Ultra Wide Band Receiver based on Turbo-Equalization

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Résumé – La technologie de l'Ultra-Large-bande (UWB) est actuellement étudiée comme une solution utile pour les systèmes de communications sans fil de grande capacité. Le rapport élevé de la largeur de bande du signal à la largeur de bande de l'information rend la technologie d'UWB attrayante pour des applications d'accès multiple. La synchronisation et l'égalization du canal sont les questions cruciales dans le développement de la technologie d'UWB, dû à la courte durée des signaux transmises. Dans cette contribution, nous proposons un turbo-égaliseur pour des récepteurs d'UWB, afin d'améliorer l'exécution de l'approche conventionnelle (récepteur RAKE). En particulier, les résultats obtenus ont démontré un perfectionnement d'exécution, en termes de taux d'erreurs sur les bits, avec une complexité computationelle menable.

Abstract – *Ultra-Wide-band (UWB) technology is currently being investigated as a promising solution for high-capacity wireless communications systems. The high ratio of the transmitted signal bandwidth to the information signal bandwidth makes UWB technology attractive for multiple-access applications. Channel equalization and time synchronization are crucial issues in the development of the UWB technology, due to the short duration of the transmitted pulses. In this contribution, we propose a turbo-equalizer for UWB receivers, in order to improve the performance of the conventional approach (i.e. Rake receiver). In particular, the obtained results have evidenced a performance enhancement, in terms of bit error rate, with a tractable computational complexity.*

1. Introduction

Ultra-Wide-band (UWB) technology is currently being investigated as a promising solution for high-capacity wireless communications systems. The very small power spectral densities (PSDs) of UWB systems ensure only minimal mutual interference between UWB and other communication applications [1]-[2]. The high ratio of the transmitted signal bandwidth to the information signal bandwidth makes UWB technology attractive for multiple-access applications. A time-hopping (TH) sequence is applied in UWB systems to eliminate catastrophic collisions in multiple access [10]. Several modulation techniques have been proposed for UWB signals, including pulse-position modulation (PPM) and several forms of pulse amplitude modulation (PAM) such as binary phase-shift keying (BPSK) and on-off keying (OOK) [3], [10]. Currently, TH-PPM and TH-BPSK UWB systems are often considered as alternatives for a given application, although the differences between the two systems lead to different performance characteristics [4].

Moreover, UWB technology is characterized by the transmission of very short pulses which occupy large frequency bandwidths. Due to a very short impulse occupies a bandwidth much greater than the transmitted symbol rate, UWB signals can also be considered as a spread spectrum technology. Channel equalization and time synchronization are crucial issues in the development of the UWB technology, due to the short duration of the transmitted pulses. Conversely, achieving the potential of UWB is challenging due to the difficulty of accurate synchronization and channel estimation, inhibiting a receiver's ability to fully exploit the multi-path diversity. Rake receiver, as one of the most popular solutions for the channel equalization, has been proposed for the UWB system to capture multi-path energy and mitigate inter-symbol interference (ISI) [5]-[7]. Novel channel estimation strategies can be devised [8].

This is the key point that this work focuses on, addressing some of the previous issues. In this contribution, in fact, we propose a turbo-equalizer for UWB receivers, in order to improve the performance of the conventional methods. We are showing in the following sections that the turbo-equalization approach allows implementing a more efficient UWB receiver than the conventional scheme (i.e. Rake receiver), in terms of bit error rate, with tractable computational complexity. Turbo-equalization is an iterative equalization and decoding technique that can achieve equally impressive performance gains for communication systems that send digital data over channels that require equalization, i.e. those that suffer from ISI [9]. The way that most practical receivers have been designed is to first process the received observations to account for the effects of the channel and to make estimates of the transmitted channel symbols that best fit the observed data. A number of criteria for performance have been used for such equalizers, ranging from those attempting to simply invert the channel to linear and non-linear equalizers based on minimizing a mean-squared error (MSE) metric to even those that are symbol-error-rate (SER) optimal [9].

This work is organized as follows. Section 2 describes the system model while Section 3 illustrates in details the proposed turbo-equalization technique. In Section 4, the UWB receiver we propose is depicted in details, while in Section 5 simulation results are used to show the performance benefits of the proposed approach. Conclusions are finally depicted in Section 6.

2. System Model

In this contribution, as channel model we utilize the same channel model that has been worked out by the IEEE 802.15SG3a research group and described in [12]. This model is inspired by the Markovian Saleh/Valenzuela (S/V) channel model: the multi-path components scattered from the same impulse are grouped in *cluster*, at the receiver side. Each cluster is composed by some *rays*, i.e. by some pulses. The clusters arrival time is modelled as a Poisson process with rate Λ while the rays arrival time is characterized by a rate λ. In the S/V model, the gain of each ray is a complex random variable whose phase can uniformly vary in the interval [$-\pi$, π]; in the channel model we assume, it becomes a real variable whose phase, now a discrete random variable, can assume only two values: π (in case of direct ray) or $-\pi$ (reflected ray) with the same probability. In this work, we choose a Direct Sequence/Spread Spectrum (DS/SS) UWB system based on a BPSK modulation. This choice has been driven by the fact that, according to [11], time-based DS/SS UWB systems are characterized by better performance in terms of bit-error-rate (BER) than time-based TH UWB systems. Hence, in a DS/SS UWB system, every bit, c_k, is transmitted on N_S pulses with amplitude given by:

$$x_k = A \cdot p_k \cdot (-1)^{c_k}, \qquad \mathrm{k} = 0,1,\cdots,N_s-1 \tag{1}$$

where p_k is the k-th pseudonoise (PN) code and A is a constant depending on the power used during transmission. Therefore, the signal transmitted by the i-th user can be expressed as [12]:

$$s^{(i)}(t) = \sum_k x_k^{(i)} \sum_{n=0}^{N_s-1} p_n^{(i)} w(t - nT_f - kN_sT_f) \tag{2}$$

where T_f is the frame time and *w(t)* the transmitted waveform. Different users are identified by different PN sequences, chosen to be orthogonal one to the other, in order to minimize the effects due to the cross-interference.

Another crucial issue that must be addressed is the problem of time-synchronization. In fact, time-synchronization is still a great challenge in UWB systems design, because of the short time duration of the pulses (i.e. of the order of *ns*). Moreover, n UWB signal is affected by time jitter. This means that the signal delay τ_k (i.e. the signal delay corresponding to the k-th frame) can be modelled as a Gaussian random process as follows [14]:

$$\tau_k = \tau_{k-1} + \xi, \qquad \xi = \mathrm{N}\left(0, \sigma_\xi^2\right) \tag{3}$$

The synchronization is acquired during the preamble. The synchronization algorithm must be repeated at least every frame in order avoid time jitter, updating the optimal sampling instant [13]. The low computational complexity of the synchronization algorithm makes all these iterations possible: in fact, the algorithm estimates the signal delay on the current frame as $\hat{\tau}_k = \hat{\mu}_k T_S$, where $T_S = T_f / N_f$ is the sampling time and N_f the number of samples per frame. Therefore, there are only N_f possible values of $\hat{\mu}_k$ among which the algorithm can choose, according to the following rule:

$$\hat{\mu}_k = \underset{0 \le \mu_k \le N_f - 1}{\arg\max} \left\{ \sum_{m=0}^{M_f-1} \sum_{l=0}^{L-1} \left(r_{m,[l+\mu_k]_{N_f}} - \frac{1}{M_f} \sum_{j=0}^{M_f-1} r_{j,[l+\mu_k]_{N_f}} \right)^2 \right\} \tag{4}$$

where:

$$r_{m,[l+\mu_k]_{N_f}} = \begin{cases} r((k+M_f-1)T_f + (l+\mu_k)T_s), & l+\mu_k \le T_f \\ r((k+M_f-2)T_f + (l+\mu_k)T_s), & l+\mu_k > T_f \end{cases} \tag{5}$$

and *r(t)* is the received signal.

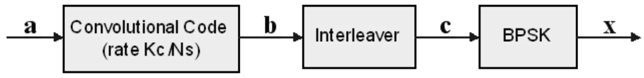

Fig. 1: block scheme of an UWB transmitter

3. Turbo Equalization

In this section, we are showing how to implement a turbo-equalizer receiver for an UWB system. According to the scheme of fig. 1, using a convolutional code of rate K_c/N_S, the encoder produces an output of $N_S = 2K_c$ bit $\mathbf{b} = [b_0, b_1, \ldots, b_{N_S-1}]^T$ given an input of K_c bit $\mathbf{a} = [a_0, a_1, \ldots, a_{K_c-1}]^T$. An interleaver is also added, to avoid long error bursts, giving N_S bit $\mathbf{c} = [c_0, c_1, \ldots, c_{N_S-1}]^T$ as output. Finally the BPSK mapping produces the symbols to be transmitted.

The turbo-equalization scheme we use in this work is composed by four steps in cascade: once the transmitted channel symbols have been estimated, they can be de-mapped into their associated code bits, de-interleaved and finally de-coded using a bit error rate (BER) optimal decoder for the error control coding (ECC). Once the ECC processes the information, it can, in turn, generate its own information (i.e. the “soft” information [9]) indicating the relative likelihood of each of the transmitted bits. This soft information from the decoder could then be properly interleaved and taken into account in the equalization process, creating a feedback loop between the equalizer and the decoder. This feedback loop structure is essentially the proposed turbo-equalization approach, i.e. the *a posteriori* information (the output of the decoder) can be used as the *a priori* information (input for the equalizer). Analogously, the output of the equalizer can be used to obtain some information to feed up the decoder in the following iteration.

The block scheme is illustrated in fig. 2, where $\boldsymbol{y}$ and $\hat{\mathbf{h}}$ represent, respectively, the received signal and the estimated channel impulse response, expressed by their representative vectors. In our turbo-equalization scheme, as in the turbo decoding approach in general, only extrinsic information is fed back, as depicted in fig. 2. Feeding back intrinsic information would create a direct positive feedback, which would lead to fast convergence but typically far from the globally optimal solution.

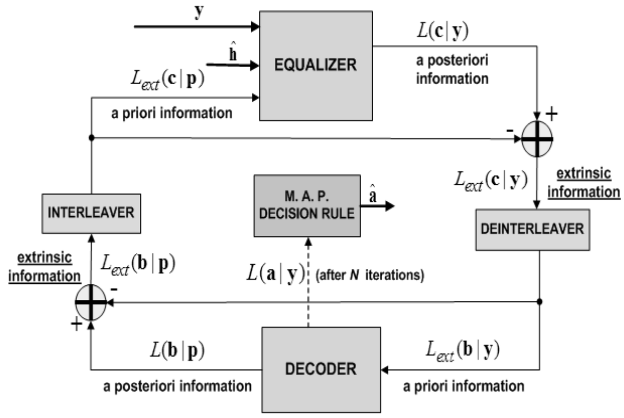

Fig. 2: Block scheme of the proposed turbo-equalizer receiver.

The interleaver and de-interleaver are included into the iterative loop to further minimize the direct feedback effect. Moreover, a common *maximum a posteriori probability* (MAP) rule is used in the scheme to make a decision on the received bit [9]. The MAP decision is based on the optimal decision rule that leads to the choice of the bit *0* if $L(a_k|\mathbf{y}) \geq 0$, and of the bit *1* if $L(a_k|\mathbf{y}) < 0$ being $L(a_k|\mathbf{y}) = \ln(P(a_k=0|\mathbf{y}) \,/\, P(a_k=1|\mathbf{y}))$ the *a posteriori* likelihood ratio (see fig. 3). As illustrated in fig. 2, the equalization forward/backward algorithm needs the channel impulse response $\hat{\mathbf{h}}$, that can be obtained using a least square technique.

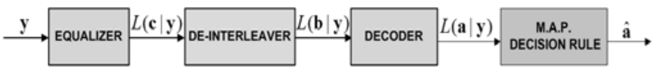

Fig. 3: MAP decision rule

4. UWB Receiver

The synchronization algorithm needs to know the channel impulse response. During the preamble, the CIR can be easily estimated thanks to the knowledge of both the received and transmitted signal (the preamble is known at the receiver side), but problems arise at the end of the preamble. The receiver's design is therefore based on the following idea: once the preamble is over, the least square algorithm uses both the received samples and the estimates of the transmitted signal, i.e. the outputs of the turbo equalizer. The problem is that the turbo equalizer will not produce any bit, if the synchronization block is not updated before. On the other hand, the synchronization algorithm needs the channel estimates, that will not be evaluated, if the turbo equalizer doesn't work in the proper way (see fig.4).

Thanks to the short duration of both the UWB frame time (10÷100ns) and the symbol time, we can consider the channel as time-invariant (or at least slowly variant) during one symbol time. So, once the preamble is over, both the synchronization and the turbo equalization algorithm use the channel estimates evaluated by the least square algorithm, during the reception of the previous symbol. More in details, the synchronization algorithm requires the observation of at least M_f frames to properly work while the turbo-equalizer needs, obviously, N_S frames (one symbol). Therefore, the length of the preamble must be at least of $(M_f + N_S)$. Until the $(M_f + N_S)$-th frame has been received, the only active block in the receiver is represented by the synchronization algorithm. Then, once the $(M_f + N_S)$-th frame has been received, the turbo-equalizer can evaluate the first K_c data bits (i.e. the first symbol) using the estimates realized by the synchronization algorithm and corresponding to the last symbol of the preamble.

As depicted in fig. 4, from these K_c data bits (i.e. the bits corresponding to the first symbol), re-applying the convolutional code, the interleaver, and the BPSK mapping, the proper signal level ($\hat{x}_k$) can be obtained. This latter, jointly with the received samples, allow the least square algorithm to estimate the channel coefficients that will be used both from the synchronizer and the turbo equalizer, during the reception of the second information symbol. Hence, from the reception of the second symbol until the end of the communication, the channel coefficients, estimated through the least square algorithm, are used by the synchronizer to sample the received signal at the optimal sampling instant, and by the turbo-equalizer to estimate the bit transmitted during the sub-sequent symbol.

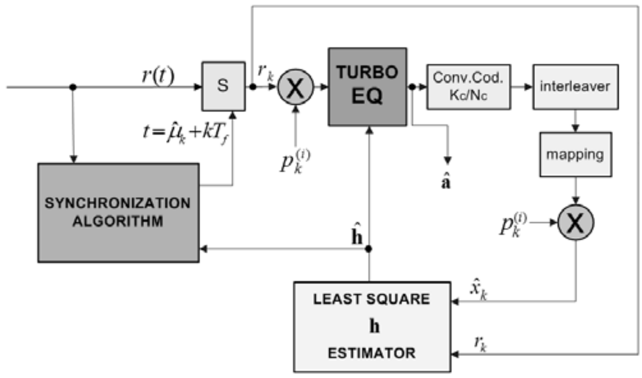

Fig. 4: Turbo-equalization and synchronization algorithm

5. Simulation Results

We are showing in this section that the turbo-equalization approach allows implementing a more efficient UWB receiver than the conventional approach, in terms of bit error rate, with tractable computational complexity. We have used simulation analyses to evidence the achievable gain of the turbo-equalization technique applied to a UWB receiver, compared with the conventional approach (i.e. Rake receiver), as shown in the following figures. For this purpose a number of simulations have been carried out. The obtained results that we are showing in this contribution finally confirm the effectiveness of the proposed turbo-equalization procedure in presence of ISI.

The convolutional code was chosen with $K_c = 4$ and $N_S = 8$, i.e. with a rate $R = 1/2$. We choose so low values for K_c and N_S in order to estimate the channel response as often as possible, because of the instability of the channel (following the model described in [12]). The number of considered multi-path components $L = K{\cdot}N$, being K and N, respectively, the maximum number of clusters and rays inside one cluster, was chosen equal to 106. fig. 5a shows the performance of the two receivers (Rake and Turbo-equalizer). From the graph, it can be easily seen that when no *a priori* information is used, i.e. when $N = 0$, the performance behavior is the same for both the receivers. The case $N = 1$ shows how important is the role played by the *a priori* information, in terms of minimizing the effects of the interference. This trend is confirmed and enhanced using greater values for the number of iterations. Moreover, in our simulation trials we have taken into account the effects due to different speeds of channel variations. All the curves depicted in fig. 5b refer to the case $N = 4$ of the turbo equalizer. In particular, the curve with M = 256 of fig. 5b corresponds to the curve with N = 4 in fig 5a, and refers to the situation where the channel response change in a significant way, every 256 frames (i.e. ≈ 3.277 μs). Remembering that, for each received frame, the channel impulse response is estimated from the previous $N_S = 8$ received frames, the performance of the system obviously degrades if M decreases. In fact, if $M = 2$ the channel change every two frames while the CIR is estimated and updated only every 8 frames.

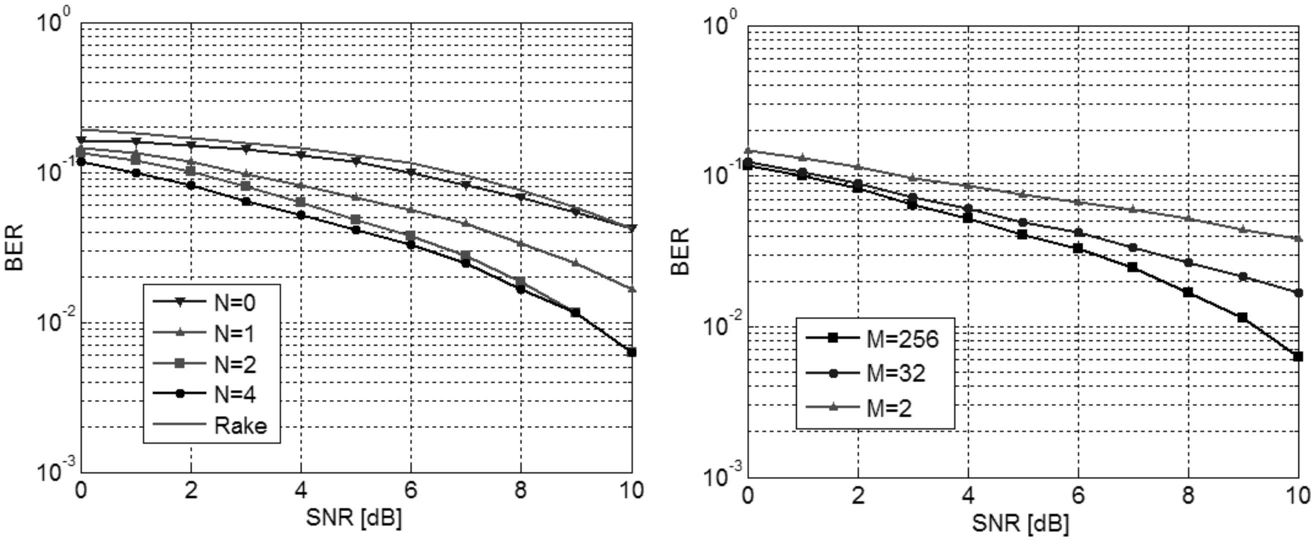

Fig. 5: Performance of the UWB turbo-equalizer receiver varying the number of iterations (left) versus the conventional approach (i.e. Rake receiver) and (right) with different channel variation speeds.

6. Conclusions

In this contribution, we proposed a turbo-equalizer for UWB receivers, in order to improve the performance of the conventional approach (i.e. Rake receiver). The turbo-equalization phase we use in this work is composed by four steps in cascade: once the transmitted channel symbols have been estimated, they can be de-mapped into their associated code bits, de-interleaved and finally de-coded using a bit error rate (BER) optimal decoder for the error control coding (ECC). We showed that the turbo-equalization approach allows implementing a more efficient UWB receiver than the conventional approach, in terms of bit error rate, with tractable computational complexity. We have used simulation analysis to evidence the achievable gain of the turbo-equalization technique applied to a UWB receiver. For this purpose, a number of simulations have been carried out. The obtained results finally confirm the effectiveness of the proposed turbo-equalization procedure in presence of ISI.

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