Increasing the Performance of 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.**

An appropriate ultra-wideband multipath channel model such as IEEE 802.15.3a may be considered for this optimization process. Basic method uses a single integration window with a constant gain, capturing only significant useful power of the signal replicas presented in the front of the received signal, and neglecting later signal.

Instead of a rectangular integration window, it is proposed to use an integration window with a linear descending gain. This may be simply obtained by adding a supplementary integration block. In this way, the front-side useful signal power is integrated with a better gain in comparison with later, predominant noise, received signal.

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

***Index Terms*—ultra-wideband communications, pulse-position modulation; non-coherent detection; 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 [1].

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 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]. Generally, non-coherent receiver architectures include transmitted reference (TR), differential TR (DTR), and energy-detection (ED) schemes [3].

In the sequel we analyze the energy-detection receiver of binary pulse position modulated (2PPM) UWB signal, that offers a low cost analog front end and could be considered for medium to high data rate communication [4].

A major performance-degrading factor is the noise floor, which is aggravated for UWB signals with a large time-bandwidth product [5]. For noise suppression, different techniques have been developed, regarding the optimization of the integration window length or weighted energy detection over multiple integration windows.

As a new solution, it is proposed a double integration of the signal instantaneous power, however using a single window integration time. Simulations show that this supplementary integration of energy enhances the bit-error-performance of conventional non-coherent energy detector.

II. The 2PPM Noncoherent UWB System Model

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

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

where $w(t)$ is a unit energy waveform with support in $[0,\ T_b/2]$ interval, such as $w(t)$ and $w(t-T_b/2)$ are time-orthogonal, T_b is the bit duration, split into two subintervals each of length $T_b/2$. Depending on the binary information $b_j \in \{0,1\}$, 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, we adopt $w(t)$ as a fifth-order Gaussian pulse, with a duration of 0.6 ns, and with a 2 GHz bandwidth [6].

After the propagation over the channel, the incoming signal at the receiver, has the expression:

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

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

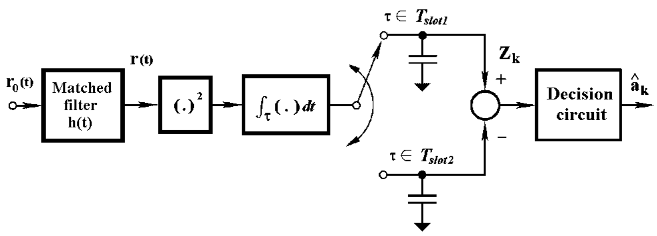

Figure 1. The basic 2PPM energy-detection receiver

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The main block, in contrast to coherent demodulator, is the squaring device, which removes any phase/polarity [7]. It is followed by 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 evaluates the received bit [8].

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

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

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 $y_0 \geq y_1$, 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 :

$$a_k = \begin{cases} 0, \text{ if } Z_0 > Z_1 \\ 1, \text{ if } Z_1 > Z_0 \end{cases} \tag{4}$$

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 $B \cdot T_i$ product. 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 [9].

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:

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

The performance can be improved if the "observation" window is divided into several weighted sub-windows [10]. 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.

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 time integrated, then 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:

$$\begin{aligned} &\int_0^{T_s}\int_0^t r^2(u)dudt = \int_0^{T_s}(t-T_s)'\int_0^t r^2(u)dudt \\ &= (t-T_s)'\int_0^t r^2(u)du\Big|_0^{T_s} - \int_0^{T_s}(t-T_s)r^2(t)dt \\ &= \int_0^{T_s}(T_s - t)r^2(t)dt \end{aligned} \tag{6}$$

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 are taken in account with middle gain; on the last part, the remaining signal, consisting only of 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.

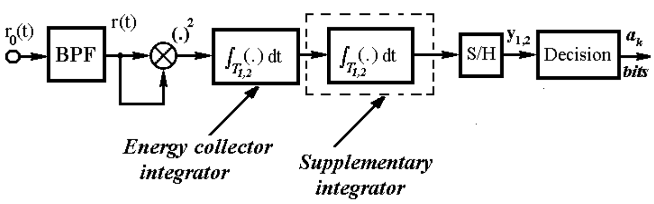

Figure 2. The proposed double-integrator ED receiver

In comparison of *SinW-C* method, our proposed scheme 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 [11]-[12]. 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.

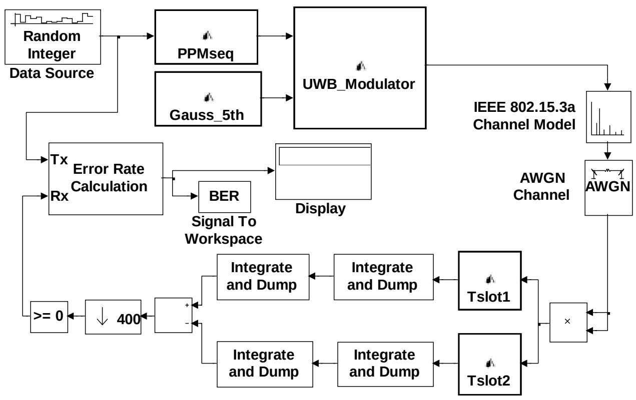

Figure 3. Simulink model of UWB transmission system

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.

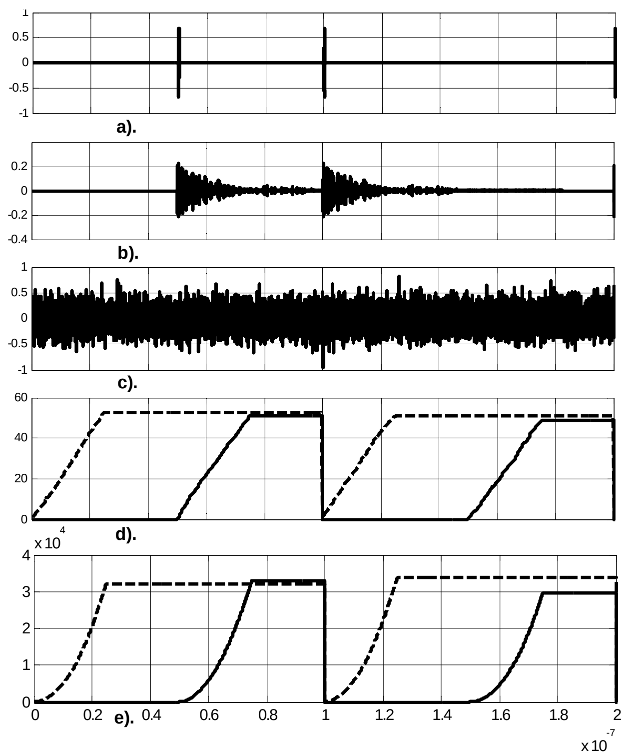

Figure 4. Waveforms of signals over trasmission system

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}*.

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 [13]. For simplicity, we don't consider here the effect of channel coding, therefore one information bit is represented by one PPM modulated pulse, contained into the 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 [14]-[15].

The Simulink model is run 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 EVALUATION

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 $B \cdot T_{int}$ [16] . 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, $N>1$, the BER for 2PPM signal detection can now be estimated as [17]-[18]:

$$p_b = \frac{1}{2^N} exp\left(-\frac{E_b}{2N_0}\right)\sum_{i=0}^{N-1}\frac{1}{2^i}L_i^{N-1}\left(-\frac{E_b}{2N_0}\right) \approx Q\left(\frac{E_b/N_0}{\sqrt{2E_b/N_0+2N}}\right) \quad (7)$$

where L_i is the generalized Laguerre polynomial of i^{th} order and $Q(.)$ is the Q-function.

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

TABLE I. BER PEFORMANCE OF 2PPM ENERGY-DETECTION

Coherent	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$
Non-Coherent (AWGN)	$\frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right)$
Non-Coherent (Multipath)	$Q\left(\frac{E_b/N_0}{\sqrt{2E_b/N_0+2N}}\right)$

The exact formula may be used for the ideal AWGN channel, when we have optimal integration window over the pulse duration only. The approximation formula may be used for large integration windows, needed to collect multiple time-dispersed pulses as in the case of a multipath channel. The formula must be used carefully, because E_b represents the whole bit energy [16]. Then, we need to make a reasonable supposition that no inter symbol interference (ISI) occurs and that the energy of the bit is contained in the integration windows T_{int}. In Fig. 5, we illustrate the theoretical dependencies of BER versus E_b/N_o, for the following situations: coherent detection, 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.

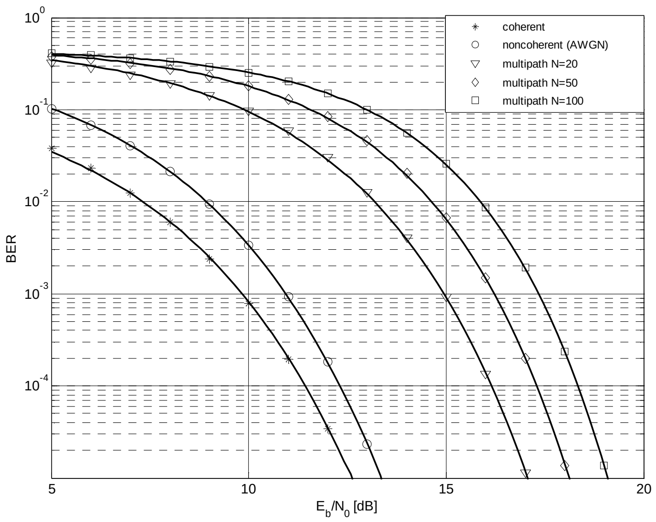

Figure 5. Performance comparison of BER in four case of demodulation

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 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 was used, which is adopted as a reference UWB channel by IEEE802.15.3a study group [19]-[20]-[21].

Our investigations are intended for an UWB system operating in an indoor environment, using CM1 and CM2 channel models within a distance of range 0-4 m and CM3 and CM4 for a range 4-10 m, respectively. First, for these UWB systems, we need to find the optimal integration time for better detection. We choose an $E_b/N_o=15dB$ 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.

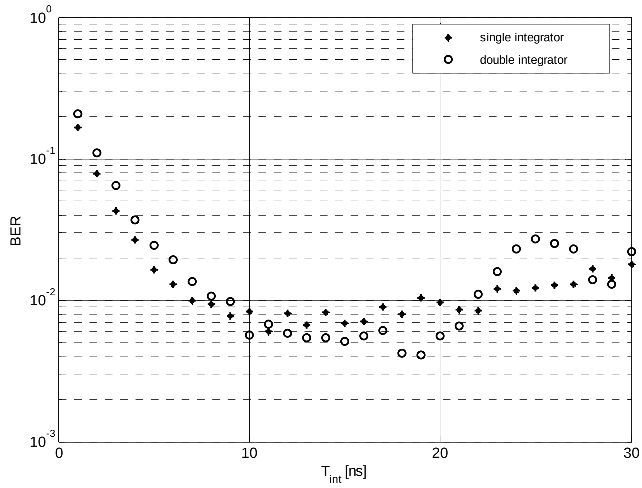

Figure 6. Optimizations of integration window size for CM1 channel

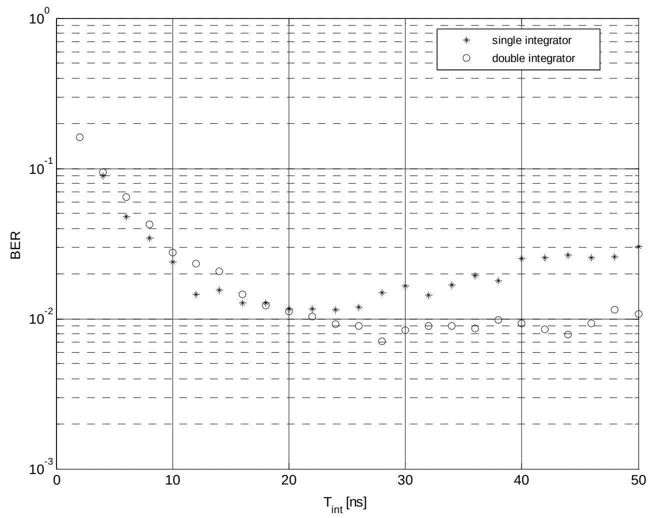

Figure 7. Optimizations of integration windows size for CM2 channel

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* [22]-[23]. 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 ($BER=4\cdot 10^{-3}$) in comparison with single-integrator ($BER=6\cdot 10^{-3}$).

The CM2 channel is of type Non-line-of-sight (NLOS) and 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.

The CM3 and CM4 channels are of Non-line-of-sight (NLOS)- type, for a range of 4-10 m and the received signal presents more significant dispersed components. This implies larger optimal integration window, the optimization process being illustrated in Fig.8.

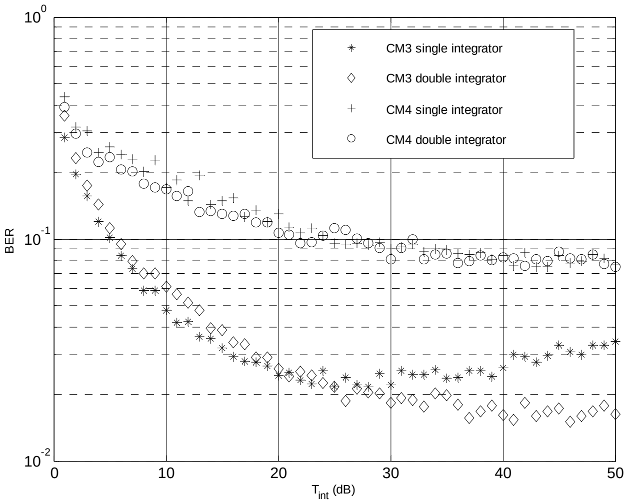

Figure 8. Optimizations of integration window size for CM3 and CM4 channel

The parameters of IEEE 802.15.3a wireless channel models and corresponding optimal size of integration windows are synthesized in Table II [24].

TABLE II. CHANNEL MODELS PARAMETERS AND OPTIMAL WINDOW SIZE

Model Parameter	CM1 LOS 0-4 m	CM2 NLOS 0-4m	CM3 NLOS 4-10 m	CM4 NLOS 4-10 m
τ_m [ns] (mean excess delay)	5.0	9.9	15.9	30.1
τ_{rms} [ns] (rms delay spread)	5	8	15	25
$NP_{10dB]}$(number of paths within 10 dB of the strongest path)	12.5	15.3	24.9	41.2
NP (85%) (number of paths that capture 85% of channel energy	20.8	33.9	64.7	123.3
Optimum single integration interval	12	20	24	42
Optimum double integration interval	18	28	45	50

C. Performance Comparison

Next, with these two types of optimized ED demodulators, single and double integration, respectively, we simulate the UWB system for different E_b/N_o values and plot the performance in terms of obtained BER [25]. 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. *Bertool* has also implemented an interpolation algorithm of simulation values, providing the continuous representation curves [26].

For indoor channel CM1 and CM2, the diagrams *BER(Eb/No)* are presented in Fig. (9) and (10), respectively.

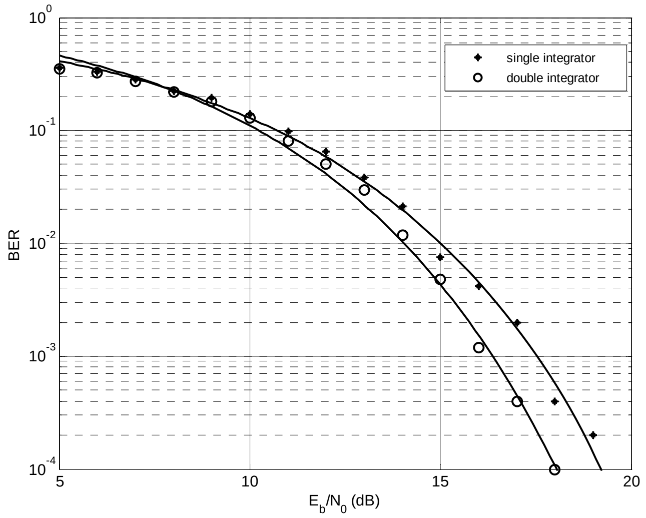

Figure 9. Performance comparison of two optimal energy-detection schemes for CM1 channel

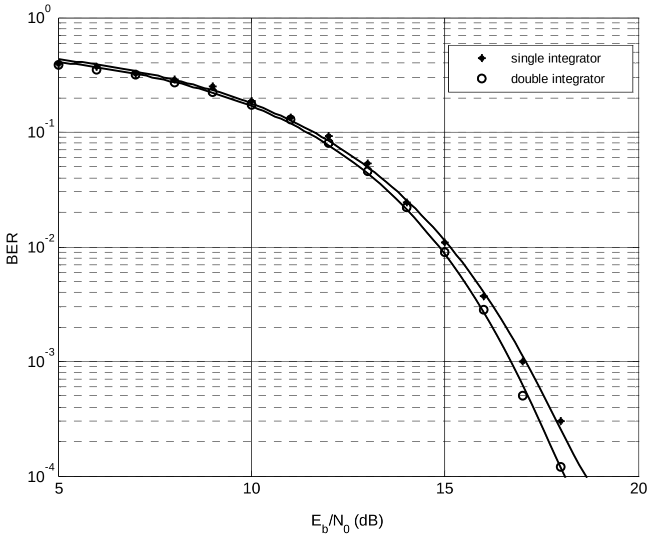

Figure 10. Performance comparison of two optimal energy-detection schemes for CM2 channel

In either case of CM1 or CM2 channel, 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.

The performance is also improved for more dispersed CM3 channel with 0.5 dB. In the case of CM4 channel, with strong delayed components, and consequently with a larger integration window time, about the size of entire subframe, the BER is the same in either case of single or double integration, as we observe in Fig. 11.

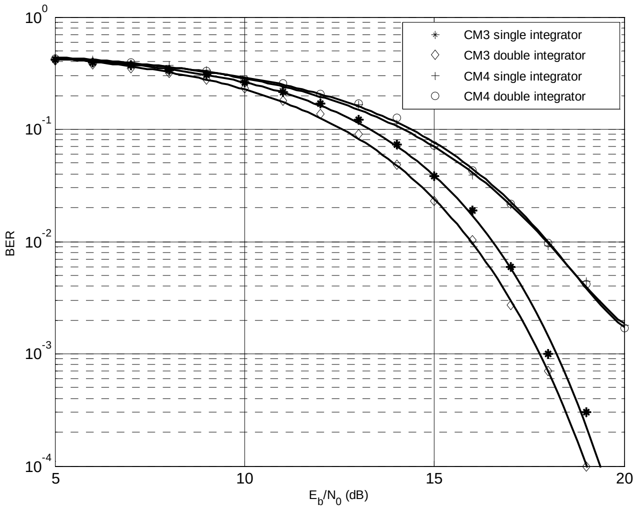

Figure 11. Performance comparison of two optimal energy-detection schemes for CM3 and CM4 channel

VI. Conclusions

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. In order to obtain a satisfactory performance for the basic energy-detection method, the size of the integration windows may be optimized for each type of multipath propagation channel. Another more complex method uses weighted energy detection over multiple integration windows, but at the expense of a higher sampling rate and/or usage of several integrators.

It is proposed an adaptation of basic energy-detection scheme by adding a supplementary integrator block. The proposed double integrator makes a progressive accumulation of energy, having a similar effect of multiple integration windows with gradually decreasing weight.

The simulations performed in Matlab/Simulink show a small but worth taking into consideration improvement of BER in comparison with optimized single-integration method in the case of IEEE802.15.3a CM1, CM2 and CM3 wireless channels and the same performance in the case of strong multipath CM4 channel.

The basic schematic is easily modified to obtain this new demodulator and can be used for a low-cost, low-power-consumption and medium data rate UWB receiver. It is also an interesting theoretical result that encourages further studies of the property of multiple 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 signal.

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