Turbo Multi-Packet Detection: An Efficient Technique to Deal with Collisions

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Abstract - In this paper we propose a turbo multi-packet receiver for packet separation in the presence of successive collisions that is suitable for SC-FDE schemes (Single-Carrier with Frequency-Domain Equalization). Our technique allows high throughputs, since the required number of transmissions is equal to the number of packets involved in the collision. Since we consider SC-FDE schemes and the complexity is concentrated in the receiver, this technique particularly appealing for the uplink of broadband wireless systems. [1]

I. Introduction

In wireless multiple users might try to access a given channel and the objective of MAC protocols (Multiple Access Control) is to allow this in an efficient way. When different users are simultaneously accessing a given channel we have a collisions, an event that is almost unavoidable in wireless systems. The simplest and more common approach to cope with collisions is to assume that all packets involved are lost. This means that we need to retransmit all packets involved in a collision, which leads to significant reduction in the system throughput. To reduce the chances of multiple collisions a given user transmits in the next available slot with a given probability. With this strategy, if two packets collide we need three time slots to complete the transmission (more if there are multiple collisions), which reduces the system throughput.

However, the signal associated to a collision contain information on the packets involved, which can be used to improve the system performance [1]. In fact, if we do not discard collided packets and we use proper retransmissions we can efficiently resolve collisions. To overcome this problem, a TA (Tree Algorithm) was combined with a SIC scheme (Successive Interference Cancelation) [2]. Within this SICTA technique, we do not discard the signal associated to a collision. Instead, if the packets of users A and B collide then, once we receive with success the packet of one of those users, we can subtract the corresponding signal from the signal with collision and recover the packet from the other user. With this strategy, if two packets collide we need two time slots to complete the transmission, unless there are multiple collisions. The major problem with this technique is that packet errors might lead to a deadlock problem [3]. Moreover, the required number of transmissions might be high if we have successive collisions.

The problem with these techniques is that we do not take full advantage of the information in the collision. The ideal situation would be to use the signals associated to multiple collisions to separate the packets involved.

In this paper we propose a turbo multi-packet receiver that allows an efficient packet separation in the presence of successive collisions. We consider the uplink transmission within broadband wireless systems. For this reason, we adopt an SC (Single-Carrier) modulation with FDE (Frequency-Domain Equalization), which is an excellent option for the uplink of severely time-dispersive channels [4], [5]. We propose a frequency-domain multi-packet detection scheme which has relatively low complexity, even for severely time-dispersive channels, since it allows an FFT-based implementation (Fast Fourier Transform).

This paper is organized as follows: The system characterization is made in sec. II and our multi-packet detection technique is described in sec. III. A set of performance results is presented in sec. IV and sec. V is concerned with the conclusions of this paper.

II. System Characterization

In this paper we consider the uplink transmission in wireless systems employing SC-FDE schemes. We have a slotted system and each user transmits a packet during a given time slot (for the sake of simplicity, it is assumed that the packets associated to each user have the same duration and correspond to an FFT block). Whenever more than one user targets a given time slot we have a collision.

It is assumed that, in the event of collision, the different packets arrive simultaneously, i.e., there is some time-advance mechanism able to compensate different propagation times (in practice only a coarse compensation is required, since some time mismatches can be absorbed by the cyclic prefix that is added to each FFT block). We also have perfect synchronization between different local oscillators (once again, only a coarse synchronization is required, since residual frequency offsets can easily be estimated and compensated using a technique similar to the one proposed in [6]).

The time-domain block associated to the pth user (i.e., the corresponding packet) is $\{a_{n,p}; n = 0, 1, \ldots, N-1\}$, where

[1] This work was partially supported by the FCT (Fundação para a Ciência e Tecnologia), under the pluriannual funding, and the C-MOBILE project IST-2005-27423.

$a_{n,p}$ is selected from a given constellation and N is the FFT size. When we have the collision of N_P packets we retransmit the packets involved $N_P - 1$ times.

The received signal associated to a given time-slot is sampled and the cyclic prefix is removed, leading to the time-domain block $\{y_n^{(r)}; n = 0, 1, \ldots, N-1\}$. If the cyclic prefix is longer than the overall channel impulse response then the corresponding frequency-domain block is $\{Y_k^{(r)}; k = 0, 1, \ldots, N-1\}$, where

$$Y_k^{(r)} = \sum_{p=1}^{N_P} A_{k,p} H_{k,p}^{(r)} + N_k^{(r)}, \tag{1}$$

with $N_k^{(r)}$ denoting the channel noise and $\{A_{k,p}; k = 0, 1, \ldots, N-1\}$ is the DFT (Discrete Fourier Transform) of $\{a_{n,p}; n = 0, 1, \ldots, N-1\}$. $H_{k,p}^{(r)}$ is the overall channel frequency response for the pth user and the rth transmission attempt.

III. Solving Multiple Collisions

A. Receiver Structure

Let us assume that N_P packets are involved in a collision and each user retransmits its packet $N_P - 1$ times. Therefore, the receiver has N_P versions of the signals associated to the N_P packets. Since the interference levels between packets are very high when we have a collision, we need to jointly detect all packets involved. We can use the N_P versions of each packet for multi-packet separation (a similar concept was proposed for LST (Layered Space-Time) systems [9]).

We consider an iterative receiver with successive interference cancelation, where each iteration consists of N_P detection stages, one for each packet. When detecting a given packet we remove the residual interference from the other packets, as well as the residual inter-symbol interference associated to the packet that is being detected. For a given iteration, the receiver structure for the detection of the pth packet is illustrated in fig. 1. We have N_P frequency-domain feedforward filters, one for each retransmission, and N_P frequency-domain feedback filters, one for each packet. This structure can be regarded as an equalizer with interference suppression properties.

The kth frequency-domain sample associated with the pth packet is

$$\tilde{A}_{k,p} = \sum_{r=1}^{N_P} F_{k,p}^{(r)} Y_k^{(r)} - \sum_{p'=1}^{P} B_{k,p}^{(p')} \overline{A}_{k,p'}, \tag{2}$$

where the average values $\overline{A}_{k,p'}$ are obtained as follows. The block $\{\overline{A}_{k,p'}; k = 0, 1, \ldots, N-1\}$ is the DFT of the block $\{\overline{a}_{n,p}; n = 0, 1, \ldots, N-1\}$, where $\overline{a}_{n,p}$ denotes the average symbol values conditioned to the FDE output. For QPSK constellations it can be shown that

$$\overline{a}_{n,p} = \tanh\left(\frac{L_{n,p}^I}{2}\right) + j \tanh\left(\frac{L_{n,p}^Q}{2}\right), \tag{3}$$

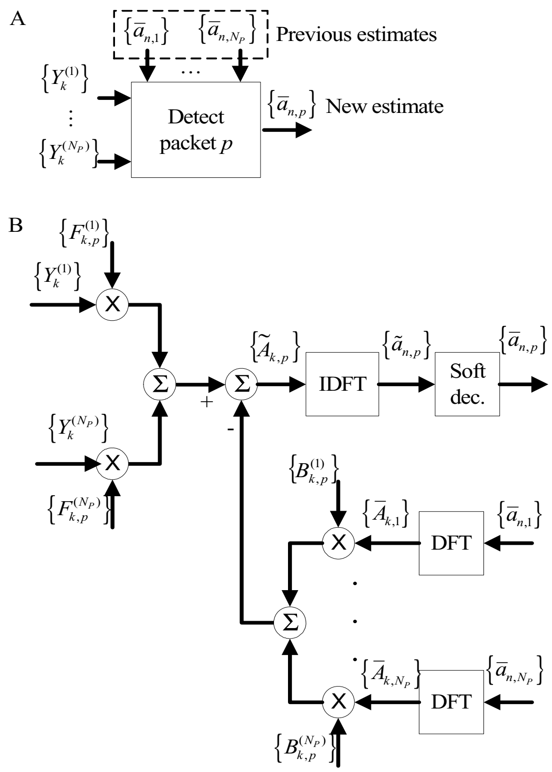

Fig. 1. Block for detecting the pth packet (A) and detail (B).

with

$$L_{n,p}^I = \frac{2}{\sigma_p^2} \mathrm{Re}\{\tilde{a}_{n,p}\} \tag{4}$$

and

$$L_{n,p}^Q = \frac{2}{\sigma_p^2} \mathrm{Im}\{\tilde{a}_{n,p}\} \tag{5}$$

denoting the LLRs (LogLikelihood Ratios) of the "in-phase bit" and the "quadrature bit", associated to $a_{n,p}$, respectively, and $\{\tilde{a}_{n,p}; n = 0, 1, \ldots, N-1\}$ = IDFT $\{\tilde{A}_{k,p}; k = 0, 1, \ldots, N-1\}$. The variance σ^2 is given by

$$\sigma_p^2 = \frac{1}{2} E[|a_{n,p} - \tilde{a}_{n,p}|^2] \approx \frac{1}{2N} \sum_{n=0}^{N-1} |\hat{a}_{n,p} - \tilde{a}_{n,p}|^2, \tag{6}$$

where $\hat{a}_{n,p}$ are the hard-decisions associated to $\tilde{a}_{n,p}$.

The optimum feedforward coefficients that minimize the "signal-to-noise plus interference ratio", for a given packet and a given iteration, can be written as

$$F_{k,p}^{(r)} = \frac{\breve{F}_{k,p}^{(r)}}{\gamma_p}, \tag{7}$$

with

$$\gamma_p = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{r=1}^{N_P} \breve{F}_{k,p}^{(r)} H_{k,p}^{(r)}, \tag{8}$$

and $\breve{F}_{k,p}^{(r)}$ obtained from the set of N_P equations:

$$(1-\rho_p^2)H_{k,p}^{(r)*}\sum_{r'=1}^{N_P}\breve{F}_{k,p}^{(r')}\breve{F}_{k,p}^{(r')}$$
$$+\sum_{p'\neq p}(1-\rho_{p'}^2)H_{k,p'}^{(r)*}\sum_{r'=1}^{N_P}\breve{F}_{k,p}^{(r')}H_{k,p'}^{(r')}+\alpha\breve{F}_{k,p}^{(r)}=$$
$$=H_{k,p}^{(r)*},\ \ r=1,2,\ldots,N_P, \qquad (9)$$

where the correlation coefficient ρ_p is given by

$$\rho_p=\frac{1}{2N}\sum_{n=0}^{N-1}(|\mathrm{Re}\{\overline{a}_{n,p}\}|+|\mathrm{Im}\{\overline{a}_{n,p}\}|). \qquad (10)$$

The feedback coefficients are given by

$$B_{k,p}^{(p')}=\sum_{r=1}^{N_P}F_{k,p}^{(r)}H_{k,p'}^{(r)}-\delta_{p,p'} \qquad (11)$$

($\delta_{p,p'}=1$ if $p=p'$ and 0 otherwise).

B. Use of Channel Decoder Outputs in the Feedback Loop

We can define a multi-packet detector that employs channel decoder outputs instead of the uncoded "soft decisions" in the feedback loop. The receiver structure is similar, but with a SISO channel decoder (Soft-In, Soft-Out) employed in the feedback loop. The SISO block, that can be implemented as defined in [10], provides the LLRs of both the "information bits" and the "coded bits". The input of the SISO block are LLRs of the "coded bits" at the multi-packet receiver, given by (4) and (5). Once again, the feedforward coefficients are obtained from (7)-(9).

C. Dealing with Fixed Channels for Retransmissions

It should be pointed out that the correlation between channels associated to different retransmissions should be low (if not, the system of equations (9) might not have a solution or it can be ill conditioned). This means that different channels should be employed for each packet retransmission (e.g., a different frequency band or a different antenna), unless the channel changes significantly between retransmissions For systems where this is not practical, we could assume that the frequency domain block associated to the rth retransmission of the pth packet, $\{A_{k,p}^{(r)};k=0,1,\ldots,N-1\}$, is an interleaved versions of $\{A_{k,p};k=0,1,\ldots,N-1\}$. Since this is formally equivalent to assume that $\{H_{k,p}^{(r)};k=0,1,\ldots,N-1\}$, $r=2,\ldots,P$ are interleaved versions of $\{H_{k,p};k=0,1,\ldots,N-1\}$, the channel correlations for each frequency can be very small. However, to avoid transmitting signals with very large envelope fluctuations, it is better to assume that $\{A_{k,p}^{(r)}=A_{k+\zeta_r,p};k=0,1,\ldots,N-1\}$, i.e., it is a cyclic-shifted version of $\{A_{k,p};k=0,1,\ldots,N-1\}$, with shift ζ_r. This means that the corresponding time-domain block is $\{a_{n,p}^{(r)}=a_{n,p}\exp(j2\pi\zeta_r n/N);n=0,1,\ldots,N-1\}$, with a suitable ζ_r. Therefore, this technique is formally equivalent to have $A_{k,p}^{(r)}=A_{k,p}$ and $H_{k,p}^{(r)}$ a cyclic-shifted version of $H_{k,p}^{(1)}$, with shift $-\zeta_r$. The larger ζ_r the smaller the correlation between $H_{k,p}^{(r)}$ and $H_{k,p}^{(1)}$, provided that $\zeta_r<N/2$ (since we consider cyclic shifts, $\zeta_r=N$ is equivalent to have $\zeta_r=0$).

IV. Performance Results

In this section, we present a set of performance results concerning the proposed detection technique in the presence of multiple collisions. We consider the uplink transmission where an SC-FDE modulation is employed. Each packet has $N=256$ data symbols, corresponding to blocks with length 4μs. The data symbols are selected form a QPSK constellation, with Gray mapping. The channel encoder is the well-known rate-1/2 64-state convolutional code with generators $1+D^2+D^3+D^5+D^6$ and $1+D+D^2+D^3+D^6$. We can use the channel decoder outputs in the feedback loop, as in conventional turbo detection schemes, or soft decisions based on the mupti-packet detector output. The radio channel associated to each packet is characterized by the power delay profile type C for HIPERLAN/2 (HIgh PERformance Local Area Network) [11], with uncorrelated Rayleigh fading on the different paths and the signals associated to all users have the same average power at the receiver (i.e., the base station), which corresponds to a scenario where an "ideal average power control" is implemented. We consider perfect synchronization and channel estimation conditions. The channels for each packet retransmission are assumed to be uncorrelated. We could draw the same conclusions for a fixed channel combined with the technique described in III-C, provided that the channel is severely time-dispersive, although there is some performance degradation (larger values of N_P mean higher performance degradation, but it is usually bellow 2 dB, even for $N_P=4$).

We assume that the base station knows how many packets are involved in the collision, as well as the user that transmitted each packet. This means that the information concerning user identification needs extra protection. After detecting a collision the base station informs the users how many retransmissions are required (and, eventually, the slots that will be used for those retransmissions, to avoid collisions by additional users).

Figs. 2 and 3 show the average PER (Packet Error Rate), averaged over al users, for different iterations, when N_P=1 or 2, respectively. Clearly we are able to separate different packets involved in a collision. In fact, the performance with collision of two packets is better than without collision. This results from the fact that our packet separation technique is very powerful; moreover, when we have retransmissions we increase the power spent to transmit a packet, reducing the sensibility to noise[2]. By using the channel decoder in the feedback loop we can improve significantly the performance, especially in the presence of collisions.

Fig. 4 shows the average PER after 4 iterations and different values of N_P. Clearly our technique is able to cope with a large number of collisions, with improved performances as we

[2]It should be pointed out that different packets have different performances, with packets detected first having worse performance due to higher interference levels; however, after four iterations the packets have almost the same performance.

increase the number of packets involved in the collisions (and, consequently, the number of retransmissions). The gains is we use the channel decoder in the feedback loop are about 2dB without collision and 3dB with collisions.

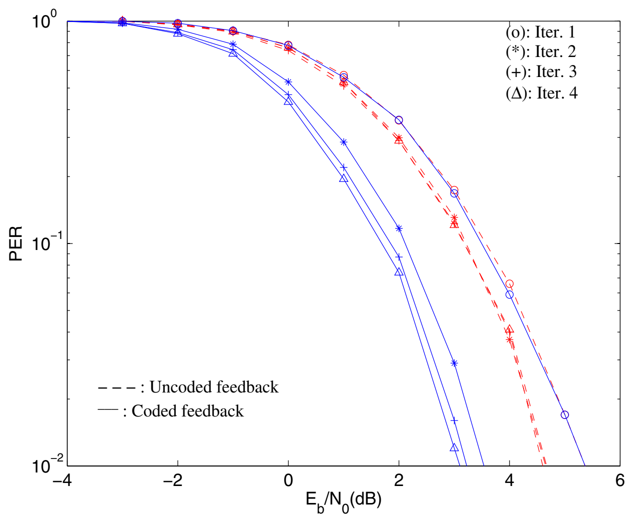

Fig. 2. PER without collisions, for iterations 1, 2 and 4.

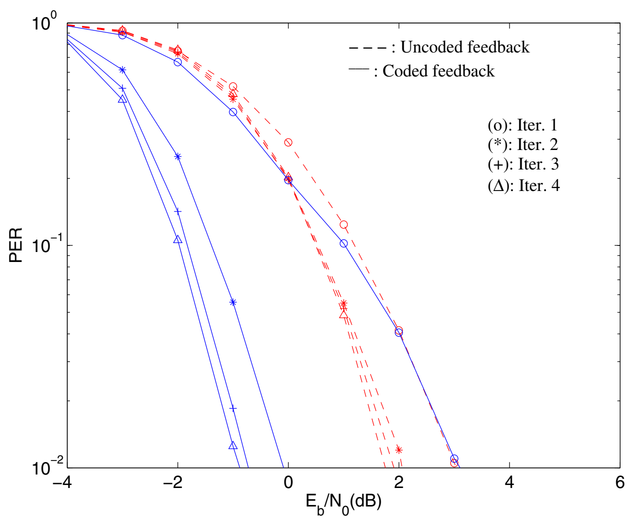

Fig. 3. PER with $N_P = 2$, for iterations 1, 2 and 4.

V. Conclusions

In this paper we proposed a turbo multi-packet receiver for packet separation in the presence of successive collisions. We considered the uplink transmission employing SC-FDE schemes. We consider an iterative frequency-domain receiver with interference cancellation. This interference cancellation can use either uncoded soft decisions of soft decisions at the channel decoder output.

Our performance results show that our technique that allows efficient packet separation, even when uncoded soft decisions are used for packet separation, although the performance is

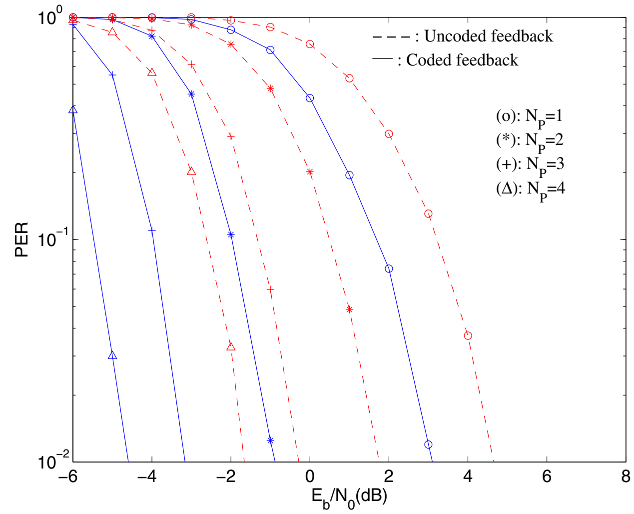

Fig. 4. PER after 4 iterations, for $N_P = 1$ (without collision), 2, 3 and 4.

much better when we involve the channel decoder in the interference cancellation procedure. Since the required number of transmissions is equal to the number of packets involved in the collision, we can have very high throughputs. Moreover, the complexity is concentrated in the receiver, making this technique particularly appealing to the uplink of broadband wireless systems.

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