Performance Evaluation of Coded UWB-IR on Multipath Fading Channels

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***Abstract*— In most research on error correction coding for UWB techniques, the channel is assumed to be Gaussian, whereas the multipath case is neglected. In this paper, we evaluate the performance of a realistic and feasible UWB-IR system in a severe multipath environment. We model the nonlinearities introduced by UWB antennas, by using their real characteristics obtained through the measurements. We present a general coding-modulation scheme for UWB communications and focus on two particular cases, namely, one using superorthogonal convolutional coding, and the other based on simple UWB frame repetition. Our theoretical results, confirmed by simulations, show that superorthogonal convolutional coding provides a more effective way of protection against errors than simple frame repetition.**

***Index Terms*— Ultra-wideband, channel coding, frame repetition, multipath.**

I. Introduction

Ultra-wideband Impulse Radio (UWB-IR) has several unique characteristics that make it a promising candidate for future wireless communications. Exceptionally low transmission power and very large available bandwidth enable a UWB system to co-exist with narrowband systems. The large bandwidth occupied by UWB systems allows for high data rate transmission. However, the interference issues pose restrictions on the maximum data rate. One possible solution to ensure a desired data rate and simultaneously maintain a certain performance level is to apply channel coding. Although several channel coding schemes have already been proposed [1], [2], [3], research into their performance under realistic UWB channel conditions is limited. Such performance evaluation is of great importance, since the investigations up to now, for instance in [1], [3], have been limited to the AWGN case, which does not correspond to the conditions in a typical indoor environment.

The goal of this paper is to evaluate the performance of UWB-IR systems incorporating superorthogonal convolutional (SOC) coding or a frame repetition scheme in the presence of severe multipath. The investigated UWB-IR system employs a differential autocorrelation receiver with a realistic and accurate UWB channel model. The channel model used in our simulations is a modified Saleh-Valenzuela model [4] that has been recently proposed by the IEEE 802.15.3a channel modeling subcommittee for the evaluation of the UWB physical layer submissions. This model is based on measurements spanning the frequency spectrum from 2 to 8 GHz. In this model, the path resolution time equals 0.167 ns, enabling reliable estimation of the real UWB channel behavior.

We evaluate the performance of the UWB-IR system using theoretical analysis as well as Monte Carlo simulations. For the case of a multipath fading channel, both line-of-sight (LOS) and non-line-of-sight (NLOS) environments are considered. Our results show that the performance of the UWB-IR system can be significantly enhanced by the use of SOC coding instead of the frame repetition scheme, without costs in terms of additional bandwidth expansion.

This paper is organized as follows. Section II describes the structure of the considered UWB-IR system with insight into modulation format, pulse shaping, channel model, and receiver architecture. Furthermore, principles of the proposed coding-modulation scheme are given in detail. Section III focuses on the performance evaluation of the considered UWB-IR system by means of theoretical and numerical analysis. Finally, Section IV presents conclusions.

II. System Model

A. General Coding-Modulation Scheme

The proposed general coding-modulation scheme for a UWB-IR technique is depicted in Figure 1. Every packet consists of a number of information bits, each of duration T_b. A selected channel coding scheme is applied on k information bits, resulting in n output code symbols. Every code symbol is then represented by N_f UWB frames, each of duration T_f. Every frame consists of one pulse that is pseudorandomly assigned to one of N_p time slots. In this paper, we consider a single user scenario. We focus on two particular cases of the general coding-modulation scheme, one further referred to as a UWB-IR system with a SOC code, for which $k = 1, n > 1$, and $N_f = 1$, and the other, further referred to as a UWB-IR system with frame repetition, in which there is no coding scheme applied, i.e., $k = n = 1$ and $N_f > 1$. In order to allow a fair comparison between the two schemes, we choose

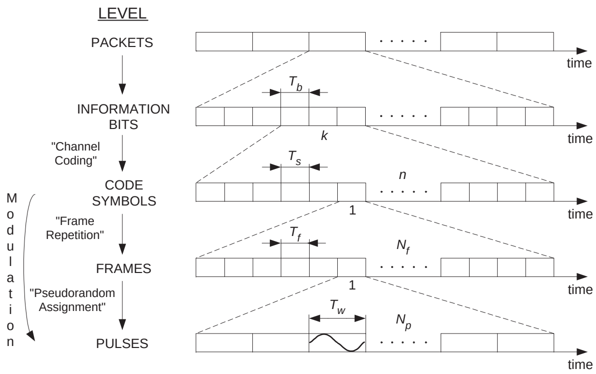

Fig. 1. Diagram showing a general coding-modulation scheme in a UWB-IR system.

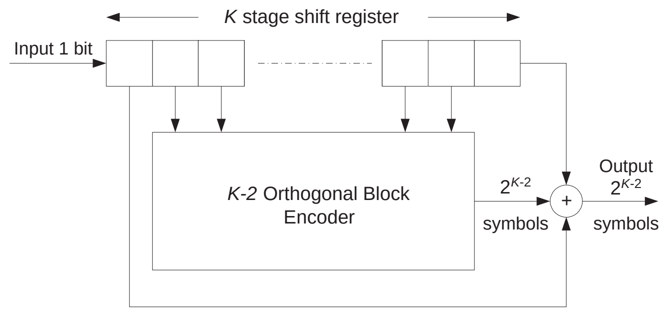

Fig. 2. Diagram showing a superorthogonal convolutional encoder architecture.

the n of the SOC code equal to the N_f of the frame repetition scheme. In this way, an equal number of transmitted pulses per information bit is guaranteed.

B. SOC Coding

In the UWB-IR system with the SOC code, a data information bit is encoded by the SOC encoder with code rate of $R = 1/n$, where $n = 2^{K-2}$ and K is the constraint length. The SOC encoder consists of a K-stage shift register, a bit orthogonal block encoder, and a modulo-2 adder with 3 inputs, as it is shown in Figure 2. The block encoder is a Hadamard-Walsh encoder with length $K - 2$. The decoding process is performed with the use of the Viterbi algorithm with 2^{K-1} states. The branch metrics are calculated according to the soft output of the differential autocorrelation receiver. An important feature of the SOC decoder is that processing complexity of the decoder grows only linearly with K, making the decoder feasible even for high values of K [5].

C. Modulation Format

We consider a differential autocorrelation modulation format with the following set of signal waveforms [6]: $S = \{s_0(t) = \ s(t),\ s_1(t) = -s(t)\}$, where $s(t)$ is defined as

$$s(t) = \sum_{j=0}^{N_f-1} w(t - jT_f - c_j T_{w)}, \quad 0 \leq t < T_s, \qquad (1)$$

where $w(t)$ is the Gaussian monocycle, N_f is the number of pulses transmitted per code symbol, and T_f is the frame time, also known as the average pulse repetition time. The term c_jT_w determines the position of the pulse within a frame and T_w denotes the pulse duration. The pseudorandom code sequence $c_0, \ \ldots, \ c_{N_f-1}$ assigning the pulse within the frame is fixed for every packet and generated according to the uniform distribution in the range $0 \leq c_j \leq N_p - 1$. As in [6], we call the transmission of a logical code symbol ”1” as H_1 and the transmission of a logical code symbol ”0” as H_0. When H_0 is true, the transmitter generates the same signal waveform as transmitted in the previous symbol time. Conversely, when H_1 is true, the transmitter switches to the antipodal signal waveform.

D. Pulse Shape

We model the transmitted pulse as a distorted Gaussian monocycle. The Gaussian monocycle is the first derivative of the Gaussian pulse and is given by

$$w(t) = \frac{2At}{\sigma^2} e^{-(\frac{t}{\sigma})^2}, \qquad (2)$$

where A is the amplitude and σ is the temporal width parameter. The practical advantage of the Gaussian monocycle, in comparison to the Gaussian pulse, is that it does not contain a DC component, allowing for simplified transmitter architecture. In order to characterize the UWB-IR system as accurate as possible, we model distortions introduced by a bandpass filter and amplifier by a third-order passband Chebyshev filter with the cutoff frequencies $f_1 = 2$ GHz and $f_2 = 8$ GHz, on which the magnitude response of the filter equals -0.2 dB. In Figure 3, the transfer function of this filter is denoted as $H_2(f)$. Moreover, we model the effect of the transmitter and receiver antennas on the pulse shape, by employing the data collected in [7]. In Figure 3, the transfer function of the antenna is denoted as $H_1(f)$. The width of the transmitted pulse T_w corresponds to the channel model time resolution and equals $T_w \cong 0.167$ ns. The original and modeled received pulses are depicted in Figure 4.

E. UWB Channel Model

Since the performance analysis of a UWB-IR system is based on statistics of the channel, we select a model providing an accurate description of the real UWB channel conditions. The chosen channel model was developed at Intel [4] and is a modified Saleh-Velenzuela (S-V) model. The main difference is that instead of a Rayleigh probability density function (p.d.f), the Intel model employs a lognormal p.d.f. for the fading channel coefficients. The impulse response is given by [4]

$$h(t) = \sum_{l=1}^{L} \sum_{m=1}^{M} \alpha_{m,l} \delta \left(t - T_l - \tau_{m,l} \right), \qquad (3)$$

where M is the number of paths within a cluster, L is the number of clusters, $\alpha_{m,l}$ is the multipath gain coefficient, T_l is the delay of the l-th cluster, and $\tau_{m,l}$ is the delay of the

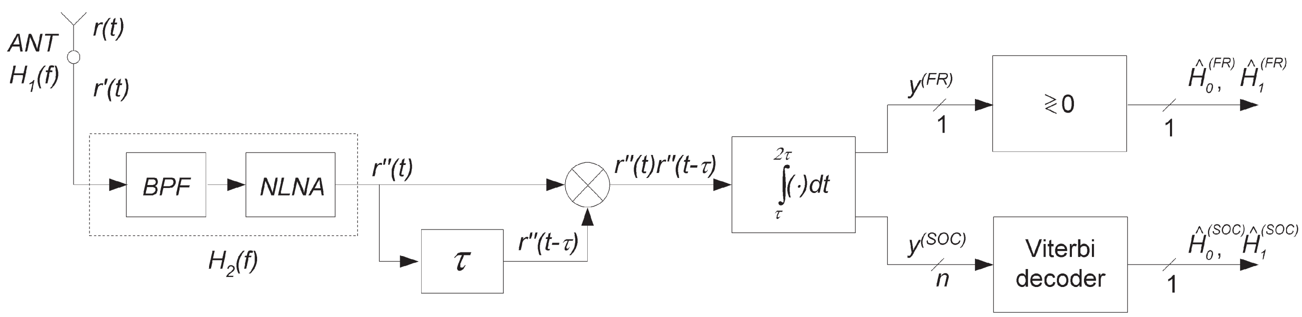

Fig. 3. Diagram showing the modeled UWB-IR receiver architecture.

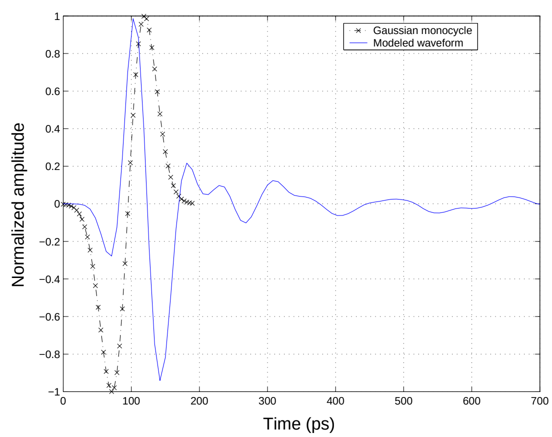

Fig. 4. The Gaussian monocycle and the modeled received waveform.

m-th multipath component relative to the l-th cluster arrival time T_l. The multipath channel coefficients are defined as follows: $\alpha_{m,l} = p_{m,l}\beta_{m,l}$, where $p_{m,l}$ denotes the sign of the coefficient and is equally likely to take values of ± 1, and $\beta_{m,l}$ is the lognormal fading term where $20\log(\beta_{m,l})$ follows a normal distribution. The inter-cluster and inter-path arrival times are exponentially distributed. The main characteristics of the model are RMS delay spreads and mean number of significant paths ranging from 5-25 ns and 20-120, respectively. Table I shows the set of parameters used in our model, as suggested in [4], for LOS and NLOS environments. The parameter NP_{10dB} denotes the number of significant paths that cross a 10 dB threshold.

F. Receiver Architecture

A simplified block diagram of the modeled UWB-IR receiver is shown in Figure 3. The input to the receiver is a signal $r(t)$. After passage through an antenna, the signal $r'(t)$ feeds a bandpass filter, and then a nonlinear amplifier. Next, a resulting signal $r''(t)$ is directed to a differential autocorrelator that correlates the signal with its symbol-delayed version. Depending on the coding scheme used, the results of correlation are directed to a threshold detector or a Viterbi decoder.

Receivers that are based on aurocorrelator are feasible and have numerous implementation advantages compared to other

TABLE I
CHANNEL CHARACTERISTICS

Environment	LOS	NLOS
RMS Delay Spread (ns)	9	15
NP_{10dB}	7	35

types of receivers including, for instance, RAKE receivers. Such receivers do not require a priori knowledge of the pulse to correlate and are less susceptible to jitter on the receiver clock. However, the price for all of these advantages is that BER performance is worse than that of the system employing the RAKE receiver. When H_0 is true, the received waveform can be expressed as [6]

$$H_0 : r(t) = (s_m(t) + s_m(t - T_s)) * h(t) + n(t), \quad (4)$$

whereas when H_1 is true, the received waveform is

$$H_1 : r(t) = (s_m(t) + s_n(t - T_s)) * h(t) + n(t), \quad (5)$$

where $m = 0, 1$, $n = (m + 1)\text{mod } 2$, $0 < t \leq 2T_s$, $n(t)$ is zero mean additive white Gaussian noise, and $*$ denotes the convolution. The autocorrelator output is given by

$$y = \int_{T_s}^{2T_s} r(t)r(t - T_s)dt. \quad (6)$$

III. PERFORMANCE EVALUATION

We compare the performance of the UWB-IR system incorporating superorthogonal convolutional coding with the performance of the UWB-IR system with frame repetition. The data rates of both systems are the same and the bandwidth expansion introduced by SOC coding and the frame repetition scheme is equal. We will show that superorthogonal convolutional coding provides significant coding gain in comparison with the simple frame repetition scheme. Table II shows the parameters of the considered UWB-IR system models.

A. Bounds on Bit Error Probabilities on AWGN Channel

The upper bound on the bit error probability of the UWB-IR system with the superorthogonal convolutional code is derived

TABLE II
SIMULATION PARAMETERS

Bandwidth		$B = 6$ GHz
Modulation		Differential Autocorrelation
Pulse Width		$T_w \simeq 0.167$ ns
Bit Rate		$R_b = 125$ Mbps
Processing Gain		$G_p = 48$
SOC Channel Coding	Coding Scheme	SOC
	Constraint Length	$K = 4, 5$
	Code Rate	$R = 1/4, 1/8$
	Decoding Algorithm	Soft-Input Viterbi Algorithm
Frame Repetition	Coding Scheme	None
	Number of Frame Repet.	$N_f = 4, 8$
Number of Pulse Positions		$N_p = 12, 6$
Channel Model		AWGN, LOS, NLOS

from the graph generating function of the code that is given by [5]

$$T_{SOC}(W,\beta) = \frac{\beta W^{K+2}(1-W)}{1-W[1+\beta(1+W^{K-3}-2W^{K-2})]}, \quad (7)$$

where $W = Z^{K-3}$. Expanding the above expression we get a polynomial in which the exponent of W gives the path weight and the exponent of β gives the path length, that is, the number of state transitions associated with the path. The parameter β denotes the information error weight. The parameter Z can be calculated from the Bhattacharyya bound as

$$Z = \int_{-\infty}^{\infty} \sqrt{p_0(y)p_1(y)}dy, \quad (8)$$

where $p_0(y)$ and $p_1(y)$ are the density functions of the receiver/channel output conditioned on the input symbol being 0 and 1, respectively. The upper bound on the bit error probability of the UWB-IR system is expressed as

$$P_b < \left.\frac{\partial T_{SOC}(W,\beta)}{\partial \beta}\right|_{\beta=1} = \frac{W^{K+2}}{(1-2W)^2}\left(\frac{1-W}{1-W^{K-2}}\right)^2. \quad (9)$$

For a Gaussian channel, the parameter W can be calculated as $W = \exp(-\gamma)$, where γ denotes the signal-to-noise ratio at the input of the SOC decoder. Since the relationship binding the input and output signal-to-noise ratio of the differential autocorrelation receiver for the Gaussian monocycle is compound, for simplicity, as in [6], we consider a rectangular monocycle waveform having

$$\gamma \cong \frac{G_p \gamma_{in}}{1+(2\gamma_{in})^{-1}}, \quad (10)$$

where γ_{in} can be calculated from

$$\gamma_{in} = \frac{E_b}{N_0} G_p^{-1}. \quad (11)$$

The parameter G_p denotes the processing gain of the UWB-IR system and is defined as

$$G_p = \frac{B}{R_b} = BN_fN_pT_w\frac{n}{k}, \quad (12)$$

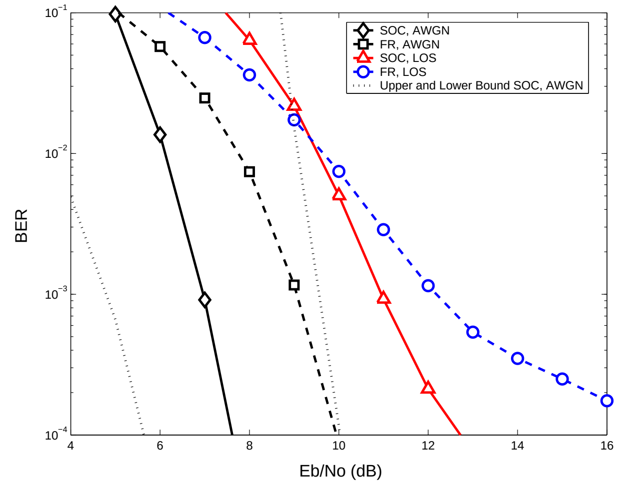

Fig. 5. BER performance of the UWB-IR systems with superorthogonal convolutional (SOC) coding and frame-repetition (FR) for $N_f = 8$, $N_p = 6$, $K = 5$ in AWGN and LOS environments.

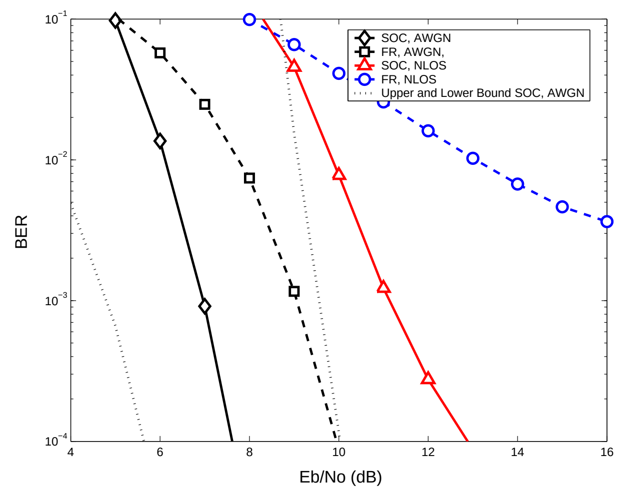

Fig. 6. BER performance of the UWB-IR systems with superorthogonal convolutional (SOC) coding and frame-repetition (FR) for $N_f = 8$, $N_p = 6$, $K = 5$ in AWGN and NLOS environments.

where B is the bandwidth and R_b is the bit rate. From (7) we can also compute free distance of the SOC code with the constraint length K as $d_f^{(SOC)} = 2^{K-3}(K+2)$. Comparing this value with the free distance of the simple frame repetition scheme $d_f^{(FR)} = 2^{K-2}$, it can be easily observed that SOC coding enables substantially better performance in comparison to frame repetition.

The lower bound on the bit error probability of the UWB-IR system incorporating the SOC code can be calculated as [1]

$$P_b \geq Q\left(\left(\frac{\mu^2}{\sigma^2}d_f\right)^{1/2}\right), \quad (13)$$

where μ and σ^2 are the mean and the variance of the autocorrelation receiver output conditioned on the input symbol

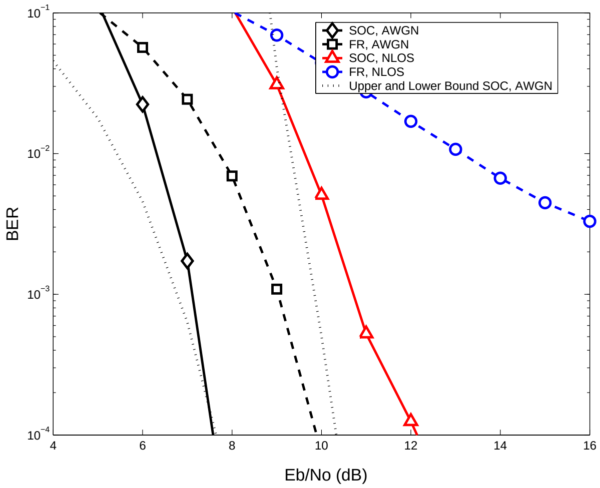

Fig. 7. BER performance of the UWB-IR systems with superorthogonal convolutional (SOC) coding and frame-repetition (FR) for $N_f = 4$, $N_p = 12$, $K = 4$ in AWGN and NLOS environments.

being zero. In Figures 5-7 the lower and upper bounds are represented as dotted lines without the markers.

B. Simulation Results

Apart from the theoretical analysis, we evaluate the performance of the considered UWB-IR systems using Monte Carlo simulations. The BER performance is examined using 40 channel realizations and 2000 bits in every packet. Our assumption is that the channel is invariant during the duration of a single data packet, and the synchronization is ideal. Figure 5 illustrates a comparison between the BER performance of the UWB-IR systems incorporating the superorthogonal convolutional code or the frame repetition scheme in two environments: AWGN and LOS. As can be seen from Figure 5, the performance of the UWB-IR system in a LOS environment is noticeably worse than that in AWGN. The difference in the bit energy between the UWB-IR systems incorporating the SOC code with $K = 5$ on a BER $= 10^{-3}$ level, for AWGN and the case of LOS, equals circa 4 dB. Comparing the performance of the UWB-IR systems based on the SOC code and frame repetition in a LOS environment only, we observe the reduction of 1 dB of the bit energy on BER $= 10^{-3}$ level that is introduced by the SOC coding scheme.

Figures 6 and 7 show the BER performance of the evaluated UWB-IR systems in AWGN and NLOS environments for different set of system parameters. When considering a NLOS environment, we notice much larger coding gain that introduced by the SOC coding scheme in comparison to the LOS case. The application of SOC coding in a NLOS environment enables the reduction of more than 6 dB of the bit energy when a considered bit error rate level equals BER $= 10^{-3}$.

IV. Conclusions

In this paper, we evaluated the performance of UWB-IR systems incorporating the superorthogonal convolutional coding or the frame repetition scheme using a realistic multipath channel model. We demonstrated that SOC coding significantly outperforms the frame repetition scheme. The coding gain introduced by the SOC scheme is noticeably higher in the NLOS environment. Due to the simple structure of the SOC encoder, decoder and the differential autocorrelation receiver, the UWB-IR system with the SOC scheme can be easily implemented into a hardware platform.

Acknowledgment

This work was partially funded by the Dutch Min. Econ. Affairs and via the *Airlink* project under the Freeband - Impulse Program.

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