Sliding windows multiuser detectors for TD-SCDMA system

A. Bifano**, A. Colamonico*, M. Nicoli**, V. Rampa***, U. Spagnolini**
* Siemens ICN, Cinisello Balsamo (MI) Italy, armando.colamonico@icn.siemens.it
**DEI-Politecnico di Milano, Piazza L. Da Vinci 32, Milano Italy, {nicoli,spagnoli}@elet.polimi.it
*** CSTS-CNR, Politecnico di Milano, Via Ponzio 34/5, 20133 Milano Italy, rampa@elet.polimi.it

In CWTS TD-CDMA systems, block-based algorithms adopted in the BTS are well suited for multiuser detection (MUD) in presence of ISI. Block-based algorithms exhibit high computational load for large blocks; usually these algorithms are implemented as sub-optimal ones at the expense of some performance degradation. However, for time-varying channel, block-based MUD introduces a high latency degree and cannot be easily modified to cope with an adaptive receiver design. In this paper, we propose to exploit the sliding window approach to limit the high latency degree common to the block-based algorithms without degrading the performance figures. Both block-based MUD and SWD algorithms are compared in terms of performance, computational complexity and HW/SW implementation issues.

INTRODUCTION

Linear space-time (S-T) multi-user detection (MUD) for frequency selective fading channels has always been considered a prohibitive computational task in CDMA systems. In time slotted CDMA, block based MUD involves the inversion of a large matrix that depends on the block size and on the number of users. Suboptimal techniques are computationally efficient but show some performance degradation.

Reduced complexity detectors can be either block-type or one-shot. Efficient computational solutions for block-type receivers for CWTS TD-SCDMA are available [1]-[2]. However, the intrinsic latency caused by the block-style processing limits the possibility to update the channel estimation from decisions (adaptive receiver). This fact motivates the use of MUD for single-shot or reduced block sizes such as in sliding window decorrelator (SWD) [3]. This paper follows the approach shown by the authors in the TDD-UTRA reference [4] and it is focused on the comparison between block-based MUD and SWD algorithm for S-T processing in term of performance, computational complexity, parallelism, and considerations about hardware implementation.

TD-SCDMA SIGNAL MODEL

In TD-SCDMA systems, such as the CWTS standard [7], K users ($K \leq 8$) are active in the same frequency band and in the same time slot. Each user transmits bursts consisting of $2N$ QPSK symbols ($N = 352/Q$) with a spreading factor Q ($Q \in \{1, 2, 4, 8, 16\}$) assumed here constant for all users. The $M(NQ + W - 1) \times 1$ signal vector $\mathbf{y} = \mathbf{A}\mathbf{d} + \mathbf{n}$, that is received by the array of M antennas ($M = 8$), is filtered by the whitening S-T matched filter to get the $NK \times 1$ vector $\mathbf{y}_{\mathrm{MF}} = \mathbf{A}^{\mathrm{H}}\mathbf{y}$. Linear MUD is then performed on the filter output to estimate the NK data symbols: $\hat{\mathbf{d}} = \mathbf{R}^{-1}\mathbf{y}_{\mathrm{MF}} = \left(\mathbf{A}^{\mathrm{H}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{H}}\,\mathbf{y}$ where $\mathbf{R}^{-1}$ is the $NK \times NK$ decorrelating matrix. Vector $\mathbf{n}$ represents both noise and intercell interference, while $\mathbf{d}$ denotes the transmitted data vector of size $(NQ + W - 1) \times 1$. Considering, without any loss of generality, a zero forcing (ZF) detector, the S-T correlation matrix $\mathbf{R} = \mathbf{A}^{\mathrm{H}}\mathbf{A}$ depends on the structure of matrix $\mathbf{A} = [\mathbf{A}_1^{\mathrm{H}} ... \mathbf{A}_M^{\mathrm{H}}]^{\mathrm{H}}$ whose component $\mathbf{A}_m$ is shown in Fig. 1. Each sub-matrix $\mathbf{A}_m$ of size $(NQ + W - 1) \times KN$ contains shifted copies of the composite signatures $\mathbf{S}_m$ representing the convolution between the spreading codes and propagation channels. Therefore, $\mathbf{A}$ involves shifted copies of the temporal signatures $\mathbf{S}_m$ for all the antennas ($m = 1, .., M$). In the following part of this document the noise $\mathbf{n}$ is considered as Gaussian, while channel state information is assumed to be known.

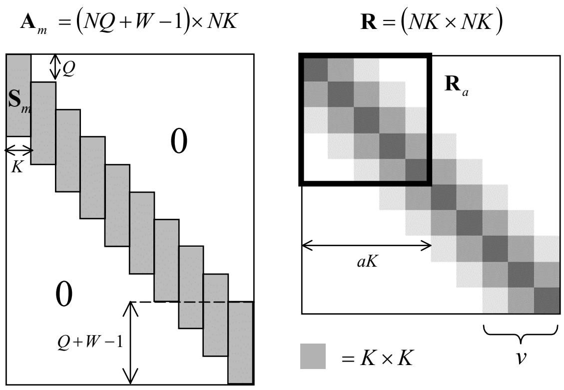

Figure 1: Matrices $\mathbf{A}_m$ and $\mathbf{R} = \mathbf{A}^H\mathbf{A}$.

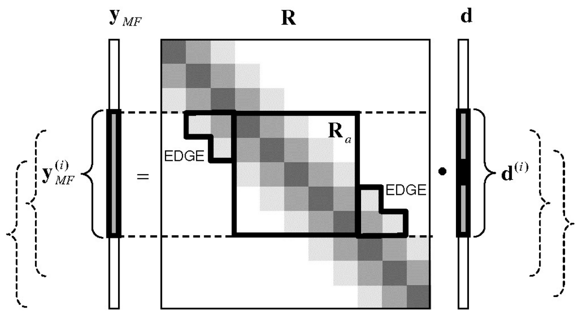

Figure 2: Description of the vectors $\mathbf{y}_{MF}^{(i)}$, $\mathbf{d}^{(i)}$ e matrix $\mathbf{R}_a$ used in the SWD algorithm.

DETECTOR COMPUTATIONAL COMPLEXITY

Most of the complexity of the linear detector arises from the inversion of the large block-Toeplitz correlation matrix $\mathbf{R}$ and the computation of the matched filter $\mathbf{y}_{\mathrm{MF}}$. The former is obtained by performing the Cholesky factorization of the matrix $\mathbf{R}$: $\mathbf{R} = \mathbf{L}^{\mathrm{H}}\mathbf{L}$. Then, using the backward/forward (B/F) algorithm, the lower triangular system $\mathbf{L}^{\mathrm{H}}\mathbf{x} = \mathbf{y}_{\mathrm{MF}}$ and the upper triangular system $\mathbf{L}\hat{\mathbf{d}} = \mathbf{x}$ are computed sequentially.

The computation of the Cholesky factor $\mathbf{L}$ for a generic $NK \times NK$ matrix requires a number of operations in the order of $O[K^3N^3]$ which is prohibitive for large block size N and/or high number of users K. However, here the correlation matrix $\mathbf{R}$ is block Toeplitz and block band with only $2v - 1$ non null block diagonals, where $v = \lceil (Q + W - 1) / Q \rceil$ is the delay spread expressed in symbol intervals (Fig. 1). More efficient solutions can be adopted for the factorization of this particular structure, such as the block Schur (BS) algorithm that reduces the complexity to $O[8NK^3v]$.

Table 1 summarizes the MUD computational complexity for the aforementioned factorization algorithm assuming the numerical values from the CWTS TD-SCDMA standard: $K = 8$, $v = 2$, $N = 22$, $Q = 16$ and $W = 16$. The computational load takes into account also the derivation of the generators for the BS algorithm [6]. Both single antenna $M = 1$ (second column from left) and antenna array of $M = 8$ elements (third column from left) are addressed. Notice that the cost of the matched filter dominates in the case of $M = 8$, however its calculation has a high degree of parallelism that can be easily exploited.

Table 1: MUD computational complexity (in terms of real multiplications $\times 10^5$) using Schur algorithm for the Cholesky factorization of block Toeplitz matrices. The numerical values are chosen as $K = 8$, $v = 2$, $N = 22$, $Q = 16$, $W = 16$.

Operation	Comp. complexity	
	$M = 1$	$M = 8$
MF	0.436	3.491
B/F	0.342	0.342
Cholesky fact.	1.077	1.901
Total MUD	1.855	5.734

In order to reduce the computational load due to the inversion of $\mathbf{R}$, approximate algorithms can be employed as described below. It can be observed that the Cholesky factor $\mathbf{L}$ of a block multidiagonal Toeplitz matrix $\mathbf{R}$ is not block Toeplitz itself even if it is still block diagonal. However, if N is large and $v << N$, the Cholesky factor $\mathbf{L}$ is nearly block Toeplitz [5]. The matrix $\mathbf{L}$ can thus be obtained by calculating the first a block columns of the Cholesky factor of $\mathbf{R}$ and then replicating them in $\mathbf{L}$ for all N columns. This is equivalent to compute the Cholesky factor (e.g., using the BS algorithm for block-Toeplitz matrices) of the top left $aK \times aK$ sub-matrix $\mathbf{R}_a$ and then copying the smaller blocks (see also Fig. 1). This method is referred to as approximate Cholesky decorrelator (ACD). In order to avoid edge effects the approximation size has to be selected with $a \geq v$: in the CWTS standard it is $a \geq v = 2$.

The sliding window decorrelator (SWD) [3] is an alternative low complexity detector based on the segmentation of the block $\mathbf{y}_{\mathrm{MF}}$ into smaller sub-blocks $\mathbf{y}_{\mathrm{MF}}^{(i)}$ of size aK (see Fig. 2). For each observation window of size a, only the central s symbols are detected for all K users ($1 \leq s \leq a$). This implies the computation to $(N - a + s) / s$ linear systems of size $aK \times aK$. Each linear system can be solved by the Cholesky factorization of $\mathbf{R}_{\mathrm{a}}$ followed by the appropriate backward and forward substitutions [4]. In order to reduce the edge effects (the influence of symbols outside the window of size a), the parameter s should be selected according to a so that $a \geq s + 2(v - 1) = s + 2$ (note that ISI spans $v - 1$ symbol intervals).

ALGORITHM COMPARISON AND SIMULATION RESULTS

Computational complexity and performance of SWD and ACD approximate detectors are compared for a single antenna system ($M = 1$) and for varying a and s. Tables 2 and 3 show the computational complexity expressed in terms of 10^5 real multiplications (or, equivalently, multiply and accumulation operations - MAC of a generic single cycle DSP) for the detection of 2 data blocks of N symbols each (one burst period). Clearly, parameter s influences only the SWD detector and it has no meaning when referred to the ACD algorithm. Both ACD and SWD require the computation of $2NK$ samples of the S-T matched filter and the Cholesky factorization of the $aK \times aK$ matrix $\mathbf{R}_a$. This factorization is performed only once per period by the BS algorithm.

Table 2: Computational complexity (in terms of real multiplication $\times 10^5$) of approximate detectors SWD and ACD. The parameters adopted are the same used in Table I.

a	s	Cholesky fact.		B/F	
		$M=1$	$M=8$	SWD	ACD
3	1	0.213	1.038	0.603	0.342
5	3	0.304	1.128	0.440	0.342
7	5	0.395	1.219	0.383	0.342
9	7	0.485	1.310	0.385	0.342

Table 3: Computational complexity (in terms of real multiplication $\times 10^5$) of the MUD algorithms shown in Table II. The parameters adopted are the same used in Table I.

a	s	Total MUD			
		$M=1$		$M=8$	
		SWD	ACD	SWD	ACD
3	1	1.252	0.991	5.132	4.871
5	3	1.181	1.082	5.059	4.961
7	5	1.214	1.173	5.093	5.052
9	7	1.306	1.263	5.186	5.143

In the ACD, the large Cholesky factor is derived from $\mathbf{R}_a^{1/2}$ by copying the last column; then the overall system is solved by forward and backward substitutions that require $O(16vK^2N)$ real multiplications. Likewise, in the SWD, for each window, the s central symbols are detected for all K users by performing at first a forward substitution and then a partial backward substitution of dimension aK. The B/F processing of the $N_w = \lceil (N-(a-s))/s \rceil \propto N/s$ windows requires $O(16vK^2a\frac{N}{s})$ real multiplications.

In Fig. 3 and 4, the performances of the approximate MUD algorithms are compared in terms of BER for uncoded bits for varying E_b/N_0. The channel model used is the COST-207 typical urban (TU) multipath propagation channel with 6 rays. It can be observed that $a=3$ in the SWD algorithm is enough to guarantee negligible impacts on the performance, still requiring only 20% more calculations with respect to the ACD with $a=3$ (see also Table 2 and 3).

Last figure shows how the MUD algorithms approximate the exact detector in terms of the windowing parameter a (and s when usable). Fig. 5 indicates that the approximations introduced in the detectors has no measurable effects on the performances if $a=2$ is selected for the ACD algorithm and $a=3$ with $s=1$ for the SWD one.

It has to be noted that SWD has a lower convergence speed with respect to the ACD. Indeed the SWD attempts

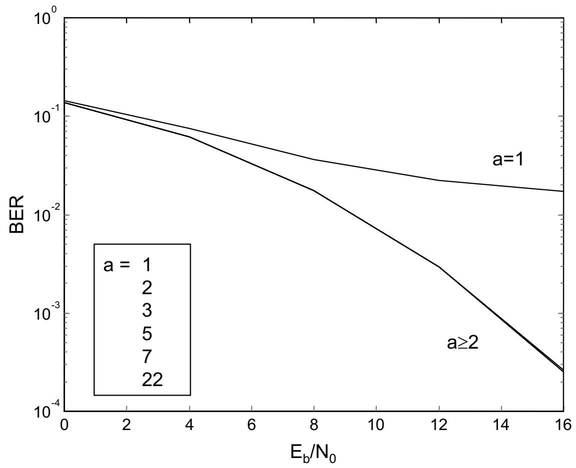

Figure 3: Performance of MUD in terms of BER vs. SNR for ACD (TU environment, burst type 1, $N=22$, $W=16$, $Q=16$, $K=8$, $M=1$, AWGN noise).

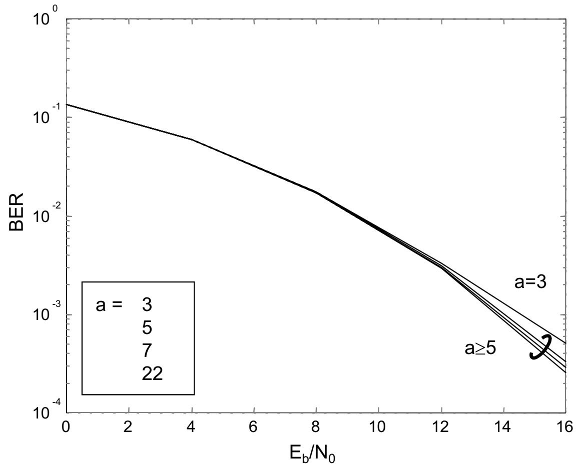

Figure 4: Performance of MUD in terms of BER vs. SNR for SWD using the same parameter values of Fig. 3 with $s=a-2$.

to limit the memory length of the decorrelator to $a<N$ by approximating $\mathbf{R}^{-1}$ with a block band matrix with bandwidth a. While the SWD operates on the inverse filter, the ACD approximates the direct filter $\mathbf{R}^{1/2}$ and does not truncate the memory length of the decorrelator. For the same size a, the edge effects introduced by the SWD are stronger than those due to the ACD: the SWD needs a larger window size respect to the ACD. To obtain the same BER vs. SNR performances, the SWD must adopt a larger windowing parameter a slightly increasing the computational complexity with respect to the ACD.

HARDWARE ISSUES

Several parallel implementation of the SWD algorithm may be foreseen [8]. For instance, the authors introduced

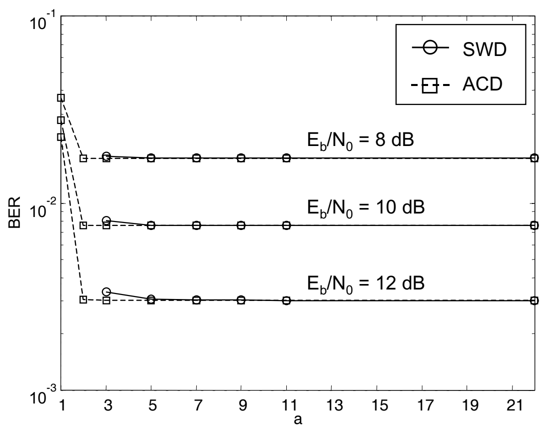

Figure 5: Performance of MUD in terms of BER vs. a for ACD and SWD using the same parameter values of Fig. 3 and 4.

in [4] a fine grained systolic architecture. It is a 2-D orthogonal array with $aK \times (aK + 1)$ cells composed of three different processor types. The array is fed with the matrix $\mathbf{R}_\mathrm{a}$ and the filtered vectors $\mathbf{y}_\mathrm{MF}^{(i)}$ properly interleaved and arranged to form the input matrix. For $3 \leq a \leq 5$, $N = 22$, $W = 16$, $Q = 16$, $K = 8$, $1 \leq s \leq 3$, $M = 8$, the number of cells $N_\mathrm{p} = aK(aK + 1)$ varies from 600 to 1640 while the number of clock cycles N_c required to process the whole burst increases linearly according the equation $N_\mathrm{c} = 4aK + N_\mathrm{w} - 2$.

However, this array is difficult to be implemented due the high number of nodes required and their high area occupation. A linear array with $N_\mathrm{p} = aK$ nodes ($24 \leq N_\mathrm{p} \leq 40$ for $3 \leq a \leq 5$) can be derived from the 2-D systolic architecture previously described. Every node is more complex respect to the previous one but a slower architecture with serialized internal units may be implemented to reduce area occupation at the cost of an increased number of cycles required. The VHDL description of this architecture is under development but first results seem promising. It is worth noticing that a preliminary software implementation of the same SWD algorithm with fixed-point DSP shows that a single T.I. TMS320C6414-600 is enough.

Even if the SWD algorithm requires more operations than the other approximated methods previously described, its hardware implementation has several attractive properties. First of all, an adaptive receiver can be easily implemented by updating, with channel state information, the values of $\mathbf{R}_\mathrm{a}$ into the processing nodes (or into the DSP in the SW version). In addition, user priority can be assigned during the detection phase. Finally, the part of the array used to compute $\mathbf{R}_\mathrm{a}^{-1}$ may be tuned to match the required area-speed constraints and to limit the number of multiplication and division operations.

CONCLUSIONS

Performance evaluation for ACD and SWD multiuser detectors has indicated that suitable array implementations may be employed. Design trade-off may be exploited to tune system performances and keep costs at a reasonable level.

The comparison of the presented methods for S-T MUD in CWTS-SCDMA system has shown that the major computational cost is due to the matched filter and the Cholesky factorization. SWD has a complexity that is similar to the block-type factorization, but it becomes the preferred choice in adaptive MUD when it is mandatory to track the channel variations within the bursts. Finally, the SWD algorithm can be easily implemented in hardware using parallel array architectures that exploit its implicit parallelism.

REFERENCES

[1] Y. Pigeonnat, “Joint detection for UMTS: complexity and alternative solutions”, Proc. IEEE VTC 1999, Vol. 1, pp. 546-550, 1999

[2] H. R. Karimi, N. W. Anderson, “A novel and efficient solution to block-based joint-detection using approximate Cholesky factorization”, Proc. IEEE PIMRC 1998, Vol. 3, pp. 1340-1345, 1998.

[3] M. J. Juntti, B. Aazhang, “Finite memory length linear multiuser detection for asynchronous CDMA communications”, IEEE Trans. on. Comm. Vol. 54, N. 5, pp. 611-622, May 1997.

[4] M. Beretta, A. Colamonico, M. Nicoli, V. Rampa, U. Spagnolini, “Space-Time multiuser detectors for TDD-UTRA: design and optimization”, Proc. IEEE VTC 2001, Vol. 1, pp. 78-82, 2001.

[5] J. Rissanen, “Algorithms for Triangular Decomposition of Block Hankel and Toeplitz Matrices with Application to Factoring Positive Matrix Polynomials”, Math. Comp. Vol. 27, N. 121, pp. 147-154, Jan. 1973.

[6] M. Vollmer, M. Haardt, J. Götze, “Shur algorithms for joint-detection in TD-CDMA based mobile radio systems”, Ann. Telecommun. Vol. 54, N. 7-8, pp. 365-378, 1999.

[7] CWTS, “China Wireless Telecommunication Standard (CWTS) Working Group 1 (WG1): Physical channels and mapping of transport channels onto physical channels”, TS C102 v3.3.0 (2000-09).

[8] P. Quinton, Y. Robert, “Systolic Algorithms and Architectures,” Prentice Hall, 1991.