MAP Multiuser Detection with Soft Interference Cancellation for UTRA-TDD receivers

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Abstract

A new multiuser detector (MUD) exploiting the MAP algorithm is proposed for channels affected by severe multipath and is then suitable for Time-Division Duplexing (TDD) CDMA receivers. After coherent combining the received multipaths, a multidimensional MAP non-linearity is employed to compute step-by-step the A Posteriori Probabilities (APPs) of the transmitted data for each user separately and then their expected values conditional to the available observations. These are then employed for soft ISI and MAI removal from the received sequences so that the APPs can be more reliably re-computed. The procedure is iterated in a multistage structure until final decisions are taken. From the comparison with other existing techniques (interference cancellation, zero-forcing) the proposed Reduced MAP-MUD receiver exhibits better performance and equal or minor complexity.

1. Introduction: The Problem and the System Model

Third-generation radio-mobile communication systems (UMTS, IMT-2000) are foreseen to employ the CDMA technique. In particular, Frequency-Division (FDD) and Time-Division (TDD) concepts have been recently selected by the European standardisation bodies (ETSI-SMG) for the UMTS Terrestrial Radio Access (UTRA) and are European candidates for IMT-2000 [8].

The TDD system exhibits the same chip rate (4.096 Mcps) as the W-CDMA but a smaller spreading factor Q = 16 (or even less, i.e. Q = 8, 4, 2: see [10, Sect.6.2]), corresponding to a larger symbol rate f_s = 256 kbaud (or more). The received signal is then impaired by inter-symbol (ISI) and multiple-access (MAI) interference spanning over a large number of received data samples (up to 6 or 7 samples for Q = 16 when the channel time spread is about 20 μsec, as in non-urban open areas).

Moreover, in TDD the number K of active (and synchronous) users is so small (less than K = 8) that the MAI cannot be treated as additional Gaussian noise and traditional single-user receivers give poor performance. In such environment Multi-User Detection (MUD, see [1] for a recent survey) not only is feasible (because K is small) but is also mandatory to satisfy the required quality of service.

Classic solutions for the TDD are the Zero Forcing (ZF) and the Minimum Mean Square Error MUDs [9]. Even though K is small, MUD still remains a very time-consuming task so that many algorithms are currently investigated with the purpose of improving the cost/performance trade-off.

The MUD receiver proposed in this paper assumes that the received TDD signal, sampled at chip rate f_c, is preliminary subject to coherent combining (CC) and despreading for each of the K users. The TDD employs short-length spreading codes with periodicity equal to the spreading factor Q so that the following K sequences $\{y^{(k)}(n)\}$, k = 1,..., K, are obtained (at symbol rate f_s) after CC:

$$y^{(k)}(n) = \sum_{i=1}^{K} \sum_{m=-L_g}^{L_g} [g^{(i,k)}(m)\, d^{(i)}(n-m)\,] + w^{(k)}(n), \qquad k = 1, ..., K, \qquad (1)$$

where $\{d^{(k)}(n)\}$ are the K transmitted data sequences; $\{w^{(k)}(n)\}$ are K additive (Gaussian) observation noise sequences obtained after CC and despreading of the thermal noise; $\{g^{(i,k)}(n)\}$, with i,k = 1,..., K, are the baseband discrete-time (sampled at f_s) equivalent channel impulse responses (S-CIRs) between the i-th user and the output of the k-th despreader, having (maximum) length $2L_g+1$. As a consequence of the CC operation, the S-CIRs are non-causal and, in particular, $\{g^{(k,k)}(n)\}$ exhibit conjugate symmetry.

In vector notation eq.(1) becomes:

$$y^{(k)}(n) = \sum_{i=1}^{K} [\underline{g}^{(i,k)\,T}\, \underline{d}^{(i)}(n)] + w^{(k)}(n), \quad k = 1,...,K, \tag{2}$$

where $\underline{d}^{(i)}(n) \equiv [\, d^{(i)}(n+L_g) \ldots d^{(i)}(n-L_g)\,]^T$ is the "state" vector of the i-th user and $\underline{g}^{(i,k)} \equiv [\, g^{(i,k)}(-L_g) \ldots g^{(i,k)}(L_g)\,]^T$ are the S-CIR vectors ($\underline{v}^T$ denotes the transpose of vector $\underline{v}$).

The CC operation mitigates ISI and MAI only partially so that the sequences $\{y^{(k)}(n)\}$ are not suitable for direct threshold detection. Further processing is then performed by the proposed MUD receiver which is based on the single-user Maximum A posteriori Probability (MAP) equaliser shortly described in the next Section.

2. The Single-User MAP Algorithm

The (single-user) symbol-by-symbol MAP algorithm was introduced in [2] and recently re-stated in reduced-cost versions (see, in particular, [3] and [4]). Basically, the MAP algorithm computes step-by-step the A Posteriori Probability (APP) vector $\underline{p}^{(k)}(n) \equiv [\, P(\underline{d}^{(k)}(n) = \underline{m}_1) \ldots P(\underline{d}^{(k)}(n) = \underline{m}_M)]^T$ of the possible $M = S^L$ channel states $\underline{m}_1, \ldots, \underline{m}_M$ assumed at step n (where L is the channel length and S is the constellation size, e.g., S=2 in BPSK and S=4 in QPSK) on the basis of the observation from step 1 to step n of the received sequence $\{y^{(k)}(n)\}$.

The “channel” APP (C-APP) vector $\underline{p}^{(k)}(n)$ is recursively computed on the basis of the following equations:

$$C^{(k)}(n) = \mathrm{diag}\{\, \exp(-|\, y^{(k)}(n) - \underline{g}^{(k,k)\,T}\, \underline{m}_1 |^2 / N_0),\ldots, \exp(-|\, y^{(k)}(n) - \underline{g}^{(k,k)\,T}\, \underline{m}_M |^2 / N_0)\, \}, \tag{3}$$

$$\underline{p}^{(k)}(n) = \mathrm{norm}\{\, C^{(k)}(n)\, F\, \underline{p}^{(k)}(n-1)\, \}, \tag{4}$$

where diag$\{\underline{v}\}$ is a matrix with the elements of the vector $\underline{v}$ along its main diagonal, and zeroes outside; norm$\{\underline{v}\}$ is the vector $\underline{v}$ after normalising to unit the sum of its elements; N_0 is the noise level power; F is the transition probability matrix of the channel state having elements:

$$F_{i,j} = P(\underline{d}^{(k)}(n) = \underline{m}_i \mid \underline{d}^{(k)}(n-1) = \underline{m}_j). \tag{5}$$

The APPs of the constellation symbols (S-APPs) at step n-D are computed (with delay D equal to the channel memory L-1) by properly summing over the elements of the C-APP vector $\underline{p}^{(k)}(n)$ and are collected in the S-APP vector $\underline{q}^{(k)}(n-D) = A\,\underline{p}^{(k)}(n)$. Following the MAP rule, the maximum element of $\underline{q}^{(k)}(n-D)$ gives the decision about $d^{(k)}(n-D)$.

3. The multistage soft-parallel (or soft-sequential) IC receiver

The "soft" statistics available from the MAP algorithm in the form of C-APPs or S-APPs were employed in [5],[7] for channel estimation purposes. In this paper they are exploited to carry out a soft (partial) MAI cancellation for each user separately, using a multistage structure.

In the first considered solution, a first stage processes the received sequence $\{y^{(k)}(n)\}$ via K separate single-user MAP modules. Each of them attempts to remove the self-ISI induced by the S-CIR $\{g^{(k,k)}(n)\}$ and computes the S-APPs $\underline{q}^{(k)}(n)$ pertaining to the symbol $d^{(k)}(n)$. From $\underline{q}^{(k)}(n)$ the expected value $E\{d^{(k)}(n)\}$ of $d^{(k)}(n)$ conditional to the available observation is calculated as the probabilistic average of the constellation symbols $s_1,\ldots, s_S$:

$$E\{d^{(k)}(n)\} = \underline{s}^T\, \underline{q}^{(k)}(n), \tag{6}$$

where $\underline{s} = [s_1,\ldots, s_S]^T$. The expected value of the MAI generated at step n by user #i over user #k is then obtained as:

$$E_y^{(i,k)}(n) = \sum_{m=-L_g}^{L_g} g^{(i,k)}(m)\, E\{d^{(i)}(n-m)\} \tag{7}$$

and the expected value of the overall MAI affecting user #k at step n is finally calculated as:

$$I^{(k)}(n) = \sum_{i=1, i\neq k}^{K} E_y^{(i,k)}(n|n-1). \tag{8}$$

In the second stage the difference sequences $\{y^{(k)}(n) - I^{(k)}(n)\}$, exhibiting a reduced MAI, are fed to the K single-user MAP modules which re-computes the S-APPs. The procedure is repeated in the other stages until, in the last stage, the S-APPs are directly employed for MAP detection.

The above-described soft-parallel interference cancellation solution can be improved by performing MAI calculation on the basis of the updated S-APPs available in the same stage for the previous symbols of all other users and for the actual symbols of the users preceding the current one. In this case it is useful to order the users with decreasing received power (or better with decreasing signal-to-interference ratio) so that the low-energy users keep maximum benefit from the successive IC strategy.

Such soft-sequential interference cancellation solution also allows a partial MAI cancellation from the past and (some of the) actual symbols in the first stage too.

4. The Reduced MAP-MUD Receiver

The solutions described in the previous Section do improve the performance of the CC receiver but their effectiveness is not as large as it was expected.

By analysing a TDD link with one user only (i.e., with ISI but no MAI) we verified that this phenomenon is due to the particular structure of the S-CIR $\{g^{(k,k)}(n)\}$ resulting after the CC operation. In fact, the (central) main tap $g^{(k,k)}(0)$ is generally strongly correlated with the lower-amplitude surrounding taps so that when it is in a fading also the other taps are in a fading. This limits the inherent "temporal diversity" typical of a multipath channel with many independent paths, which is successfully exploited by the MAP equaliser for single-user TDMA links.

However, another multistage MAP-MUD solution exploiting the MAP algorithm is proposed in this paper by considering that, from the above observations, only the tap $g^{(k,k)}(0)$ indeed needs to be fully taken into account by the single-user MAP. In this case the MAP algorithm assumes a channel length L=1, and the S-dimensional C-APP vector $\underline{p}^{(k)}(n)$ of (4) collects the probabilities of the constellation symbols at step n, i.e., it coincides with the S-APP vector. Eqs.(4),(6) constitute now a simple S-dimensional non-linearity computed at time n on the basis of the received sample $y^{(k)}(n)$, the actual channel tap $g^{(k,k)}(0)$ and the constellation symbols $s_1,\ldots, s_S$:

$q^{(k)}(n) = p^{(k)}(n) =$

$= \mathrm{norm}\{ [\exp(-| y^{(k)}(n) - g^{(k,k)}(0)\, s_1 |^2 / N_0),...,\exp(-| y^{(k)}(n) - g^{(k,k)}(0)\, s_M |^2 / N_0)]^T \};$
(9)

from (6), the expected value of $d^{(k)}(n)$ is computed on the basis of the following MAP non-linearity:

$$E\{d^{(k)}(n)\}= \alpha \sum_{i=1}^{S} s_i \exp(-|y^{(k)}(n)-g^{(k,k)}(0)s_i|^2/N_0), \qquad (10)$$

where α is the normalising factor of $q^{(k)}(n)$. Obviously, the complexity of the memoryless MAP is much lower than that of the MAP with memory.

Regarding the self-ISI affecting user #k, at step n the expected values of past (i.e., $d^{(k)}(n-1),\dots, d^{(k)}(n-L_g)$) and future (i.e., $d^{(k)}(n+1),\dots, d^{(k)}(n+L_g)$) data samples are available from the same stage and from the previous stage, respectively. From these the expected value of the self-ISI can be then calculated and subtracted from $y^{(k)}(n)$ at the input of the memoryless MAP together with the expected value of the MAI, calculated as in the soft-sequential solution described in the previous section. The expected total interference $I^{(k)}(n)$ due to both ISI and MAI affecting user #k at epoch n is then calculated as:

$$I^{(k)}(n) = \sum_{i=1, i\neq k}^{K} [\sum_{m=-L_g}^{L_g} g^{(i,k)}(m)\, E\{d^{(i)}(n-m)\}] + \sum_{\substack{m=-L_g,\\ m\neq 0}}^{L_g} g^{(k,k)}(m)\, E\{d^{(i)}(n-m)\},\ k = 1,\dots, K \qquad (11).$$

The basic structure of such multistage Reduced MAP-MUD (RMM receiver) is sketched in Fig.1, where the vector $\underline{y} \equiv [y^{(1)}(1), ..., y^{(1)}(N), ..., y^{(K)}(1), ..., y^{(K)}(N)]^T$ collects a block of N consecutive received samples for all users; the vectors $\underline{e}_P$ and $\underline{e}_C$ collects the expected values of the elements of $\underline{y}$ computed as in (10) in the previous and in the current stages, respectively; the vector $\underline{I} \equiv [I^{(1)}(1), ..., I^{(1)}(N), ..., I^{(K)}(1), ..., I^{(K)}(N)]^T$ collects the corresponding estimates of ISI and MAI affecting the received data.

5. The multistage PIC Detector

Extending the approach of [6] we designed a multistage parallel interference canceller well suitable for the TDD environment for channels affected by severe multipath. After coherent combining, tentative decisions are computed at each stage via a “soft” non-linearity and the total ISI and MAI affecting the current sample user is evaluated. This is then progressively subtracted from the received signal, with weights growing from one stage to the others.

In particular, for our tests an optimised structure has been found by using $N_s = 4$ stages with a hyperbolic tangent non-linearity in the first three stages and a hard-limiter in the last stage (the optimised weights are 0.5, 0.7, 0.9, 1). We implemented such multistage sequential IC solution in both parallel (MPIC) and sequential (MSIC) versions, the latter giving slightly better performance for large SNRs and requiring one less stage.

6. Results

The performance of the proposed RMM receiver has been evaluated via computer trials simulating at chip rate the whole CDMA transmission system model. For every trial a large number of timeslots has been generated, each constituted by N independent symbols. The channel follows the classic Wide-Sense Stationary Uncorrelated Scattering (WSSUS) random model with Rayleigh-distributed magnitude, uniform-distributed phase and assigned power-delay profile. Channel realisations are kept constant along each timeslot and are independent from a timeslot to another. While simulating the uplink they are also independent from a user to another, even though the same power-delay profile is assumed for all the users. The CC takes into account all nonzero C-CIR coefficients (assumed perfectly known) from which the S-CIRs are computed and then employed for ISI and MAI calculation.

In the simulations a TDD system with QPSK modulation, K=8 users, spreading factor Q=16 and chip rate of 4.096 Mcps has been assumed [8], while packet length is N = 40. Orthogonal Walsh spreading codes have been employed.

For comparison purposes the performance of the ZF detector [9] and the MPIC-MSIC solutions of Sect.5 is also reported.

The simulated receiver performance is shown in Fig.2 for the Vehicular A and Vehicular B test channels of Tab.I. The number N_S of stages employed in SSIC and RMM has been selected so that increasing it does not substantially change the performance. For the RMM we also considered the insertion of an additional-stage where ISI and MAI cancellation is performed after hard-limiting the expected values $E\{d^{(i)}(n)\}$, thus obtaining slightly better results for large SNRs (15 dB).

From the presented results (and from others not reported here) the effectiveness of the RMM receiver is verified. In particular, it outperforms both ZF and SSIC and is not far from the ideal case of perfect interference cancellation where, after CC, ISI and MAI are calculated from error-free hard-decisions and subtracted from the received samples.

In Fig.3 we evaluate the robustness of the RMM detector with respect to channel estimation errors which are emulated by replacing at the receiver side the true C-CIR tap c with $c(1+e)$, where e is a zero-mean complex random variable with (complex) variance P_{ch_err}. For the same conditions of Fig.2 the performance loss seems to be negligible when P_{ch_err} is not large (less than about -15 dB).

7. Conclusions

The arithmetical complexity of the RMM solution is that associated to the computation of the total interference as in (10), where $K(2L_g+1)-1$ complex products are executed per user and per received sample, plus that of the CC (L complex product per user and per sample if L is the number of the non-negligible C-CIR coefficients) plus that of the MAP non-linearity which is given only by the S complex product per user and per sample implied by (6), because (9) can be properly computed via low-cost operations. Such complexity is much smaller than that of the ZF and is nearly the same of the MSIC.

We conclude that the proposed multistage RMM receiver exhibits better performance than MSIC or MPIC at the same computational cost and largely outperforms the ZF solution which is much more complex. It then constitutes a feasible solution for TDD receivers. Further work is currently in progress to improve the effectiveness of the RMM receiver.

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Veh.B	Delay	0	$2T_c$	$4T_c$	$6T_c$	$8T_c$	$38T_c$	$55T_c$	$83T_c$
	Power	-14.1	0.0	-0.6	-12.3	-17.1	-12.7	-8.8	-16.4
Veh.A	Delay	0	$2T_c$	$4T_c$	$6T_c$	$8T_c$	$10T_c$	$12T_c$	
	Power	-16.8	0.0	-2.8	-8.6	-14.5	-14.9	-20.0	

Tab.I - Power-delay profiles of the WSSUS Vehicular A and B test channels at chip rate T_c^{-1} = *4.096 Mcps employed in the simulations.*

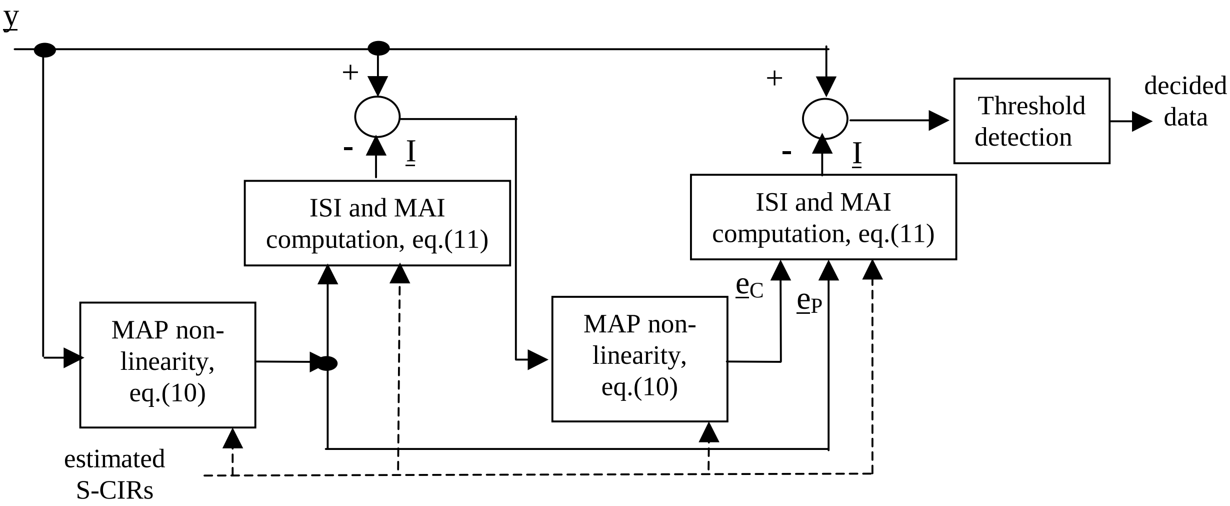

Fig.1 – Basic structure of the proposed multistage RMM receiver (example case of N_S = *2 stages).*

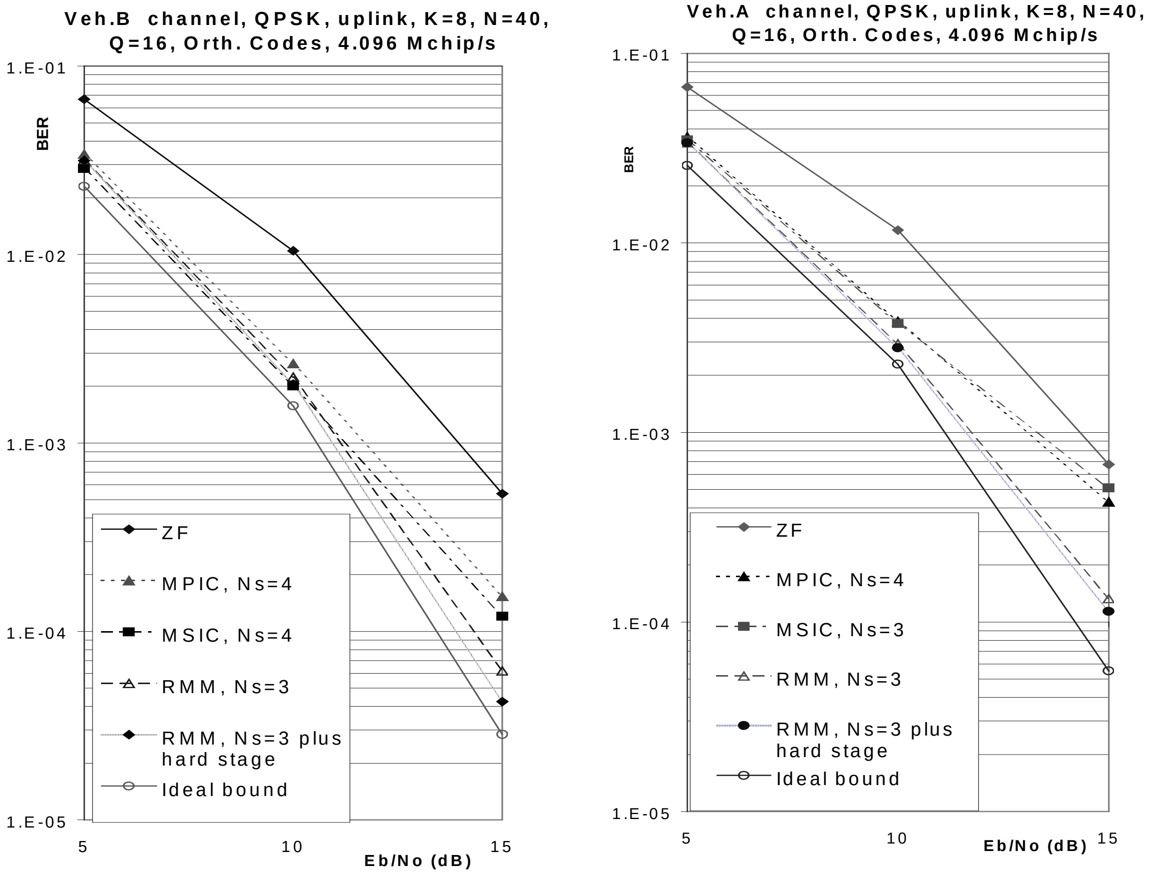

Fig.2 – Simulated BER vs SNR performance of the proposed RMM receiver and comparison with ZF and MPIC/MSIC solutions for the Vehicular B (left) and Vehicular A (right) WSSUS test channel of Tab.I. The ideal case of perfect IC is also reported.

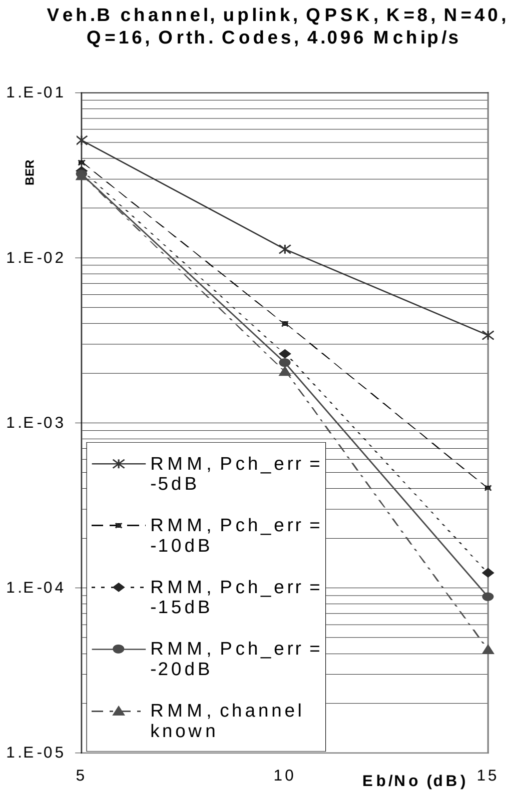

Fig.3 - BER performance of the RMM receiver for the same case of Fig.2 (and Veh.B channel) but different variances of the (relative) random channel estimation error.