Performance of MIMO Systems with a Hybrid of Transmit Diversity and Spatial Multiplexing

A. L. F. de Almeida, W. C. Freitas Jr., J. C. M. Mota, F. R. P. Cavalcanti and R. L. de Lacerda Neto.
GTEL-UFC: Grupo de Pesquisas em Telecomunicações Sem-Fio, Universidade Federal do Ceará, Fortaleza, Brazil
URL: www.gtel.ufc.br

***Abstract*— Spatial multiplexing or BLAST (Bell Labs Layered Space-Time) and space-time block-coding (STBC) are promise approaches that exploits the MIMO channel to provide higher data rates and diversity gains with no sacrifice in bandwidth. In this work we evaluate the performance of a MIMO system that combines transmit diversity and spatial multiplexing schemes. We also propose two effective receiver structures for this hybrid transmission scheme. Our simulation results show that the performance of the hybrid scheme along with the proposed receivers is excellent, outperforming pure BLAST-based systems and with higher data rates than a pure STBC system.**

***Keywords*— Downlink, MIMO, transmit diversity and spatial multiplexing.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) wireless channels are known to offer better link and/or capacity gains, which can be exploited by employing antenna arrays at both ends of the link [1]. An efficient way of exploiting the MIMO channel is the use of spatial multiplexing or V-BLAST (Vertical Bell Labs Layered Space-Time) [2], [3] that aims at providing higher data rates with no sacrifice in bandwidth. Another approach that benefits from exploiting the MIMO channel is the use of transmit diversity by means of space-time block-coding (STBC) [4], [5] where the idea is to obtain diversity gains at the receiver, with simplified receiver processing. In [4] a remarkable STBC scheme was proposed for transmission with two antennas over flat-fading channels. Due to its very simple structure, this scheme is being considered in UMTS standards as an attractive solution to provide diversity gain on downlink path, i.e., at the mobile terminal. In [5], Tarokh proposed new STBC schemes with more than two transmit antennas. The STBC schemes developed in these works are valid under the assumption of a flat-fading channel only.

However, in high-data rate wireless communications systems, the channel is frequency-selective and the orthogonality between the transmitted symbols that is needed for this schemes to work does not hold. In [6], Lindskog and Paulraj generalized the STBC for channels with inter-symbol interference (ISI), where the transmitted signals are coded on a block-by-block basis instead of a symbol-by symbol basis. This scheme has been called Time-Reversal STBC (TR-STBC). In [7], the TR-STBC was evaluated under the physical layer of the Enhanced Data Rates for Global Evolution (EDGE) [8]. All these schemes provide important diversity gains, but none of them were designed to increase the data rates over the wireless channel. On the other hand, spatial multiplexing transmission schemes such as BLAST [2] attempt to maximize the data rate sacrificing the diversity gains.

In this work we evaluate the performance of a MIMO system that combines transmit diversity and spatial multiplexing schemes. Here, transmit diversity is achieved by means of STBC while spatial multiplexing is achieved with BLAST transmission. We also propose two effective receiver structures for this hybrid scheme. The first hybrid receiver structure (HR-1) is designed to operate on flat-fading channels while the second hybrid one (HR-2) is designed for ISI channels. The performance of the hybrid transmission scheme is compared to that of pure transmit diversity and pure spatial multiplexing schemes in terms of bit-error-rate (BER). Our simulation results show that the performance of the hybrid scheme along with the proposed receivers is excellent, outperforming pure BLAST-based systems in terms of BER and providing higher data rates than a pure STBC system. Thus, the hybrid transmission system will be called BLAST-STBC.

The remainder of this paper is organized as follows. In section II we describe the channel and system model of the hybrid transmission scheme. In section III, the two proposed hybrid receivers are described. Section IV is dedicated to simulation results. The paper finishes in section V with some conclusions.

II. SYSTEM MODEL

A high-level block diagram of the BLAST-STBC system is shown in Fig. 1 for the case of e.g, M=4 transmit antennas and N=4 receive antennas. A serial data stream is split into 2 parallel sub-streams. The 4 antennas are grouped into groups of 2 and within each group STBC is applied. The first and second groups of antennas operate independently by spatially multiplexing the 2 sub-streams of data. All 4 antennas operate in a co-channel way at the same symbol rate with synchronized symbol timing. For the general M by N case, each of the M transmitted signals undergo independent fading so that the signal at each of the N receive antennas is a superposition of M faded (and possibly delayed) versions of the two transmitted signals plus white Gaussian noise. We assume that

A. L. F. de Almeida, W. C. Freitas Jr., J. C. M. Mota, F. R. P. Cavalcanti, R. L. de Lacerda Neto; Departamento de Engenharia de Teleinformática, Universidade Federal do Ceará, Fortaleza, Brasil, E-mails: {andre, walter, mota, rod, raul}@gtel.ufc.br.

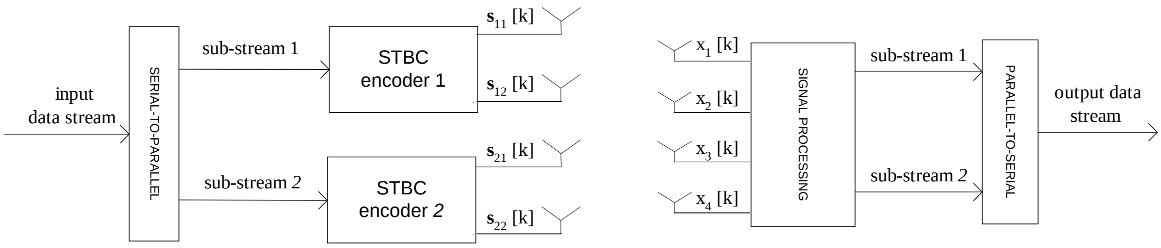

Fig. 1. Overview of MIMO transmission with the hybrid BLAST-STBC system.

the total transmitted power is fixed and normalized to 1. Ideal symbol timing is assumed at the receiver. We assume that the fading is quasi-static over every stream of data. We consider the possibility that the multipath channel is frequency-selective with impulse response of length L. At any time-instant k, the received signal vector can be expressed as

$$\mathbf{x}[k] = \sum_{m=1}^{M/2} \mathbf{G}_m \cdot \mathbf{S}_m[k] + \mathbf{n}[k] \tag{1}$$

$\mathbf{G}_m = [\, \mathbf{H}_m^{(1)} \;\; \mathbf{H}_m^{(2)} \,]$ and $\mathbf{S}_m[k] = [\, \mathbf{s}_{m1}^T[k] \;\; \mathbf{s}_{m2}^T[k] \,]^T$ have length N x $2L$ and $2L$ x 1, respectively. The matrices $\mathbf{H}_m^{(1)}$ and $\mathbf{H}_m^{(2)}$ represent the space-time coded channel for the first and second transmit antennas of each group. The same can be said for the symbol vectors $\mathbf{s}_{m1}^T[k]$ and $\mathbf{s}_{m2}^T[k]$. The summation in 1 is over all the $M/2$ groups of antennas. The N x 1 vector $\mathbf{n}[k]$ denotes the temporally and spatially additive white Gaussian noise (AWGN).

III. Hybrid Receiver Structures

We propose two receiver configurations for the BLAST-STBC scheme. The main purpose of these receivers is to cancel multiple access interference (MAI), defined here as the self interference between data streams of different groups of transmit antenas as well as to maximize the diversity gains of the space-time code. The HR-1 receiver is designed to operate on flat-fading channels only while HR-2 one is designed also for ISI channels. Both receivers are based on minimum mean square error (MMSE) spatial filtering for MAI cancellation plus modified space-time decoders for diversity extraction. In order to explain the principles of the proposed receivers, we first recall the example of a 4 transmit (Tx) and 4 receive (Rx) antennas of the previous section. In this example, the first group of 2 Tx antennas (Tx1 and Tx2) consider the second group (Tx3 and Tx4) as multiple access interferer and vice-versa. This occurs since the groups (Tx1, Tx2) and (Tx3, Tx4) are spatially multiplexing different sub-streams at the same frequency band. The idea of the proposed receivers is to apply:

(i) A MIMO-MMSE spatial filter on the first (second) group to cancel interference from the second (first) group;

(ii) A space-time block code (STBC) decoder on both groups to obtain diversity gains from the spatially multiplexed sub-streams.

After steps (i) and (ii), the 2 sub-streams are re-ordered and converted to the serial unique stream that constitutes the estimated transmitted data. Note that, for a pure STBC system with 2 transmit antennas (e.g. Alamouti's STBC) the total time needed to transmit the same amount of information as BLAST would increase by a factor of 2. On the other hand, for a pure BLAST system with the same 2 transmit antennas, the number of receive antennas necessary to provide the same diversity benefit of STBC would increase by the same factor of 2. Thus, it is reasonable to state that a hybrid combination of BLAST and STBC could achieve a trade-off between data-rate and diversity, respectively. The two receivers proposed in this work are designed to achieve this objective.

The key feature of HR-1 and HR-2 is that MIMO-MMSE spatial filtering is introduced to cancel MAI prior to space-time decoding, such that the orthogonality of the code is preserved. At any time-instant k, the output signal vector of the MIMO-MMSE spatial filter for the *m*th detection group can be expressed as

$$\mathbf{y}_m[k] = \mathbf{W}_m^H \cdot \mathbf{x}[k] \tag{2}$$

where $\mathbf{W}_m = [\mathbf{w}_{m1}, \mathbf{w}_{m2}, \ldots, \mathbf{w}_{mN}]$ is an N x N matrix for the coefficients of the MIMO-MMSE filter associated to the *m*th detection group and Assuming the detection of the *m*th group of transmitted signals, we obtain the error vector at the output of the *m*th MIMO-MMSE filter as

$$\mathbf{e}_m[k] = \mathbf{W}_m^H \cdot \mathbf{x}[k] - \mathbf{G}_m \cdot \mathbf{S}_m[k] = \mathbf{W}_m^H \cdot \mathbf{x}[k] - \mathbf{d}_m[k] \tag{3}$$

where $\mathbf{d}_m[k] = \mathbf{G}_m \cdot \mathbf{S}_m[k]$ is the target signal for the *m*th detection group, $1 \leq m \leq M/2$, consisting of the desired transmitted sequence at instant k convolved with the desired space-time coded channel impulse response. The MMSE cost function is expressed as follows

$$J_m = E\{\|\mathbf{W}_m^H \mathbf{x}[k] - \mathbf{d}_m[k]\|^2\} \tag{4}$$

The optimal coefficients are found by minimizing the above cost function, individually for each group m, $1 \leq m \leq M/2$. The solution is given by

$$\mathbf{W}_m = \mathbf{R}_{xx}{}^{-1}\mathbf{R}_{\mathbf{x}d_m} \tag{5}$$

where $\mathbf{R}_{xx} = E\{\mathbf{x}[k]\mathbf{x}^H[k]\}$ is the input covariance matrix while $\mathbf{R}_{\mathbf{x}\mathbf{d}_m} = E\{\mathbf{x}[k]\mathbf{d}_m^H[k]\}$ is a cross-correlation matrix where the desired signal is represented by $\mathbf{d}_m[k]$. The coefficients of the MIMO-MMSE spatial filter can be computed adaptively by using classical adaptive algorithms

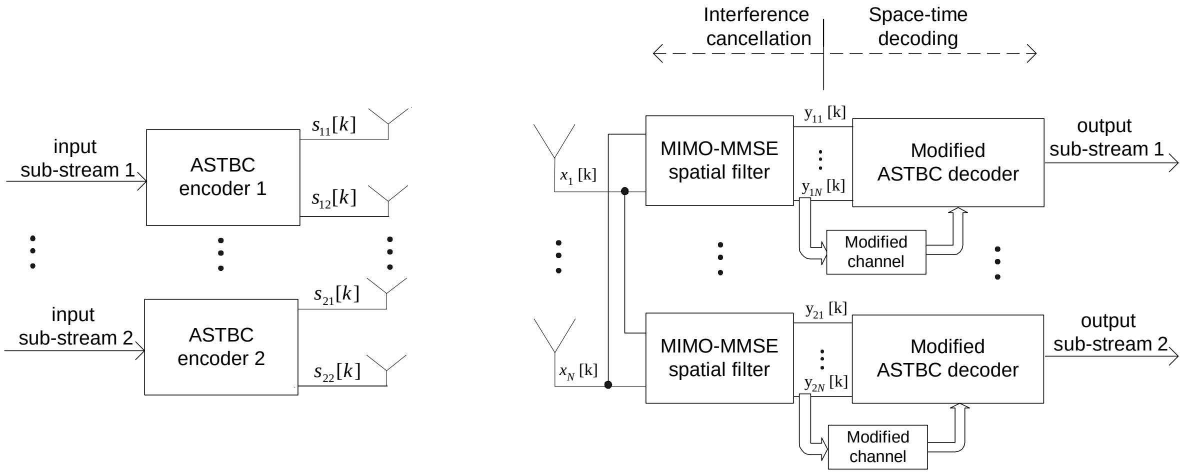

Fig. 2. Structure of the Hybrid Receiver 1 (HR-1) for flat-fading channels.

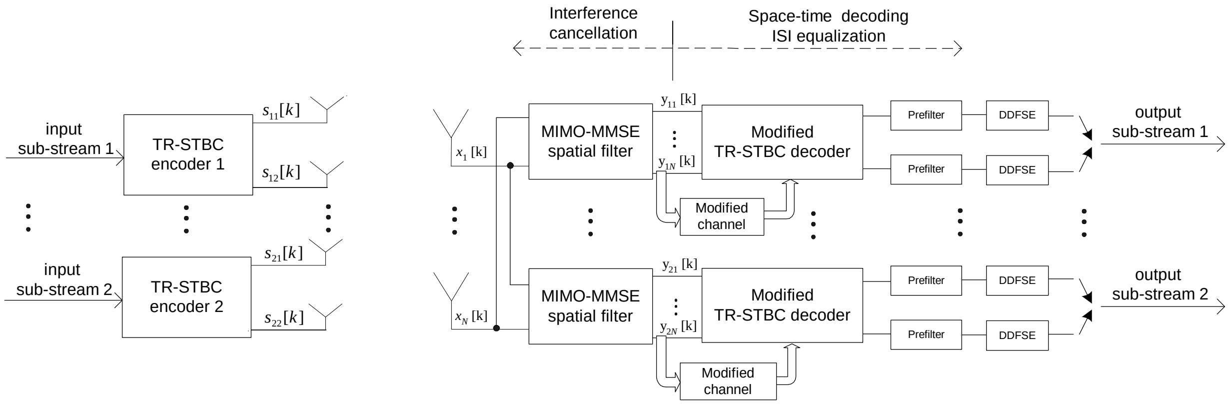

Fig. 3. Structure of the Hybrid Receiver 2 (HR-2) for frequency-selective channels.

such as the recursive least squares (RLS) [10]. In this work we assume perfect channel state information at the receiver.

Assuming residual MAI at the output of the mth MIMO-MMSE filter is negligible, the output signal can be written as

$$\mathbf{y}_m[k] = \mathbf{G}_m^{'} \cdot \mathbf{S}_m[k] + \mathbf{n}^{'}[k] \tag{6}$$

where $\mathbf{G}_m^{'} = \mathbf{W}_m^H \cdot \mathbf{G}_m$ is the modified channel matrix consisting of the original space-time coded channel combined by the coefficients of the MIMO-MMSE filter. This modified channel represents the effective channel that is handled by the space-time decoder and can be interpreted as a *virtual* channel from the 2 transmit antennas of group m to the M outputs of its respective MIMO-MMSE filter. The term $\mathbf{n}^{'}(k)$ is a spatially-colored noise vector containing filtered Gaussian noise and residual MAI.

Figure 2 shows the structure of the HR-1 receiver, designed for flat-fading channels. The HR-2 receiver, designed for frequency-selective channels is shown in Fig. 3. The main difference between these receivers are:

- The ASTBC scheme is replaced by the TR-STBC one in HR-2. This STBC scheme is suitable to provide transmit diversity on ISI channels.
- A DDFSE equalizer is used for ISI equalization. We also employ a prefilter to shorten the channel impulse response and to provide a minimum-phase equivalent of the channel to the DDFSE.

In this work we employ the optimum solution of an MMSE decision-feedback equalizer (DFE) to find the coefficients of the prefilter and those of the feedback filter of the DDFSE. It can be observed in Fig. 3 that we employ 2 independent equalization branches within each detection group, assuming that the orthogonality of the modified channel matrix $\mathbf{G}_m^{'}$ still holds. This assumption is valid if residual MAI at the output of each MIMO-MMSE filter is negligible.

IV. Simulation Results

The performance of the hybrid BLAST-STBC scheme along with the proposed receiver is shown in this section by means of computer simulations. We employ binary-phase-shift-keying (BPSK) modulated symbols and each run represents a transmitted time-slot of 140 payload symbols. We employ M=4 transmit antennas (i.e., 2 groups of 2 antennas) at the base station. The results are evaluated for different number of receive antennas at the mobile terminal, considering both

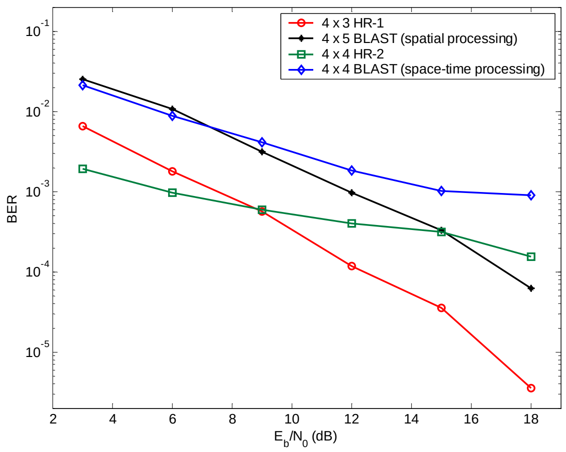

Fig. 4. Performances of the 4×3 HR-1 and 4×5 HR-2 compared to those of the 4×5 and 4×4 pure BLAST receiver, respectively.

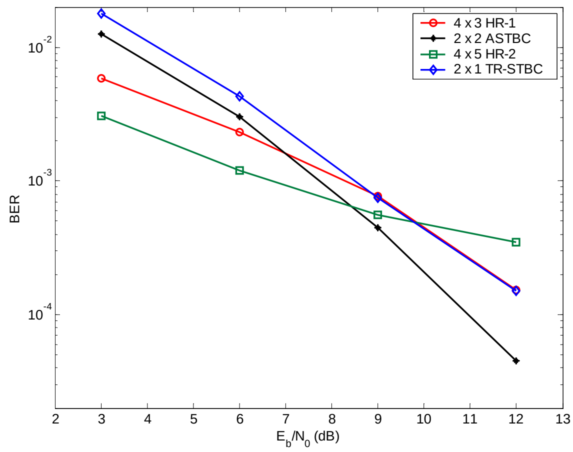

Fig. 5. Performances of the 4×3 HR-1 and 4×4 HR-2 compared to those of the 2×2 ASTBC and 4×4 TR-STBC, respectively.

flat and frequency-selective fading channels. The bit-error-rate (BER) is plotted according to the signal-to-noise-ratio per bit (E_b/N_0). We use the notation $M \times N$ to denote a scheme with M Tx and N Rx antennas.

The results for the HR-1 receiver are for a flat-fading channel and the results for the HR-2 are for a frequency-selective channel always. In the case of HR-2, the frequency-selective channel follows a two-ray Rayleigh fading model with uncorrelated and equal-power paths. The time-delay of the second path is one symbol period. In the following results, the pure BLAST and pure STBC systems are also evaluated as reference systems for comparisons. In the case of the pure BLAST system we employ linear space-time filters at the receiver for joint MAI cancellation and ISI equalization. For the pure STBC system we employ the ASTBC scheme in simulations where a flat-fading channel is assumed. For simulations with ISI, the TR-STBC scheme is used. For the HR-2 receiver, the ML trellis of the DDFSE has memory equal to 1 and the feedback filter employs 1 feedback tap.

When different transmissions schemes are considered, it is convenient to define some criterion to correctly chose the number of Tx and Rx antennas as well as to compare the receivers. In simulations where the hybrid receivers HR-1 or HR-2 are compared to a pure BLAST receiver, the criterion used to select the number of Tx and Rx antennas is the number of degrees of freedom available at the receiver for MAI cancellation. On the other hand, when comparing HR-1 and HR-2 with ASTBC and TR-STBC, respectively, the criterion used to select the number of Tx and Rx is the number of degrees of freedom available to provide a prescribed diversity gain.

In Fig. 4, the BER performance of the 4×3 HR-1 receiver is plotted against that of a 4×5 pure BLAST system with spatial processing, considering a flat-fading channel. We also compare the performance of the 4×4 HR-2 receiver to that of the 4×4 pure BLAST one, under a frequency-selective channel with $L = 2$. In this case the BLAST receiver employs a space-time filter with 5 taps per antenna. It can be seen that the performance of the HR-1 receiver is much better than that of the pure BLAST receiver. The same can be said regarding the HR-2 receiver and the BLAST one with linear space-time processing. In this case, some BER saturation is observed for both receivers, due to some unequalized ISI residual.

Now we compare the HR-1 and HR-2, considering the pure STBC and TR-STBC systems as a reference, respectively. The 4×3 HR-1 is compared to the 2×2 ASTBC under flat-fading and the 4×5 HR-2 is compared to the 2×1 TR-STBC under a frequency-selective channel with $L = 2$. The design of the number of Rx antennas for the HR-1 and HR2 are such that they can obtain the same diversity gain as the pure STBC receivers, assuming MAI is completely cancelled by the MIMO-MMSE filters. Figure 5 shows the performance of the considered schemes. Here we note that the ASTBC outperforms HR-1 as E_b/N_0 increases, where MAI dominant perturbation. The HR-2 receiver performs best at low E_b/N_0 levels, exhibiting some BER saturation as E_b/N_0 increases. Such saturation could be minimized by if more sophisticated prefilters are used. Thus, more investigation is needed to optimize the performance of this receiver. Despite some improved performance of pure STBC receivers over the hybrid ones as E_b/N_0 increases, the first ones only provide diversity gains, while the proposed ones provides both diversity and multiplexing gains with twice the data-rate of the first. However, the main limitation of the hybrid scheme is the increased number of receive antennas necessary at the mobile terminal.

V. Conclusion and Perspectives

In this work, we have evaluated the performance of a MIMO antenna system that is a hybrid of transmit diversity and spatial multiplexing. We proposed two receiver structures for this hybrid BLAST-STBC transmission scheme. Both receivers are based on MIMO-MMSE spatial filters for MAI cancellation plus a modified space-time decoder for diversity extraction.

The optimization criterion and the derivation of optimum receiver settings were presented. Our simulation results show that the performances of HR-1 and HR-2 receivers are superior to those of a pure BLAST receiver under both flat- and frequency-selective channels. Compared to pure STBC systems, the hybrid receivers showed satisfactory performance with some degradation as E_b/N_0 increases. It should be noted that the interesting trade-off between data rate and diversity achieved with hybrid schemes at downlink path, comes at the cost of an increased number of antennas at the mobile terminal. However, we point out that the proposed receivers can cope future wireless systems, where higher data rates and a more reliable downlink performance are simultaneously required.

REFERENCES

[1] G. J. Foschini and M. J. Gans, ”On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas”, *Wireless Personal Communications*, v. 6, n. 3, March 1998, pp. 311-335.

[2] G. J. Foschini, ”Layered Space-Time Architecture for Wireless Communications in a Fading Environment when using Multiple Antennas”, *Bell Labs Tech. J.*, v.1, n.2, 1996, pp.41-59.

[3] G. D. Golden, G.J. Foschini, R.A. Valenzuela, P.W. Wolniansky, ”Detection Algorithm and Initial Laboratory Results using the V-BLAST Space-Time Communications Architecture”, *Electronics Letters*, v.35, n.7, Jan., 1999, pp. 14-15.

[4] S. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal of Selected Areas in Communications*, vol. 16, pp. 1451–1458, Oct. 1998.

[5] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Transactions on Information Theory*, vol. 5, pp. 1456–1467, July 1999.

[6] E. Lindskog and A. Paulraj, “A transmit diversity scheme for channels with intersymbol interference,” in *in Proc. Int. Conf. Communications, New Orleans, LA*, (pp. 307 - 311), June 2002.

[7] D. H. K. Zangi and J. F. Cheng, “Physical-layer issues for deploying transmit diversity in GPRS/EGPRS networks,” in *in IEEE VTC Fall 2001*, (Atlantic City, NJ, USA.).

[8] ETSI TS 100 573, ”*Digital Cellular Telecommunications system (Phase 2+); Physical layer on the radio path; General description.*”

[9] A. Duel-Hallen, C. Heegard, ”Delayed Decision-Feedback Sequence Estimation”, *IEEE Trans. Comm.*, pp. 428-436, May, 1989.

[10] S. Haykin, ”*Adaptive Filter Theory*”, 3^{rd} Ed., Prentice Hall, 1996.