TURBO-CODED BLIND PER-SURVIVOR PROCESSING MULTIUSER DETECTION CDMA

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ABSTRACT

Joint data and blind channel estimation based on the principle of Per-survisor Processing (PSP) is invoked and characterised in the proposed turbo-coded multi-user detection assisted Code Division Multiple Access (CDMA) system. The turbo-coded blind PSP receiver invoked the likelihood function in its metric calculations over the Typical Urban (TU) time-variant COST 207 fading channel fluctuating at Doppler frequencies between 0.8Hz and 80Hz. The size of the turbo interleaver was shown to be critical as regards to the overall system performance and for a rectangular turbo interleaver size of 55x55 bits in conjunction with a 100x100-bit or 156x156-bit channel interleaver no transmission errors were recorded for the above two Doppler frequencies over the COST 207 TU fading channel.

1. BACKGROUND

In order to achieve a performance approaching the single user bound, in multiuser detection the explicit knowledge of the channel impulse responses (CIR) and that of the spreading sequences of all the users is invoked [1]. In order to avoid the transmission of channel sounding sequences, which reduce the effective throughput, the class of CDMA receivers known as blind receivers [2, 3, 4] estimates the transmitted data without the need for training sequences. For most of these receivers the estimation of the relevant parameters – such as the delays of the users and the CIRs – is integrated with the data estimation algorithm. In this contribution we focus our attention on the family of so-called blind Per-Survivor Processing (PSP) based detectors [5, 6]. The PSP algorithm proposed by Xie *et al.* [3] for narrowband static channels was also extended to a multiuser detector for employment in a wideband synchronous CDMA system by Nasiri-Kenari, Sylvester and Rushforth [7]. In their work, Nasiri-Kenari *et al.* combined a tree-search-based detector with convolutional coding and the Soft Output Viterbi Algorithm (SOVA) [8] for channel decoding. However, their receiver assumed perfect amplitude estimation and no CIR estimation was performed.

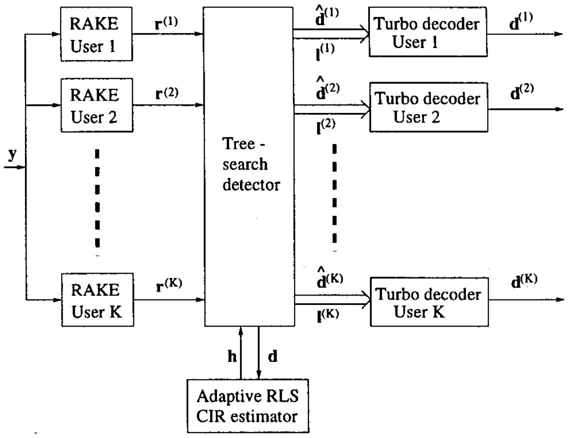

Figure 1: Schematic of the multiuser PSP receiver in conjunction with turbo decoding.

By contrast, in this contribution the CIR estimates were obtained blindly with the aid of adaptive Recursive Least Square (RLS) CIR estimators and turbo convolutional coding [9] was used over the fading COST 207 TU channel. More explicitly, the multiuser detector was combined with turbo convolutional coding in order to improve its performance, where the PSP multiuser detector generates soft outputs as reliability information for the individual turbo decoders of the users.

The outline of the paper is as follows. In Section 2 the proposed blind PSP CDMA receiver is introduced, while in Section 3 the issue of data sequence detection is addressed. This is followed by a discourse on the calculation of the associated decision metrics in Section 4, leading to the performance evaluation of the blind PSP receiver in Section 5, before concluding in Section 6. Let us now focus our attention on the outline of the receiver in the next section.

2. BLIND PSP CDMA RECEIVER

The schematic of the proposed blind PSP multiuser receiver is shown in Figure 1. The receiver consists of a bank of RAKE receivers, one for each CDMA user, followed by a reduced complexity tree-search-based data sequence es-

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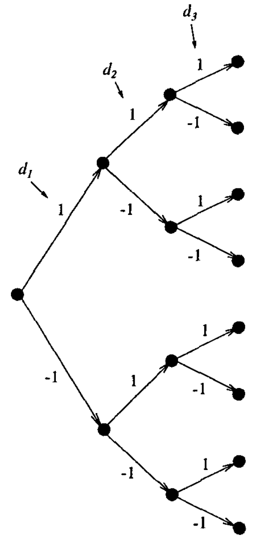

Figure 2: Tree-search diagram for a three-user symbol-synchronous system

timator that is linked to a bank of RLS CIR estimators. The receiver determines the data sequence, **d**, and the corresponding set of CIR estimates, **h**, that maximize the likelihood function [1] :

$$\Omega(\mathbf{r},\mathbf{d}) \;=\; 2\mathbf{d}^H\Lambda\mathbf{r} - \mathbf{d}^H\Lambda\mathbf{R}\Lambda^H\mathbf{d}, \qquad (1)$$

where the elements of the vector **r** represent the cross-correlation (CCL) of the received signal with each of the users' spreading sequences, i.e. the output signal of the matched filter. Furthermore, the vector **d** consists of the bits transmitted by the users; the matrix **R** is the CCL matrix of the spreading sequences. Lastly, the matrix Λ is a diagonal matrix and its main diagonal elements are the received signal amplitudes due to the transmitted symbols. In the tree-search based data sequence estimator, the data sequence leading to each surviving path in the tree is applied to an RLS estimator, in order to obtain the CIR estimates associated with that data sequence. After the CIR estimates have been obtained, a metric based on the likelihood function in Equation 1 is calculated and the corresponding high-probability subset of the paths is remembered, depending on the metric values of the paths. Finally, at the decision stage, the data sequence associated with the surviving path that yields the highest metric in Equation 1 is chosen as the most likely transmitted sequence.

3. DATA SEQUENCE DETECTION

The tree-search-based detection algorithm proposed by Xie *et al.* [3] is adopted in our receiver and its implementation is highlighted next. In order to implement a tree-search-based detection algorithm for CDMA systems, the transmitted symbols of all the CDMA users can be concatenated for generating a single data sequence. Explicitly, in a $K-$user system, where $d_n^{(k)}$ represents the n-th symbol transmitted by the $k-$th user, the data sequences of all users are concatenated as:

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

in order to be able to invoke conventional channel equalisation techniques, where N is 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 CDMA system that is symbol-synchronous, where BPSK modulation is used. At stage i, there exists a set of nodes and associated with each node is a hypothesized data sequence of length i as well as a set of CIR estimates corresponding to that data sequence. The maximum likelihood sequence detector calculates the likelihood metric of Equation 1 for each node at stage i and this is carried out exhaustively in order to obtain the most likely sequence. For wideband channels which result in ISI, the detection window has to be extended to cover a longer sequence of symbols, for example $N + W$, in order to minimize the error probability, where W is the CIR duration in terms of bit intervals. However, the complexity of the estimator increases exponentially with the window length, $N + W$, and the number of users, K. In order to implement a more practical algorithm in our receiver, the M-algorithm [10] was chosen as the reduced complexity tree-search algorithm. Hence, at each stage, i, only a subset of the nodes was kept for per-survivor processing at the next stage. Specifically, if the number of nodes at the i-th stage is M and the data modulation mode is BPSK, then the procedure for moving from stage i to stage $i+1$ can be formulated as follows :

1. For each node at stage i, extend the node to two extra nodes by hypothesizing the next data bit in the sequence to be first a logical one associated with "1" and then a logical zero, associated with "-1". This results in a total of $2M$ nodes. The corresponding data sequences associated with the $2M$ nodes are stored for CIR estimation and metric calculation.
2. For each of the new $2M$ nodes, update the CIR estimates with the aid of a RLS [14] CIR estimator and then calculate the metric value of Equation 1 based on the data bit sequence associated with that node.
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 decision stage of $i = NK$, the bit sequences and CIR estimates associated with the node that has the highest metric constitute the best joint N-bit data and CIR estimates of the K users.

4. METRIC CALCULATION

For the K–user synchronous CDMA narrowband channel the likelihood function was derived by Verdú [1], as stated in Equation 1, which can be rewritten as :

$$\begin{aligned}\Omega \;=\; & \sum_{n=1}^{N}\sum_{k=1}^{K} d_n^{(k)}\alpha_n^{(k)}\Big[2r_n^{(k)} - \\ & \sum_{m=1}^{N}\sum_{j=1}^{K}(d_m^{(j)}\cdot\alpha_n^{(k)})^{*}\cdot R_{kj}(0)\Big], \qquad (3)\end{aligned}$$

where $d_n^{(k)}$ represents the n-th symbol of the k-th user; $\alpha_n^{(k)}$ represents the received signal amplitude of the n-th symbol of the k-th user; $r_n^{(k)}$ is the output of the matched filter for the n-th symbol of the k-th user; and $R_{kj}(0)$ denotes the periodic CCL between the spreading sequences of user k and j, respectively. The notation x^* represents the complex conjugate of the variable x. Equation 3 was modified by Xie *et al.* [3] for the metric calculation.

In our approach, Equation 3 was modified to take into account the multipath channel of each user and the related mathematical derivations can be found in [11]. Here - due to lack of space - we adopt a practical approach and concentrate mainly on the achievable system performance.

5. PERFORMANCE RESULTS

The performance of the blind PSP receiver assisted by adaptive RLS CIR estimation is presented in this section. In order to resolve any phase ambiguity due to the blind CIR estimation at the receiver, Differential Binary Phase Shift Keying (DBPSK) was used. The spreading sequence length was set to $Q = 31$. The number of retained survivors in the tree-search algorithm was set to $M = 2$, in order to limit the associated complexity. A bank of RLS CIR estimators was implemented and the CIR was assumed to be time-invariant over a detected burst of $N = 100$ bits. For the CIR estimator, it was assumed that the delays of the CIR paths were known at the receiver, but not their amplitudes and the phases. The determination of the CIR path delays as well as the CIR amplitude and phase estimation was previously investigated by Xie, Rushforth, Short and Moon [4].

The channels simulated were static two-path channels, represented by the CIRs of:

$$\mathbf{h}^{(1)} = \{0.816, 0.577z^{-1}\}, \quad (4)$$

$$\mathbf{h}^{(2)} = \{0.707, 0.707z^{-1}\}, \quad (5)$$

where the notation z^{-1} indicates a delay of 1 chip.

The approach adopted by Nasiri-Kenari, Sylvester and Rushforth [7] was employed in the proposed blind PSP receiver. In their work, Nasiri-Kenari *et al.* combined a tree-search-based detector with convolutional coding and the Soft Output Viterbi Algorithm (SOVA) [8] for channel decoding. However, their receiver assumed perfect amplitude estimation and hence no CIR estimation was performed. In this section, the tree-search-based detector is modified, in order to invoke turbo-coding [9] rather than convolutional coding, and to generate soft outputs as reliability values for a Max-Log-MAP turbo decoder [12]. This receiver differs from the receiver proposed by Nasiri-Kenari *et al.* [7] in that the CIR estimates were obtained blindly with the aid of adaptive RLS CIR estimators and again, turbo convolutional coding [9] - rather than conventional convolutional coding - was used as the channel coding method. In the investigations carried out with the aid of turbo convolutional coding, the component codes that constituted the turbo code consisted of two recursive systematic half-rate convolutional codes with the constraint length of 3. The octally represented generator polynomials were 5 and 7. The turbo interleaver employed was a square interleaver where its dimensions depended on the performance requirements. Instead of the SOVA decoder employed by Nasiri-Kenari *et al.* [7], the Max-Log-MAP decoder [12] was utilized for turbo decoding. The Max-Log-MAP algorithm was developed in order to simplify the highly complex MAP algorithm [13], which is the optimal decoding algorithm. Therefore, the Max-Log-MAP decoder is a sub-optimal decoder that has however a significantly reduced complexity compared to the MAP and SOVA decoders. Turbo decoding is an iterative decoding process, where invoking eight iterations provides an attractive trade-off between BER performance and decoding complexity. The algorithm for generating the soft inputs of the Max-Log-MAP decoder is presented next.

The soft inputs required by the turbo decoder are in the form of reliability or confidence measures for each bit that is output by the PSP receiver. In traversing from stage i to stage $i + 1$ in the tree, the following steps are added after Step 2 in the tree-search block of the PSP algorithm described in Section 3.

a. Out of the $2M$ nodes that have been reached from the previous stage, consider one of the extended nodes, $\eta[i]$, and let its associated metric value be represented by μ_i, where the associated bit of d_i has an estimated bit value of δ, for $\delta \in \{1, -1\}$.

b. Let S be the set of all the other extended nodes, where the associated bit value d_i is not equal to δ.

c. From the set S, discard the node that has the same metric value of μ_i as the extended node $\eta[i]$ being considered. This is because, when DBPSK is used to resolve the phase ambiguity this results in one other node that has the opposite phase estimate, but exhibits the same metric value and which ultimately results in the same bit sequence after differential demodulation. Therefore, the node with the same metric value has to be discarded from the reliability calculations.

d. Now, from the remaining nodes in the set S, choose the node associated with the highest metric and let its metric value be represented by μ_s.

e. The reliability metric for $d_i = \delta$ of node $\eta[i]$ is calculated as $l = \delta \times |\mu_i - \mu_s|$.

f. Repeat steps (a) to (e) for all the other extended nodes, until the soft outputs for those nodes have been generated.

Again, for the performance results presented in this section, the data bits of each user were passed to a half-rate turbo codec having a constraint length of 3, where the octally represented generator polynomials of 5 and 7 were used. The turbo coded output bits were modulated using DBPSK and spread with a Gold sequence of $Q = 31$ chips. Figure 1 shows the schematic of the PSP receiver having individual turbo decoders for each user. From the composite received signal, $\mathbf{y}$, the PSP receiver generated the estimated bit sequence and the associated soft reliability values for each bit in the estimated sequence. The estimated bit sequence and the associated soft outputs were separated into two sets, namely the estimated bits, $\hat{\mathbf{d}}^{(k)}$, and the soft outputs, $\mathbf{l}^{(k)}$, for each user, which were then passed on to the individual turbo decoders of the users. The turbo decoder of each user then employed the Max-Log-MAP algorithm in order to generate the final data bits, $\mathbf{d}^{(k)}$.

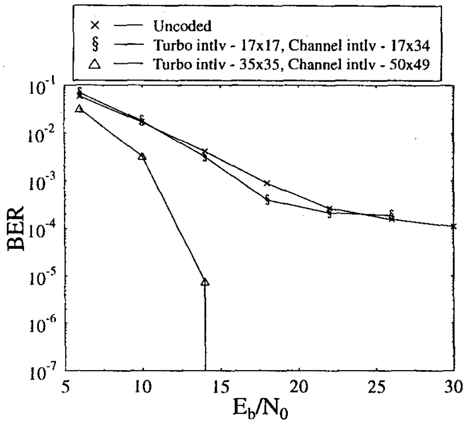

Figure 3: BER performance of a two-user CDMA system employing blind PSP receivers in conjunction with adaptive RLS CIR estimation. Half-rate turbo convolutional coding was employed with a constraint length of 3 using a Max-Log-MAP decoder. Transmission was carried out over two-path Rayleigh-faded channels having the CIRs of Equations 4 and 5.

Figure 3 shows the BER performance of the turbo-coded PSP receiver for a two-path Rayleigh-faded channel with different turbo interleaver sizes. From the performance results shown it can be observed that a large turbo interleaver with the square dimensions of (35 × 35) bits and a channel interleaver with the dimensions of (50 x 49) bits were required, in order to remove the error floor. When the turbo interleaver size was decreased to (17 x 17) bits and the channel interleaver size was reduced to (17 x 34) bits, the error floor persisted.

The BER performance over the COST 207 Typical Urban (TU) four-path channel [15] of Figure 5 is shown in Figure 4. In these investigations the CIR taps were assumed to be slow and constant over one transmission burst, but varied from burst to burst. Here, the size of the turbo interleaver was kept constant and had dimensions of (29 x 29) bits, but the channel interleaver size was varied. By increasing the channel interleaver size, the burst errors were further randomized and this benefitted the channel decoding process. From the results shown, it can be seen that it is important to randomize the burst errors with the aid of a large channel interleaver. For channel interleaver sizes of (72 x 72), (83 x 83), and (100 x 100) bits, the error floor in the BER performance was eliminated.

In Figure 6 the effect of the turbo interleaver size on the BER performance was investigated over the COST 207 Typical Urban channel of Figure 5 as before. In these investigations the channel interleaver size was maintained at (100 x 100) bits, while two different turbo interleaver sizes of (29 x 29) and (35 x 35) bits were compared. Here, in conjunction with the large channel interleaver size of (100 x 100) bits, varying the turbo interleaver size did not have a significant impact on the BER performance and the error floor of the uncoded system was eliminated with the aid of turbo coding.

Finally, the BER performance of the turbo-coded system is evaluated for the fast-fading COST 207 TU four-path channel of Figure 5. In this scenario, the fading varied continuously over the entire transmitted burst. We observe from the results shown in Figure 7 that a large turbo interleaver and a large channel interleaver were required in order to remove the error floor. The dimensions of the turbo and channel interleaver that achieved this were (55 x 55) and (156 x 156) bits, respectively, where the increased performance potential was mainly attributed to the increased turbo interleaver size.

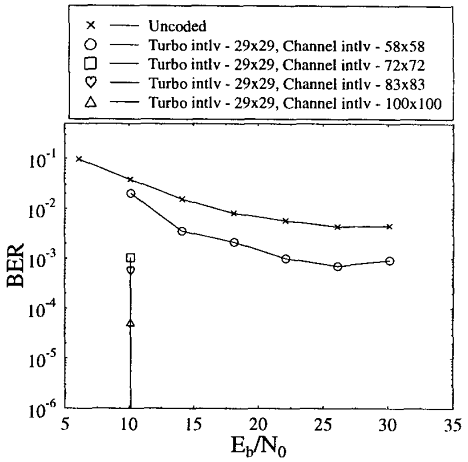

Figure 4: BER performance of a two-user CDMA system employing blind PSP receivers in conjunction with adaptive RLS CIR estimation. Half-rate turbo convolutional coding was employed with a constraint length of 3 using a Max-Log-MAP decoder. Transmissions were carried out over the slowly-fading four-path Typical Urban channel [15] of Figure 5. The fading rate was set to a Doppler frequency of 0.8 Hz. The vertical BER curves of some of the turbo-coded systems indicate that for $E_s/N_0 > 10$ dB all the errors were corrected by the turbo decoder.

6. SUMMARY AND CONCLUSION

A blind PSP receiver assisted by adaptive RLS CIR estimation was proposed and investigated over a synchronous

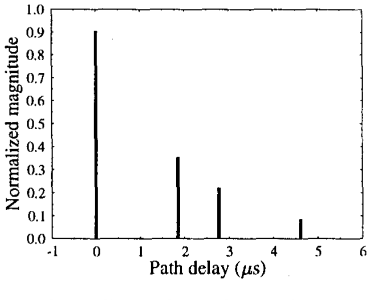

Figure 5: Normalized channel impulse response for the COST 207 [15] **four path Typical Urban (TU) channel.**

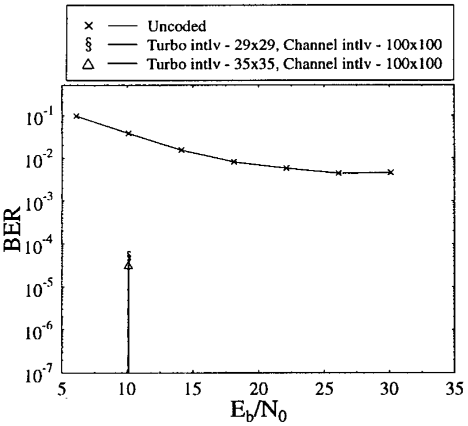

Figure 6: BER performance of a two-user CDMA system employing blind PSP receivers in conjunction with adaptive RLS CIR estimation. Half-rate turbo convolutional coding was employed with a constraint length of 3 using a Max-Log-MAP decoder. Transmissions were carried out over the slowly-fading, four-path TU channel [15] of Figure 5. The fading rate was set to a Doppler frequency of 0.8 Hz. The vertical BER curves of the turbo-coded systems indicate that for $E_s/N_0 > 10$ dB all the errors were corrected by the turbo decoder.

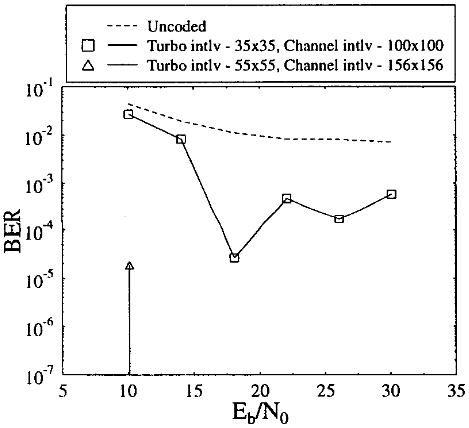

Figure 7: BER performance of a two-user CDMA system employing blind PSP receivers in conjunction with adaptive RLS CIR estimation. Half-rate turbo convolutional coding was employed with a constraint length of 3 using a Max-Log-MAP decoder. Transmission was carried out over the Rayleigh-faded, four-path TU channel [15] as shown in Figure 5. The fading rate was set to a Doppler frequency of 80 Hz. The vertical BER curve of the turbo-coded system with a turbo interleaver of size (55 x 55) indicates that for $E_s/N_0 > 10$ dB all the errors were corrected by the turbo decoder.

multipath multiuser channel. The receiver and CIR estimators operated reliably over static channels, but the BER performance degraded, resulting in an error floor, when fading was inflicted by the channel. This error floor was eliminated, when turbo convolutional coding was employed. The PSP multi-user detector was modified, in order to produce soft outputs, which were then fed to the turbo decoder. With the aid of large turbo and channel interleavers, the BER performance of the multiuser interference contaminated fading channels was improved and the error floor was eliminated. Our future work will incorporate adaptive antenna arrays and space-time coding.

7. REFERENCES

[1] S. Verdú, *Multiuser Detection*, Cambridge University Press, 1998.

[2] G. J. R. Povey, P. M. Grant and R. D. Pringle, "A decision-directed spread-spectrum RAKE receiver for fast-fading mobile channels", *IEEE Transactions on Vehicular Technology*, vol. 45, pp. 491-502, Aug. 1996.

[3] Z. Xie, C. K. Rushforth, R. T. Short and T. K. Moon, "Joint signal detection and parameter estimation in multiuser communications", *IEEE Transactions on Communications*, vol. 41, pp. 1208-1216, Aug. 1993.

[4] T. K. Moon, Z. Xie, C. K. Rushforth and R. T. Short, "Parameter estimation in a multi-user communication system", *IEEE Transactions on Communications*, vol. 42, pp. 2553-2560, Aug. 1994.

[5] N. Seshadri, "Joint data and channel estimation using blind trellis search techniques", *IEEE Transactions on Communications*, vol. 42, pp. 1000-1011, Feb/Mar/Apr 1994.

[6] R. Raheli, A. Polydoros and C.-K. Tzou, "Per-survivor-processing: a general approach to MLSE in uncertain environments", *IEEE Transactions on Communications*, vol. 43, pp. 354-364, Feb/Mar/Apr 1995.

[7] M. Nasiri-Kenari, R. R. Sylvester and C. K. Rushforth, "Efficient soft-in-soft-out multiuser detector for synchronous CDMA with error-control coding", *IEEE Transactions on Vehicular Technology*, vol. 47, pp. 947-953, Aug. 1998.

[8] J. Hagenauer and P. Hoeher, "A Viterbi algorithm with soft-decision outputs and its applications", *Proceedings of IEEE Global Telecommunications Conference, GLOBECOM'89*, (Dallas, USA), pp. 1680-1686, Nov. 27-30, 1989.

[9] C. Berrou and A. Glavieux, "Near optimum error correcting coding and decoding: turbo-codes", *IEEE Transactions on Communications*, vol. 44, pp. 1261-1271, Oct. 1996.

[10] J. B. Anderson and S. Mohan, "Sequential coding algorithms: a survey and cost analysis", *IEEE Transactions on Communications*, vol. 32, pp. 169-176, Feb. 1984.

[11] Ee-Lin Kuan, L. Hanzo: Blind Per-Survivor Processing Multiuser Detection CDMA, submitted to Globecom 2000, 27 Nov.- 1 Dec. 2000, San Francisco, USA

[12] W. Koch and A. Baier, "Optimum and sub-optimum detection of coded data disturbed by time-varying inter-symbol interference", *Proceedings of IEEE Global Telecommunications Conference, GLOBECOM'90*, pp. 1679-1684, 1990.

[13] J. G. Proakis, *Digital Communications*, Mc-Graw Hill International Editions, 1995.

[14] S. Haykin, *Adaptive Filter Theory*, Prentice-Hall International, Inc., 1996.

[15] "COST 207 : Digital land mobile radio communications, final report", , Office for Official Publications of the European Communities, Luxembourg, 1989.