An Efficient Detection Technique for SC-FDE Systems with Multiple Packet Collisions

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Abstract - Usually, packets involved in a collision are lost, requiring the retransmission of all packets. However, if we do not discard collided packets and we use proper retransmissions we can efficiently resolve collisions.

In this paper we propose a technique that allows an efficient packet separation in the presence of successive collisions. We consider an SC (Single-Carrier) modulation with FDE (Frequency-Domain Equalization) and we propose a frequency-domain multi-packet detection scheme. Since our technique requires uncorrelated channels for different retransmissions, we also propose a PS technique (Packet-Shift) for retransmissions using the same channel.

Our technique allows high throughputs, since the total number of transmissions is equal to the number of packets involved in the collision. Moreover, the complexity is concentrated in the receiver, making this technique particularly appealing to the uplink of broadband wireless systems. By employing the PS scheme we can use the same channel for the retransmissions, with only a small performance degradation.[1]

Keywords: Packet collisions, coss-layer optimization, iterative receivers, frequency-domain equalization.

I. Introduction

MAC protocols (Multiple Access Control) allow multiple users to share a given wireless channel. The traditional approach is to assume that all packets involved in a collision are lost, requiring their retransmission. Therefore, the collisions lead to significant throughput reduction.

However, collisions contain information on the packets involved, which can be used to improve the network performance. In fact, if we do not discard collided packets and we use proper retransmissions we can efficiently resolve collisions [1]. For this purpose, a TA (Tree Algorithm) was combined with a SIC scheme (Successive Interference Cancelation) [2]. Within this SICTA technique, when a packet involved in a collision is successfully detected the corresponding signal is subtracted from the signal associated to the collision. 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 is we have successive collisions.

In this paper we propose a technique 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). To be effective, our technique requires uncorrelated channels for different retransmissions. Since this is not practical in many systems, we propose a PS technique (Packet-Shift) for retransmissions where the frequency-domain block to be transmitted has different shifts for different retransmissions.

This paper is organized as follows: the system characterization is made in sec. II; sec. III describes our multi-packet detection technique, as well as the PS scheme; a set of performance results is presented in sec. IV and sec. V is concerned with the conclusions of this paper.

II. System Characterization

A. Transmitted and Received Signals

In this paper we consider the uplink transmission in wireless systems employing SC-FDE schemes. The packets associated to each user have the same duration and correspond to an FFT block (the extension to multiple FFT-blocks per packet is straightforward). Each user transmits a packet during a given time slot. Whenever more than one user targets a given time slot we have a collision.

We consider a synchronous network. This means 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). This also means that there is perfect synchronization

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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 $a_{n,p}$ is selected from a given constellation (e.g., a QPSK constellation) and N is the FFT size. Whenever there is a collision it is necessary to retransmit the packets involved (or, at least, some packets). The packet associated to rth attempt to transmit $\{a_{n,p}; n = 0, 1, \ldots, N-1\}$ is $\{a_{n,p}^{(r)}; n = 0, 1, \ldots, N-1\}$ (as with other SC-FDE schemes, a suitable cyclic prefix is added to each time-domain block). Clearly, $a_{n,p}^{(1)} = a_{n,p}$; in the following it will be clear that there are advantages of having $a_{n,p}^{(r)} \neq a_{n,p}$ for $r > 1$.

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

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

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

B. Receiver Design without Collisions

If there is no collision then the transmitted block can be recovered by a linear FDE [4], [5], as shown in fig. 1.A. However, the performance is much better if the linear FDE is replaced by a more powerful IB-DFE (Iterative Block Decision Feedback Equalizer) [7], [8], depicted in fig. 1.B. Clearly, the first iteration corresponds to a linear FDE. For the remaining iterations, the equalized samples are given by (for the sake of simplicity we dropped the dependence with p and r in this subsection)

$$\tilde{A}_k = F_k Y_k - B_k \overline{A}_k, \tag{2}$$

where

$$B_k = F_k H_k - 1. \tag{3}$$

and

$$F_k = \frac{\breve{F}_k}{\gamma}, \tag{4}$$

with

$$\gamma = \frac{1}{N} \sum_{k=0}^{N-1} \breve{F}_k H_k, \tag{5}$$

and

$$\breve{F}_k = \frac{H_k^*}{\alpha + (1-\rho^2)|H_k|^2}, \tag{6}$$

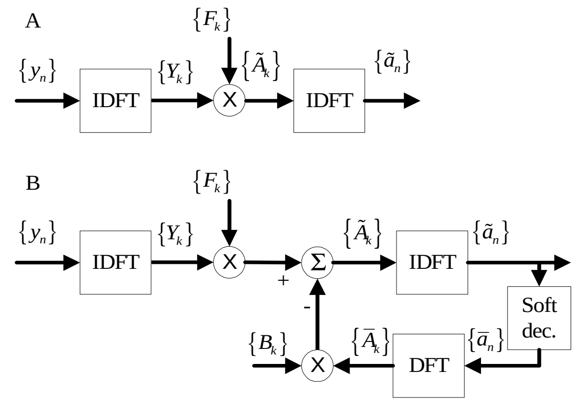

Fig. 1. Receiver structure for a linear FDE (A) and an IB-DFE (B).

with $\alpha = E[|N_k|^2]/E[|A_k|^2]$.

The samples $\overline{A}_k$ in (2) are $\{\overline{A}_k; k = 0, 1, \ldots, N-1\}$ = DFT $\{\overline{a}_n; n = 0, 1, \ldots, N-1\}$, where $\overline{a}_n$ denotes the average symbol values conditioned to the FDE output. For QPSK constellations it can be shown that

$$\overline{a}_n = \tanh\left(\frac{L_n^I}{2}\right) + j \tanh\left(\frac{L_n^Q}{2}\right), \tag{7}$$

with

$$L_n^I = \frac{2}{\sigma^2} \mathrm{Re}\{\tilde{a}_n\} \tag{8}$$

and

$$L_n^Q = \frac{2}{\sigma^2} \mathrm{Im}\{\tilde{a}_n\} \tag{9}$$

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

$$\sigma^2 = \frac{1}{2} E[|a_n - \tilde{a}_n|^2] \approx \frac{1}{2N} \sum_{n=0}^{N-1} |\hat{a}_n - \tilde{a}_n|^2, \tag{10}$$

where $\hat{a}_n$ are the hard-decisions associated to $\tilde{a}_n$. The correlation coefficient ρ is given by

$$\rho = \frac{1}{2N} \sum_{n=0}^{N-1} (|\mathrm{Re}\{\overline{a}_n\}| + |\mathrm{Im}\{\overline{a}_n\}|). \tag{11}$$

C. Strategies for Dealing with Collisions

Let us assume now that there are collisions. The conventional approach is to discard all blocks involved in the collision and to retransmit them (see fig. 2). 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

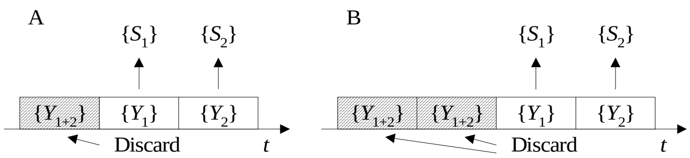

Fig. 2. Conventional strategy without multiple collisions (A) and with multiple collisions (B).

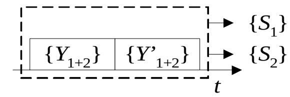

Fig. 4. Ideal strategy with multiple-packet detection.

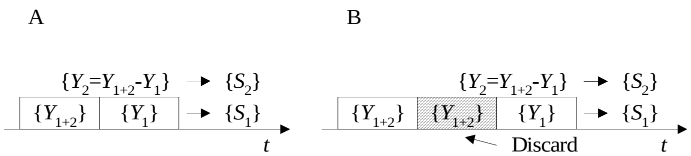

Fig. 3. SICTA strategy without multiple collisions (A) and with multiple collisions (B).

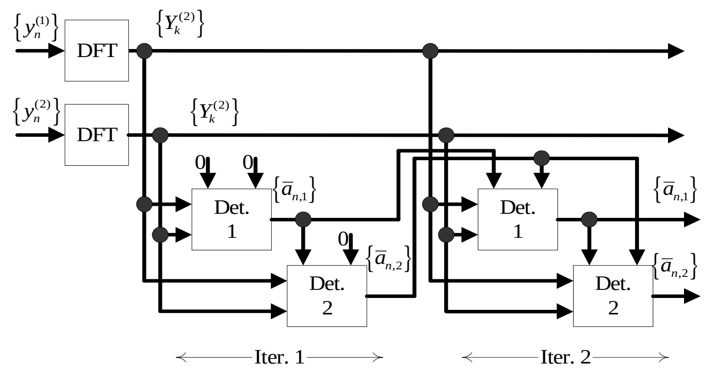

Fig. 5. Iterative receiver for detecting two packets involved in a collision ($N_P = 2$).

(more if there are multiple collisions), which reduces the throughput.

To overcome this problem, a SICTA scheme was proposed in [2], where we do not discard the signal associated to the collision. Instead, if the packets of users 1 and 2 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 (see fig. 3). With this strategy, if two packets collide we need two time slots to complete the transmission, unless there are multiple collisions. However, decision errors might lead to a deadlock.

The problem with these techniques is that we do not take total 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 (see fig. 4). In the following we will show how this can be achieved, even when we have multiple collisions.

III. Solving Multiple Collisions

A. Detection Technique

Let us assume that N_P packets are involved in a collision. Each user retransmits its packet $N_P - 1$ times (this means that $a_{n,p}^{(r)} = a_{n,p}$, leading to $A_{k,p}^{(r)} = A_{k,p}$). Therefore, the receiver has N_P version 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 SIC receiver where each iteration consists of N_P detection stages, one for each packet, as depicted in fig. 5, where it is assumed that $N_P = 2$. When detecting a given packet we remove the residual interference from the other packets, as well as the residual ISI (Inter-Symbol Interference) associated to the packet that is being detected. For this purpose, we use the average values associated to a given packet, conditioned to the FDE output.

For a given iteration, the receiver structure for the detection of the pth packet is illustrated in fig. 6. 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

$$\tilde{A}_{k,p} = \sum_{r=1}^{N_P} F_{k,p}^{(r)} Y_k^{(r)} - \sum_{p'=1}^{P} B_{k,p}^{(p')} \overline{A}_{k,p'}, \tag{12}$$

where the average values $\overline{A}_{k,p'}$ are obtained as described above. 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

$$F_{k,p}^{(r)} = \frac{\breve{F}_{k,p}^{(r)}}{\gamma_p}, \tag{13}$$

with

$$\gamma_p = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{r=1}^{N_P} \breve{F}_{k,p}^{(r)} H_{k,p}^{(r)}, \tag{14}$$

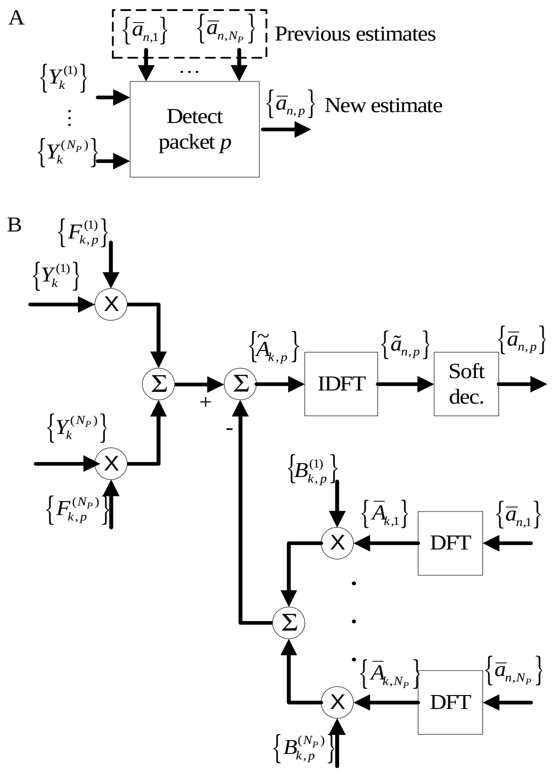

Fig. 6. Block for detecting the pth packet (A) and detail (B).

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

$$(1-\rho_p^2)H^{(r)*}_{k,p}\sum_{r'=1}^{N_P}\breve{F}^{(r')}_{k,p}\breve{F}^{(r')}_{k,p}$$
$$+\sum_{p'\neq p}(1-\rho_{p'}^2)H^{(r)*}_{k,p'}\sum_{r'=1}^{N_P}\breve{F}^{(r')}_{k,p}H^{(r')}_{k,p'}+\alpha\breve{F}^{(r)}_{k,p}=$$
$$=H^{(r)*}_{k,p},\ \ r=1,2,\dots,N_P, \qquad (15)$$

where ρ_p is defined as in (11). The feedback coefficients are given by

$$B^{(p')}_{k,p}=\sum_{r=1}^{N_P}F^{(r)}_{k,p}H^{(r)}_{k,p'}-\delta_{p,p'} \qquad (16)$$

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

It should be pointed out that this multipacket detection technique can still be employed when not all packets are transmitted in one or more retransmissions. We just need to set to zero the corresponding channel frequency responses.

B. SP Technique

As it will be shown in the next section, this multipacket detection technique is very efficient. However, to allow packet separation the channels associated to each retransmission should be almost uncorrelated. If not, the system of equations (15) might not have a solution or it can be ill conditioned. This means that different channels should be used for each packet retransmission (e.g., different antennas or different frequency bands). However, this is not practical in many systems. To overcome this problem, we could assume that different $\{A^{(r)}_{k,p}; k = 0,1,\dots,N-1\}$ are interleaved versions of $\{A_{k,p}; k=0,1,\dots,N-1\}$. Since this is formally equivalent to assume that $\{H^{(r)}_{k,p}; k=0,1,\dots,N-1\}$, $r=2,\dots,P$ are interleaved versions of $\{H_{k,p}; k=0,1,\dots,N-1\}$, the channel correlations for each frequency can be very small. However, the time-domain signal associated to $\{a^{(r)}_{n,p}; n = 0,1,\dots,N-1\}$ can have very large envelope fluctuations.

To allow the use of this packet separation technique when the channel is the same for different retransmissions we will assume that $\{a^{(r)}_{n,p} = a_{n,p}\exp(j2\pi\zeta_r n/N); n = 0,1,\dots,N-1\}$, with a suitable ζ_r. Clearly, this means that $\{A^{(r)}_{k,p} = A_{k+\zeta_r,p}; k = 0,1,\dots,N-1\}$, i.e., it is a cyclic-shifted version of $\{A_{k,p}; k=0,1,\dots,N-1\}$, with shift ζ_r. Therefore, this SP technique (Shifted Packet) is formally equivalent to have $A^{(r)}_{k,p}=A_{k,p}$ and $H^{(r)}_{k,p}$ a cyclic-shifted version of $H^{(1)}_{k,p}$, with shift $-\zeta_r$. The larger ζ_r the smaller the correlation between $H^{(r)}_{k,p}$ and $H^{(1)}_{k,p}$, provided that $\zeta_r < N/2$ (since we consider cyclic shifts, $\zeta_r = N$ is equivalent to have $\zeta_r=0$). In this paper we assume that the different ζ_r are the odd multiples of $N/2$, $N/4$, $N/8$, etc., i.e., $\zeta_r = 0, N/2, N/4, 3N/4, N/8, 3N/8, 5N/8, 7N/8, ...$ for $r = 1,2,3,4,5,6,7,8,...$, respectively. This allows the minimal correlation between different $H^{(r)}_{k,p}$. Moreover, envelope fluctuations on the time-domain signal associated to $\{a^{(r)}_{n,p}; n = 0,1,\dots,N-1\}$ are not too different form the ones associated to $\{a_{n,p}; n=0,1,\dots,N-1\}$[2].

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 $1+D+D^2+D^3+D^6$. The radio channel associated to each packet is characterized by the power delay profile type C for HIPERLAN/2 (HIgh PERformance Local Area Network) [10], with uncorrelated Rayleigh fading on the different paths. We consider perfect synchronization and channel estimation conditions. The channel for each packet retransmission can be either uncorrelated (denoted UC (Uncorrelated Channels)) or shifted versions of the channel in the first attempt, as described in sec. III-B (denoted SP). The signals associated to all users have the same average power at the receiver (i.e., the base

[2]For QPSK constellations the constellation associated to $\{a^{(r)}_{n,p}; n = 0,1,\dots,N-1\}$ is also a QPSK constellation for $r=2,3$ and 4.

station), which corresponds to a scenario where an ”ideal average power control” is implemented.

We assume that the base station knows how many packets are involved in the collision (and which the user transmitted each packet)[3]. After detecting a collision the base station can broadcast the number of retransmissions required (and, eventually, the slots that will be used for those retransmissions, to avoid collisions by additional users).

Let us first consider uncoded performance. The average BER (Bit Error Rate) for each iteration (averaged over all packets) is depicted in fig. 7. We consider $N_P = 2$, as well as the case without collisions ($N_P = 1$). Clearly we are able to separate different packets involved in a collision, even for the SP technique (where the channel is the same for different retransmissions). In fact, the performance with collision 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. 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 (see fig. 8, where an UC scheme is considered; similar results were observed for the SP scheme).

Fig. 9 shows uncoded BER 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 increase the number of packets involved in the collisions (and, consequently, the number of retransmissions), even for the SP technique (with the same channel for each retransmission). Naturally, as we increase the number of retransmissions the shifted versions of the channel frequency response have higher correlation between them, leading performances that are worse than with uncorrelated channels for the retransmissions. The same conclusions are valid after the channel decoder, as depicted in fig. 10, as well as for the PER (Packet Error Rate), depicted in fig. 11.

V. Conclusions

In this paper we proposed a technique that allows efficient packet separation in the presence of successive collisions. We considered an SC-FDE modulation and we proposed a frequency-domain multi-packet detection scheme. Since our technique requires uncorrelated channels for different retransmissions, we also proposed a PS technique for retransmissions using the same channel.

Our technique allows very high throughputs, since the total number of transmissions is equal to the number of packets involved in the collision. Moreover, the complexity is concentrated in the receiver, making this technique particularly appealing to the uplink of broadband wireless systems. The PS technique allows performances that are close to the ones with uncorrelated channels for different retransmissions.

[3]In a practical system, this means that the information concerning user identification needs extra protection.

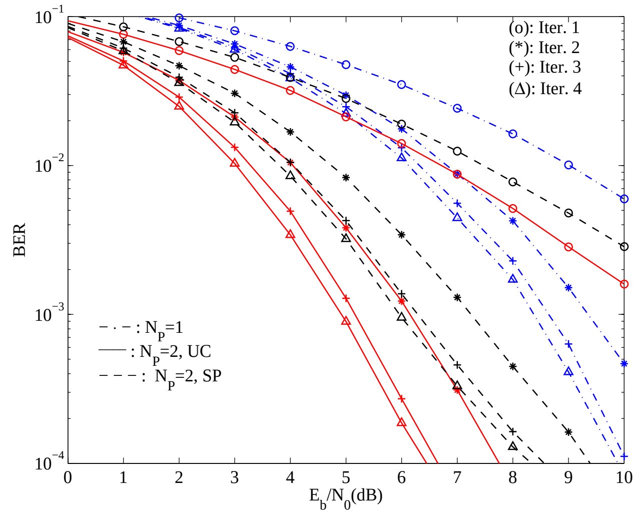

Fig. 7. Uncoded BER for different iterations.

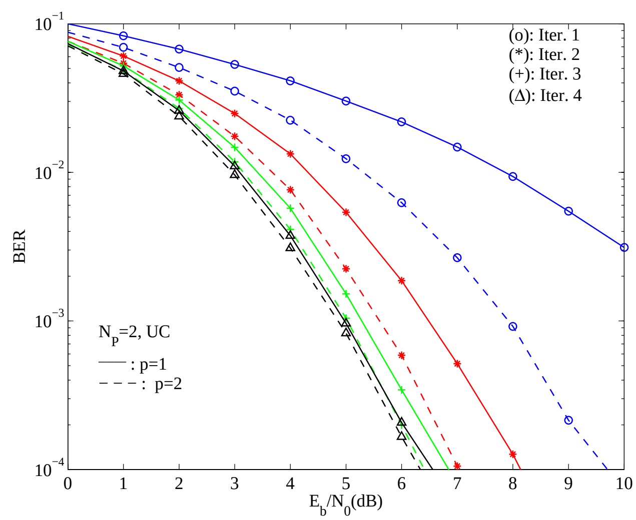

Fig. 8. Uncoded BER for each packet when $N_P = 2$ and uncorrelated channels are used for the retransmissions (UC scheme).

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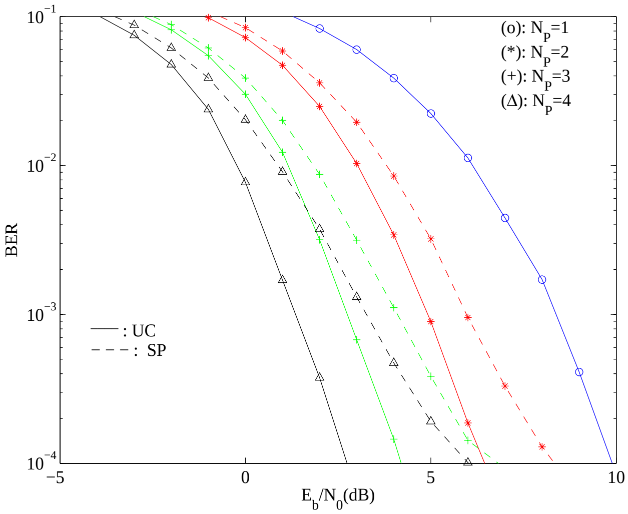

Fig. 9. Uncoded BER after 4 iterations.

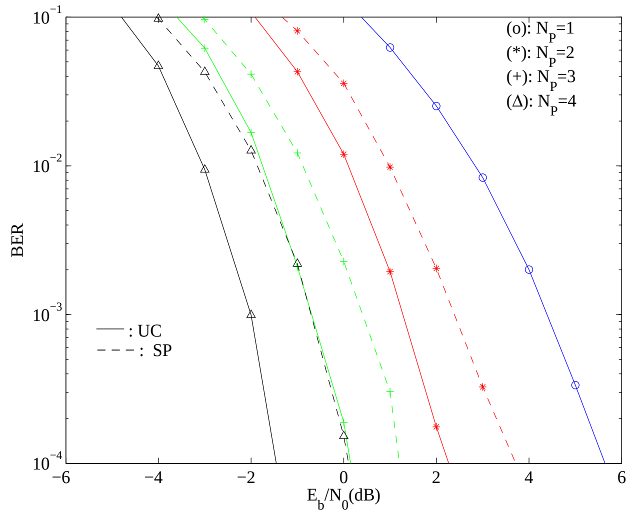

Fig. 10. Coded BER after 4 iterations.

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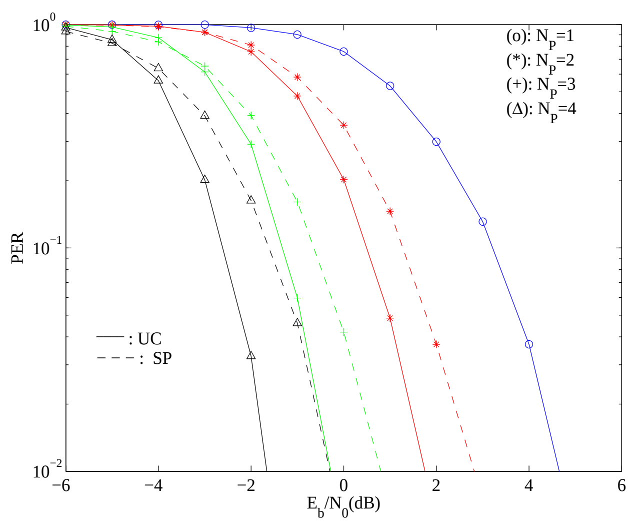

Fig. 11. PER after 4 iterations.