pulses as in the case of a multipath channel. The formula must be used carefully, because E_b represents the whole bit energy.

Then, we need to make a reasonable supposition that no inter symbol interference (ISI) occurs (which is the case if the channel excess delay is small compared to T_b and that the energy of the bit is contained in the integration windows T_{int} . Therefore, this formula is a superior limit for experimental results obtained in multipath simulations, that can't be precisely characterized.

In Fig. 5, we illustrate the theoretical dependencies of BER versus E_b/N_a , for the following situations: coherentdetection, non-coherent ideal detection (AWGN) and, for various multipath scenarios, three energy-detections with different integration window times optimized to combine the energy of $N=T_{int} \cdot B$ paths.



Fig. 5. Performance comparison of BER in four case of demodulation

In comparison to coherent detection, we observe a 1.2 dB degradation of the performance for non-coherent ideal case at $p_b=10^{-3}$. Also, the large integration window causes more loss of performance, and therefore this duration may be analyzed and optimized for each type of multipath channel in order to obtain a satisfactory result.

B. Optimizations and Performance in Multipath Channel.

In a previous section, non-coherent energy-detection in AWGN has been analyzed. Now we intend to incorporate multipath propagation, leading to energy dispersion at the input of the receiver. In this case, more propagation paths are resolvable. This happens if the product of the (baseband) signal bandwidth B and the excess delay of the channel is larger than 1. For example, with B = 2 GHz and an assumed excess delay of 50 ns, about 100 individual paths are resolvable in the time domain. We intend to collect the energy E_b of all these multipath arrivals (or of the most significant ones) without any exact channel knowledge.

Thus, the Saleh-Valenzuela multipath channel model [11] was used, which is adopted as a reference UWB channel by IEEE802.15.3a study group. Our investigations are intended for an UWB system operating in an indoor environment within a distance of range 0-4 m, using both CM1 and CM2 channel models. First, for these UWB systems, we need to find the optimal integration time for better detection. We choose an $E_b/N_o = 15 dB$ instance of quality of the signal at the input of receiver, and we tuned the T_{int} parameter and plotted the characteristic $BER(T_{int})$.

In Fig. (6) and (7) are presented these optimizations in the case of our two analyzed detection cases: with one and with two integrators and in two different types of channel models, CM1 and CM2, respectively.



Fig. 6. Optimizations of integration window size for CM1 channel





The CM1 channel has a direct line of sight (LOS), therefore first multipath component's energy is higher than subsequent multipath components. The mean excess delay time for this channel is 5 ns, and we find that for classic single-integrator detection an optimal windows integration size of 12 ns. For our proposed double-integration detection, an optimum is reached for Tint=18 ns. The graphics show that the peak of performance is superior in the case of double-integrator detection ($BER=4\cdot10^{-3}$) in comparison with single-integrator ($BER=6\cdot10^{-3}$).

The CM2 channel is of type Non-line-of-sight (NLOS), has a mean excess delay time of 10 ns, then the received signal presents more significant dispersed components. For this case, the optimal duration of energy-collection is 20 ns for single-integrator and 28 ns for double-integrator demodulator, respectively.

Next, with this two optimized ED demodulators, we simulate the UWB system for different E_b/N_o and plot the performance in terms of BER obtained. This analysis is made with the Monte-Carlo Simulink Bit Error Analize Tool (Bertool), for 10000 frames of same number of bits, with a total duration of 1 ms. At every 10 frames, the realisation of the stochastic channel is changed, so the result is a mean over the class of considered models. The diagrams *BER(EbNo)* is presented in Fig. (8) and (9) for indoor channel models CM1 and CM2, respectively.



Fig. 8. Performance comparison of the two optimal energy-detection schemes for CM1 channel



Fig. 9. Performance comparison of the two optimal energy-detection schemes for CM2 channel

In either of two situations, we can observe an improvement of performance of 1 to 1.5 dB if we use the detection based on double-integration, this difference being accentuated to medium to high signal-to-noise-ratios. The usual BER of 10^{-3} is obtained for E_b/N_o about 16.5 dB.

VI. CONCLUSION

The *Eb/N0* performance of non-coherent energy-detection of 2PPM UWB signal is strongly dependent on two parameters of demodulator: the position and the size of the integration window time. The position of integration window is related to synchronisation performance of the system, performed in the initial phase of communication.

The optimization of the size of the integration windows time has been studied, conducting to appropriate (and specific) values for various types of propagation channel or to a more complex method using multiple weighted integration windows and higher sampling rate.

We performed an analysis of the effect of a supplementary added integrator, with the aim to make a progressive accumulation of energy, having a similar effect of multiple integration windows with gradually decreasing weight. The simulations show a little improvement of BER in comparison with optimized single-integration method.

It is an interesting result that encourages the further studies of the property of integral operator in order to analogically process and improve the signal and to separate it from the noise, for this non-classical type of UWB signals.

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