Blind Per-Survivor Processing-Based Multiuser Detection for Channel-coded Multicarrier DS-CDMA Systems

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Abstract—**In this paper, we present a blind Per-Survivor Processing (PSP)-based Multiuser Detector (MUD) for synchronous Multicarrier (MC) Direct Sequence (DS) CDMA systems. We modify the branch metric conventionally used for the Single-Carrier (SC) PSP-based MUD in order to detect synchronous MC DS-CDMA signals. Subsequently we characterise the performance of rate $R = \frac{1}{2}$ Low Density Parity Check (LDPC)-coded, Convolutional-based Turbo (CT)-coded and convolutional-coded (CC) MC DS-CDMA systems, which employ four subcarriers. We assume that each subcarrier experienced uncorrelated narrowband Rayleigh fading and quantified the BER performance, computational complexity and system delay. It is observed that when interleaving is performed over a single transmission burst, it is sufficient to utilise low-complexity CC codes. When the MC DS-CDMA system was not constrained by the tolerable system delay and hence interleaving was performed over several transmission bursts, CT codes yielded the best performance. LDPC codes were also capable of approaching the performance attained by the CT codes, although at a factor of 2.4 higher computational complexity.**

I. Introduction

Blind detection constitutes an attractive receiver technique that estimates the transmitted data without the need for transmitting training sequences. Therefore, the effective throughput is increased and no transmit power is wasted. In this contribution, we explore a class of blind detection algorithms, referred to as Per-Survivor Processing (PSP), which was proposed by Raheli *et al.* [1] as well as Seshadri [2]. The terminology 'per-survivor' is invoked, since a set of parameter estimators is used for estimating the unknown Channel Impulse Response (CIR) with the aid of data corresponding to a surviving trellis sequence. To elaborate a little further, Seshadri [2] proposed a reduced-complexity blind PSP algorithm based on the sequential coding algorithm of [3] for joint data and channel estimation when communicating over wideband channels. The proposed scheme produced both the data sequence and the required CIR estimates under the constraint of minimising the overall least squares error. Rollins and Simmons [4] then utilised the PSP algorithm in combination with the simplified Kalman filter [5] in order to estimate the maximum likelihood sequence, when communicating over fast frequency-selective fading channels.

Xie *et al.* [6] employed the blind PSP algorithm for joint signal detection and CIR estimation in asynchronous multiuser DS-CDMA systems transmitting over narrowband fading channels. Their scheme employed a reduced-complexity tree-search algorithm in order to aid the data estimation and a Recursive Least Squares (RLS) estimator for estimating the received signal amplitudes of all the users for each surviving data sequence in the tree. The same authors extended this work to blind PSP-based multiuser detection, where the CIR estimation was conducted without the knowledge of the time delays of the users [7]. In [8], Kuan and Hanzo extended the PSP-based MUD designed for narrowband fading channels in [6] for employment in a wideband synchronous turbo-coded CDMA system.

In this paper, we modify the metric equations of the PSP-based MUD designed for single-carrier CDMA systems. [6], [8] in order to enable multiuser detection of synchronous MC DS-CDMA signals. Subsequently, we analyse the performance of the synchronous MC DS-CDMA system considered, when employing three different channel coding schemes, namely Low Density Parity Check (LDPC) codes [9], Convolutional-based Turbo (CT) codes [10], [11] and convolutional codes (CC). We also characterise the relationship between the BER performance, computational complexity and system delay. Turbo codes were proposed by Berrou *et al.* [10] in 1993 and their performance was shown to approach the Shannonian limit. Well before the birth of turbo codes, Gallager devised LDPC codes [9] in 1963. However, the community's interest in these codes was modest until the 1990s owing to their high storage requirements and complexity. Recently, with the advance of technology, research interests in LDPC codes have re-surfaced. Furthermore, MacKay and Neal [12] have demonstrated that the performance of LDPC codes may also approach the Shannon limit, similar to turbo codes. The third codec chosen for our investigations was the convolutional code. These codes are known to yield good performance, despite having short coding block lengths, while incurring a low computational complexity.

This paper is organised as follows. Sections II and III present an overview of our system model and the PSP algorithm employed in our investigations, respectively. This is followed by our results and discussions in Section IV. Finally, we conclude our findings in Section V.

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II. System Model

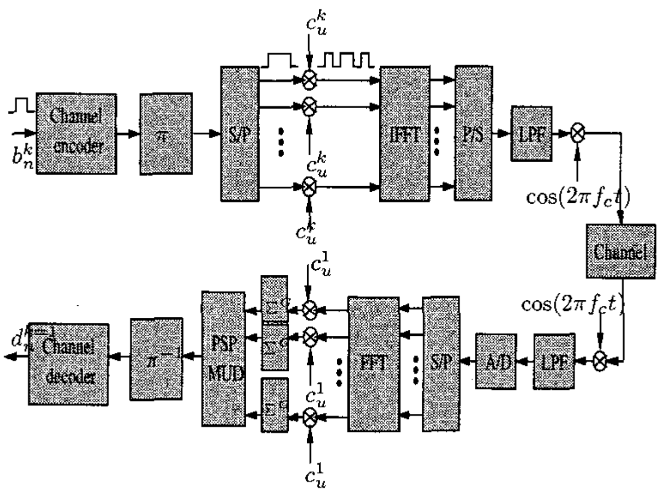

Fig. 1. System model of the channel-coded MC DS-CDMA system using a blind Per Survivor Processing-based multiuser detector.

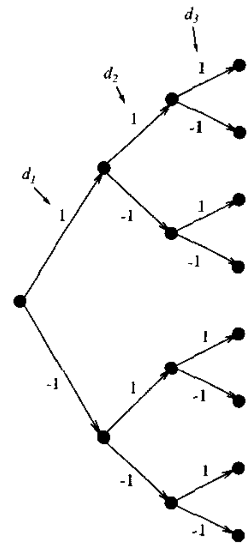

Fig. 2. Tree-search diagram for a three-user symbol-synchronous MC DS-CDMA system.

Figure 1 shows the system model of the MC DS-CDMA system employed in our investigations. At the transmitter, the input bits b_n^k, are channel encoded and channel interleaved by interleaver π. Subsequently, the W number of consecutive interleaved and coded bits a_n^k are serial-to-parallel converted. Each coded bit a_n^k is then spread by the kth user's spreading sequence of G chips in the time domain. The spread chips are fed to the IFFT block in Figure 1, whose output is low-pass filtered for the sake of generating the transmitted signal $s_n^k(t)$ of the kth user during the nth signalling interval, yielding:

$$s_n^k(t) = \sum_{w=0}^{W-1} \sum_{u=0}^{G-1} a_{n,w}^k c_u^k p(t - nT_s - uT_c) \cos\{2\pi(f_o + wf_d)t\}, \tag{1}$$

where $a_{n,w}^k$ is the nth interleaved coded bit of the kth user modulating the wth subcarrier, W is the number of subcarriers, T_s is the symbol period and T_c is the chip duration. The notation p represents the rectangular chip waveform signalling pulse defined as:

$$p(t) \triangleq \begin{cases} 1 & \text{for } 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases}. \tag{2}$$

At the receiver of the $k = 1$-st user, the received signal is multiplied by the spreading sequence and then summed over G chips. The despread signal is passed to the PSP-based MUD in Figure 1, in order to arrive at the decision variable d_n^1.

In the following section, we present an overview of the PSP algorithm employed in the context of multiuser detection.

III. Overview of PSP Algorithm

The PSP algorithm employed in our multiuser detector is a tree-search-based detection algorithm proposed by Xie *et al.* [6]. In order to contrive a tree-search-based detection algorithm for MC DS-CDMA systems, the transmitted symbols of all the MC DS-CDMA users can be concatenated, resulting in a single data sequence. For a K–user system, where $d_n^{(k)}$ represents the nth symbol transmitted by the kth user, the data sequences of all users are concatenated as:

$$\mathbf{d} = [d_1^{(1)}, d_1^{(2)}, \ldots, d_1^{(K)}, d_2^{(1)}, \ldots, d_2^{(K)}, d_N^{(1)}, \ldots, d_N^{(K)}]^T \tag{3}$$
$$k = 1, \ldots, K; \quad n = 1, \ldots, N; \quad K, N \in \mathbb{N},$$

in order to be able to invoke conventional channel equalisation techniques for multiuser detection. The notation N represents the number of symbols transmitted per user, which can also be considered as the detector window length for each user. Figure 2 shows a tree-diagram for a $K = 3$–user MC DS-CDMA system that is symbol-synchronous and BPSK is used for data modulation. Each node of stage i in the tree represents a hypothesised data sequence of length i, as well as a set of subcarrier CIR estimates corresponding to that data sequence. The maximum likelihood sequence detector calculates the likelihood metric for each node, *i.e.* for each hypothesised data sequence, at stage i and this is carried out exhaustively, in order to find the most likely multiuser MC DS-CDMA sequence of length N. Explicitly, this procedure does not minimise the BER of any of the users, it rather endeavours to find the maximum likelihood sequence. The complexity of the estimator increases exponentially both with the window length, N, and the number of users, K. Hence, in order to contrive a reduced-complexity algorithm for our receiver, the M-algorithm [3] is employed. This approach retains only a limited-sized subset of the nodes for per-survivor processing at the next stage. Specifically, if the number of nodes at the i-th stage is M and BPSK modulation is used, then the procedure used for proceeding from stage i to stage $i+1$ can be formulated as follows:

1) For each tree node at stage i, extend the node to two extra nodes by hypothesising the next data bit in the sequence to be first a logical one associated with "1" and then a logical zero, associated with bit "-1". This procedure results in a total of $2M$ nodes. The corresponding data sequences associated with the nodes are stored for subcarrier CIR estimation and metric calculation.
2) For each of the $2M$ number of new nodes, update the subcarrier CIR estimates with the aid of a Recursive Least Squares (RLS) [5] estimator and then calculate the associated metric value based on the hypothesised data bit sequence associated with the node considered. The likelihood metric calculation employed will be elaborated on below.
3) Out of the total of $2M$ nodes, select the M nodes associated with the highest metric values for the next stage, namely for stage $i+1$.

At the final decision stage of $i = NK$, the specific bit sequence and subcarrier CIR estimates associated with the node that has the highest metric constitute the best joint data and subcarrier CIR estimates of the K users.

In the PSP-based MUD designed for MC DS-CDMA systems, we have modified the metric computations employed by Xie *et al.* [6] for SC DS-CDMA transmission over narrowband fading channels. Specifically, in the context of MC DS-CDMA systems, the likelihood metric must jointly consider the received signals corresponding to all subcarriers. Hence, the MC DS-CDMA-based PSP metric equation associated with extending the trellis from stage $I-1$ to I can be written as:

$$m[I] = m[I-1] + R\Bigg\{ \sum_{w=1}^{W} d_i (h^{\zeta(i)}(w))^* [2r_i(w) - \sum_{j=1}^{K-1} (d_{i-j})^* (h^{\zeta(i)}(w)) R_{\zeta(i),\zeta(i-j)}(0)] \Bigg\}, \tag{4}$$

where $h(w)$ and $r_i(w)$ represent the subcarriers' CIR and received signal associated with the wth subcarrier. The term $\zeta(i) = [(i-1) \mod K] + 1$ is the mapping function that maps the data bit detected at the tree-stage i to the corresponding $n = \lceil \frac{i}{K} \rceil$-th symbol of the k-th user. The notation $R_{\zeta(i),\zeta(i-j)}(0)$ represents the periodic cross-correlation between the spreading sequences of users $\zeta(i)$ and $\zeta(i-j)$ respectively.

Having presented the system model and an overview of the PSP-based MUD algorithm, we now proceed to discuss their achievable performance.

IV. Results and Discussion

In our investigations, we have considered a bit-synchronous MC DS-CDMA system using 32-chip orthogonal Walsh codes. The number of subcarriers was $W = 4$ and each subcarrier experienced uncorrelated narrowband Rayleigh fading. Each transmission burst consisted of 100 symbols spread by the 32-chip Walsh codes. We employed Differential BPSK (DBPSK) modulation in order to resolve any phase ambiguity due to the blind CIR estimation at the receiver.

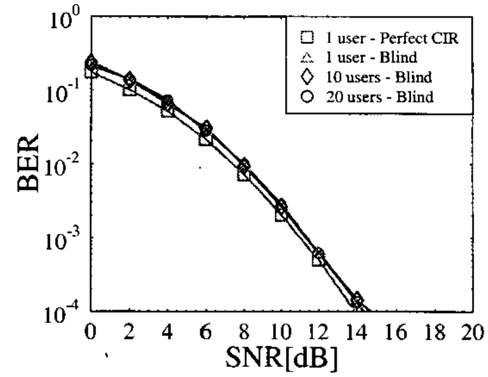

Fig. 3. Performance of the blind PSP-based MUD for 1 user, 10 users and 20 users employing 32-bit Walsh codes and four subcarriers. Each subcarrier experiences uncorrelated narrowband Rayleigh fading.

Figure 3 depicts the performance of the uncoded MC DS-CDMA system for single-user, 10-user and 20-user scenarios. It was observed that the single-user MC DS-CDMA system employing the blind PSP-based MUD advocated was capable of approaching the performance of the MUD possessing perfect CIR knowledge. In addition, we also observed that the performance of the 10-user and 20-user MC DS-CDMA systems approached the single-user performance, indicating that the blind MUD was capable of mitigating the effects of multiuser interference. Next, we characterise the performance of various channel-coded MC DS-CDMA system scenarios.

Channel Codec Parameters	
CC codes	Rate R= $\frac{1}{2}$, Constraint length $K_c = 5$ G[0]=35_8, G[1]=23_8 SOVA-based decoder
CT codes	Rate R= $\frac{1}{2}$, Constraint length $K_c = 4$ G[0]=13_8, G[1]=15_8 4 turbo decoding iterations Max-Log-MAP-based decoder
LDPC codes	Rate R= $\frac{1}{2}$ Row weight $R_w = 3$ Column weight $C_w = 3$ 20 LDPC decoding iterations Belief propagation-based decoder

TABLE I

Parameters of the convolutional codes, convolutional-based turbo codes and LDPC codes.

We commence by analysing the relationship between the channel interleaving length, the number of channel decoding iterations and the achievable BER performance in the context of single-user MC DS-CDMA systems. The parameters of the three channel codecs employed are summarised in Table I.

Figure 4 depicts the performance of single-user MC DS-CDMA, when channel interleaving is performed over F=

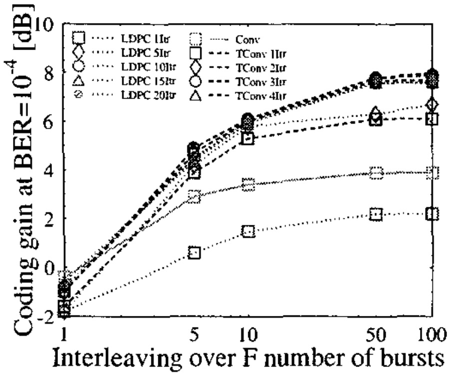

Fig. 4. Coding gain achieved by LDPC, CT and CC coded MC DS-CDMA schemes employing four subcarriers and different interleaving lengths at BER= 10^{-4}. Each subcarrier experiences uncorrelated narrowband Rayleigh fading.

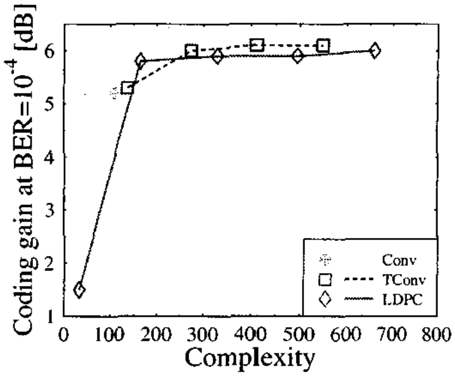

Fig. 5. Plot of coding gain achieved by the **single-user** LDPC, CT and CC coded MC DS-CDMA schemes employing four subcarriers and interleaving over 10 transmission bursts at BER= 10^{-4} versus the computational complexity incurred.

$1, 5, 10, 50$ and 100 consecutive transmission bursts. When interleaving within a single burst *i.e.* when we have F= 1, the BER performance becomes poor, since a transmission burst could be overwhelmed by channel-induced errors, hence rendering the channel decoding ineffective. In this scenario, all three codecs yielded similar performances. Therefore, it is sufficient to employ low-complexity convolutional codes. When the interleaving is performed over more transmission bursts, the effects of the associated bursty errors are mitigated and the channel decoders become more successful in correcting these channel-induced errors. However, this is achieved at the expense of increased system delay. In this scenario, the LDPC and CT codes employed outperformed the CC codes. The LDPC codes required 10 to 15 iterations, before their coding gain began to saturate, whereas CT codes necessitated only two iterations. In the context of Figure 5, we will return to the corresponding computational complexity of each of these codes. It was also observed that LDPC codes, which employ approximately 15 LDPC decoding iterations were capable of approaching the performance of turbo codes using two turbo decoding iterations. For an interleaving depth of F$\geq$ 50, the coding gain achieved by all three codecs began to saturate. In our subsequent simulations, we have opted for interleaving over F= 10 transmission bursts, as an attractive compromise between system delay and performance gain.

Next we analyse the relationship between the achievable coding gain and the computational complexity incurred. The complexity is evaluated in terms of the number of multiplications, additions and subtractions. For the sake of simplicity, we have assumed that the all these arithmetic operations incur the same complexity. Table II summarises the complexity calculations of the Max-Log-MAP-based turbo decoder [13], SOVA-based convolutional decoder [13], and belief propagation-based LDPC decoder [14].

Figure 5 shows the coding gain versus computational complexity relationship of the CC-based, CT-based and LDPC-based single-user MC DS-CDMA system performing channel interleaving over 10 transmission bursts. The points on the CT curve correspond to 1, 2, 3 and 4 turbo decoding iterations, whereas those along the LDPC curve refer to 1, 5, 10, 15 and 20 LDPC decoding iterations. It was observed that the LDPC-coded MC DS-CDMA scheme employing 20 iterations approached the performance of the CT-coded system using two turbo decoding iterations, while requiring a factor of 2.4 higher computational complexity, than that of turbo codes.

Complexity of Channel Codecs		
CC codes	CT codes	LDPC codes
$16+3K_c+3\cdot2^{K_c-1}$	$15\cdot2^{K-1}+17$	$3R_w \cdot C_w - C_w + C_w^2$

TABLE II

COMPUTATIONAL COMPLEXITY OF CHANNEL CODECS IN TERMS OF ARITHMETIC OPERATIONS. FOR SIMPLICITY WE HAVE ASSUMED THAT THE MULTIPLICATIONS, ADDITIONS AND SUBTRACTIONS INCUR THE SAME COMPUTATIONAL COMPLEXITY.

Finally we consider the performance of the channel-coded MC DS-CDMA system supporting 10 users. In Figure 6 we observe that the CT-based MC DS-CDMA system yields the best performance again, followed by the LDPC-coded scheme and the convolutional-coded system, respectively. Here, the CT-based system required three turbo decoding iterations, before the coding gain began to saturate. As in the single-user scenario of Figure 5, the LDPC codes approached the performance of the turbo-coded scheme only after performing 20 iterations, which corresponds to a factor of 1.6 higher computational complexity.

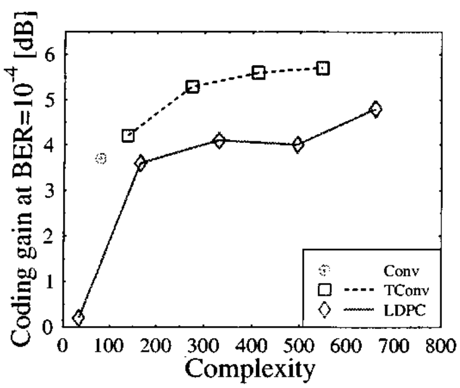

Fig. 6. Plot of coding gain achieved by the LDPC, CT and CC coded MC DS-CDMA schemes employing four subcarriers and interleaving over 10 transmission bursts supporting **10 users** at BER= 10^{-4} versus the computational complexity incurred.

V. Conclusion

We have shown that the synchronous MC DS-CDMA system employing the blind PSP-based MUD is capable of approaching the single-user performance, despite supporting 20 users. In addition, we have also characterised the performance of the CC-coded, CT-coded and LDPC-coded MC DS-CDMA systems considered. It was observed that when we interleaved over F=1 transmission burst, all three codecs yielded similar performances. Therefore, it is sufficient to invoke low-complexity CC codes in this scenario. When channel interleaving is performed over a higher number of transmission bursts, the effects of bursty errors are more efficiently mitigated and the CT codes and LDPC codes considered outperform the CC code. In the context of a single-user MC DS-CDMA system, the LDPC codec benefitting from channel interleaving over 10 transmission bursts becomes capable of approaching the performance of the CT-coded system, although this is achieved at the cost of a 2.4 times higher computational complexity. When the number of users supported by the MC DS-CDMA system is increased to 10, the LDPC codes required a factor of 1.6 higher computational complexity, in order to approach the performance of the CT-coded MC DS-CDMA system. In our future research, we will investigate the benefits of space-time coded, MUD-aided MC CDMA systems.

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