Comparison of Layered and Diversity Approaches for Increasing WCDMA Data Rates in Frequency-Selective MIMO Channels

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Abstract – **Multiple-input multiple-output (MIMO) channels have been shown to offer significant increase in system capacity (bit/s/Hz) when compared to conventional single-input single-output (SISO) systems. The current trend in the 3rd generation WCDMA system evolution is towards higher user data rates which can be achieved using MIMO techniques. So-called layered techniques increase the user data rate but they suffer from high receiver complexity. We propose a low-complexity diversity MIMO scheme which achieves a higher data rate by heavily puncturing the channel code. The proposed diversity scheme is compared to two different layered MIMO schemes in frequency-selective Rayleigh fading channels. The user data rate can be at least doubled by using (2, 2) MIMO techniques while less transmission power is required when compared to a conventional SISO system offering only single data rate.** [1]

I INTRODUCTION

An important aspect of the 3rd generation WCDMA systems is the possibility of obtaining high data rates required by various multimedia and Internet downloading applications. However, the practical rates to be achieved by the new systems as they are launched will be only moderate and are not always comparable to the speed of fixed networks. WCDMA offers a rather challenging environment for increased data rates mainly due to its limited bandwidth and sometimes severe interference levels. The use of higher-order modulation is the most straightforward way of increasing the user data rate, but this approach suffers from high sensitivity to interference. In many cases, it is possible to find more efficient techniques in terms of the required transmission power for a certain quality of service. Especially, utilization of multiantenna transmitters and receivers in order to increase the bandwidth efficiency and user data rate seems to be a promising option.

The use of multiple antennas is justified by an information theoretic result stating that the capacity of a system having N antennas both at the transmitter and the receiver increases linearly with N [1]. The capacity increase may be smaller in practice due to a low signal-to-noise ratio and limited receiver complexity. In this paper, we compare different techniques to increase the data rate of the downlink of WCDMA frequency-division duplex (FDD) system in multiple-input multiple-output (MIMO) channels. The benchmark system is a normal WCDMA downlink using QPSK modulation with a single transmit and receive antenna. To double the user data rate we apply a dual-antenna transmitter (base station) in connection to three different MIMO approaches. The number of receive antennas is limited to two, which is considered to be the maximum practical number of receive antennas in hand-held mobile terminals.

In addition to higher-order modulation, a couple of other techniques for increasing the data rate in MIMO channels can be identified: (i) layered multiantenna transmission [1], and (ii) the use of diversity transmission with a higher rate channel code [3]. The former method basically transmits several independent data streams each from its own transmit antenna. In this way, the data rate is increased but the problem of detecting these interacting data streams is left to the receiver. The latter method applies a space-time block code defined in UTRA FDD specifications to obtain full transmit diversity. The data rate is increased by heavily puncturing the channel code so that the overhead due to the error correcting channel code is reduced leaving more space for the user data symbols. The main difference of the two approaches is that the layered scheme directly applies the transmit antennas for parallel data transmissions while the punctured scheme applies the transmit and receive antennas to obtain diversity against fading to recover the loss due to a weaker channel code and due to the possibly used higher-order modulation.

The rest of the paper is organized as follows. In Section II, two layered MIMO transmission schemes and a diversity MIMO transmission scheme are defined with their respective receiver algorithms. The performance of the receiver is studied in Section III and the results are summarized in Section IV.

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II SYSTEM MODEL

We consider WCDMA FDD downlink in frequency-selective multiple-input multiple-output (MIMO) fading channels. The target is to increase the user data rate by factor 2 compared to the basic single-input single-output (SISO) system. Since in layered MIMO systems [1] different transmit antennas (or groups of transmit antennas) transmit different data streams, at least two antennas are required to achieve a double data rate. To be able to distinguish the parallel streams (layers) at least two receive antennas are required [1]. Thus we concentrate on utilization of (2, 2) MIMO channels formed by two transmit and two receive antennas which are assumed to be uncorrelated.

A. Transmitter Structures

Fig. 1 illustrates the different layered dual-antenna transmission schemes which will be used in the performance analysis. An uncoded data stream is serial-to-parallel converted to the antenna branches each having its own channel encoder of rate $R = 1/3$. By separately encoding each antenna branch a better performance can be achieved but with a higher receiver complexity. The encoder outputs are block-interleaved before modulation and transmission. In *layered scheme* 1 the shaded antenna switching block in Fig. 1 is left out, while in *layered scheme* 2 it is used so that consecutive modulation symbols are always transmitted using a different antenna. In this way a form of transmit diversity is achieved. Both schemes achieve a double data rate compared to the conventional system.

We also use a straightforward diversity approach [3] [6] which aims at maximizing the transmit and receive diversity order. Fig. 2 shows a dual-antenna transmitter which applies the well-known 2x2 space-time block code [4]. In WCDMA it is known as space-time transmit diversity (STTD). The data rate is doubled by heavily puncturing the channel code to achieve rate $R = 2/3$. Naturally, an optimized channel code with rate 2/3 could be used but puncturing is preferred for simpler receiver implementation since fewer code types need to be supported. In addition to a high rate channel code it is possible to use higher-order modulation to further increase the data rate.

B. Receiver Structures

The receiver for the punctured diversity scheme of Fig. 2 is conventional dual-antenna RAKE receiver performing STTD decoding. After this, so-called depuncturing is used in order to replace the punctured code bits (which were never transmitted) by zeros. For the channel decoder the zero-valued inputs represent maximal uncertainty of the soft bit decisions.

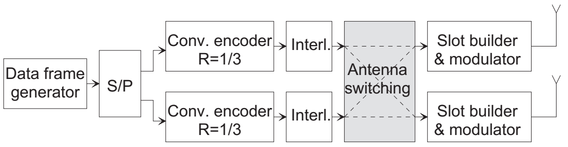

Figure 1: Transmitter for the layered MIMO schemes. The antenna switching block is left out in layered scheme 1 while it is used in layered scheme 2.

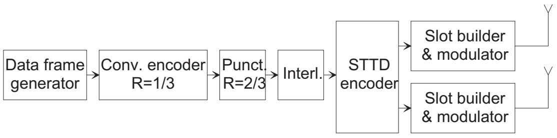

Figure 2: Transmitter for the diversity scheme using puncturing.

The receiver structures for layered scheme 1 and 2 (LS1 and LS2) are much more complex and are shown in Figs. 3 and 4, respectively. Since two interfering signals are to be detected, it is beneficial to first find out which one of the data streams experiences a better channel realization (see e.g. [5]). This is a well-known approach in successive interference cancellation which is applicable in case of LS1: a linear minimum mean-square error (LMMSE) receiver is used for detecting the stronger signal after which it is cancelled from the received signal. Note that a dual-antenna receiver is capable to ”null” one interfering signal especially in frequency non-selective channels. The second, weaker signal can then be detected without interference if no errors occured earlier. Since the layers are individually encoded, we apply the decoded bits in interference cancellation (IC) after proper re-encoding, re-interleaving and respreading have been performed. In this way, very reliable IC can be achieved.

When antenna switching is used in LS2, the two layers experience equivalent channels. Thus there is no reason for trying to detect one of the layers first. This is why, in Fig. 4, both layers are detected simultaneously using two separate dual-antenna LMMSE receivers. After decoding and re-encoding, both output signals are used in IC to produce two signal versions, which are again fed to LMMSE detectors which generate final decisions. This approach increases the complexity when compared to LS1 but is expected to improve the performance.

Both in case of LS1 and LS2, all the used dual-antenna LMMSE receivers are linear *space-time equalizers* fol-

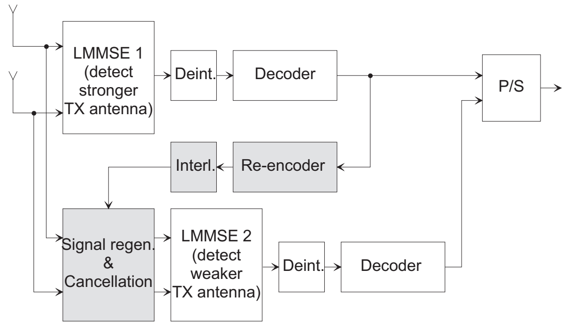

Figure 3: Receiver for layered scheme 1.

lowed by a spreading code correlator. The model for the time-limited, received signal vector at antenna $j \in \{1, 2\}$, when dual-antenna transmission has been used, is

$$\mathbf{r}_j = \mathbf{H}_{1,j}\mathbf{d}_1 + \mathbf{H}_{2,j}\mathbf{d}_2 + \mathbf{n}_j \tag{1}$$

where $\mathbf{H}_{i,j}$ is the convolutional channel matrix, the columns of which are formed by the discretized and properly delayed (vertically shifted) channel impulse responses, $\mathbf{h}_{i,j}$, from transmit antenna i to receive antenna j. All transmit and receive filters are assumed to be included in $\mathbf{h}_{i,j}$. Vector $\mathbf{d}_i$ is the antenna-specific multiuser chip vector, which is formed as a superposition of all users' chips including the effect of user power allocation, symbol modulation, spreading sequences and the scrambling code. Vector $\mathbf{n}_j$ includes noise and interference.

When interference cancellation has been used, the signal model corresponding to receive antenna j can be rewritten as

$$\tilde{\mathbf{r}}_{j,k} = \mathbf{H}_{1,j}\mathbf{d}_1 + \mathbf{H}_{2,j}\mathbf{d}_2 - \hat{\mathbf{H}}_{k,j}\hat{\mathbf{e}}_k + \mathbf{n}_j, \quad k \in \{1, 2\} \tag{2}$$

where index k is the transmit antenna which has been cancelled and $\hat{(\cdot)}$ denotes an estimate of a vector or a matrix. Vector $\hat{\mathbf{e}}_k$ is now the regenerated chip vector including only the desired user's hard symbol estimates which have been spread by the user's spreading code. In case of layered scheme 1, index k can be determined e.g. as[2]

$$k = \arg\max_i \sum_{j=1}^{2} \hat{\mathbf{h}}_{i,j}^{\mathrm{H}} \hat{\mathbf{h}}_{i,j}. \tag{3}$$

In this way, the layer (transmit antenna) received with a higher power level is detected first and then cancelled. Eq. (3) closely approximates the index of the layer which has the best post-detection signal-to-interference-plus-noise ratio (SINR).

The LMMSE space-time equalizer estimates the transmitted multiuser chip vectors, $\mathbf{d}_i$, chip by chip. The individual chip estimates can be written in form [2]

$$\hat{d}_i(n) = \sigma_d^2 \left(\hat{\mathbf{h}}_{i,1}^{\mathrm{H}}(n) \; \hat{\mathbf{h}}_{i,2}^{\mathrm{H}}(n) \right) \hat{\mathbf{C}}_{\mathbf{rr}}^{-1}(n)\mathbf{r}(n) \tag{4}$$

where σ_d^2 is the multiuser chip power and

$$\mathbf{r}(n) = \begin{pmatrix} \mathbf{r}_1(n) \\ \mathbf{r}_2(n) \end{pmatrix} \tag{5}$$

in which the signal vectors are obtained from (1) by taking a sufficient number of samples around the desired chip interval n. The required signal covariance matrix estimate is obtained as a time average

$$\begin{aligned} \hat{\mathbf{C}}_{\mathbf{rr}}(n) &= \frac{1}{2F+1} \sum_{f=-F}^{F} \mathbf{r}(n+f)\mathbf{r}^{\mathrm{H}}(n+f) \quad (6) \\ &\approx \mathrm{E}\left[\mathbf{r}(n)\mathbf{r}^{\mathrm{H}}(n)\right]. \quad (7) \end{aligned}$$

To reduce the receiver complexity, we assume that the covariance matrix is constant over a number of symbol intervals depending on the channel fading speed. A practical choice for this is one WCDMA slot interval (0.67 ms).

Finally, LMMSE symbol decisions are generated by simply correlating the estimated chip sequences by the user's spreading code. It should be noted that the chip estimates include all active users' chips but since the spreading codes are orthogonal and since the signal has been equalized the applied approach is justified and optimal in mean-square error sense. The LMMSE estimators assume that the chip vectors assigned to different transmit antennas are uncorrelated which is the case in layered MIMO transmission. Moreover, when estimating the covariance matrix in (6), it is assumed that receiver does not have any knowledge about the other active code channels in the WCDMA downlink. Hence, eq. (6) implicitly assumes that the users' spreading codes are random. Because the estimated covariance matrix automatically carries the required information about the possible residual interference, estimator (4) can be used also with the interference-cancelled signal model (2). Naturally the signal covariance matrix need to be re-estimated after interference cancellation.

III PERFORMANCE

The performance of the layered MIMO schemes, as well as the punctured diversity MIMO scheme, was evaluated by comparing their performance to a conventional non-punctured (code rate $R = 1/3$) SISO system using conventional RAKE receiver. The evaluation was carried out with two different frequency-selective channel realisations: a two-path pedestrian channel with 3 km/h velocity (PedA), and a five-path vehicular channel with 50 km/h velocity (VehA). The transmit

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[2] In this paper, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote transpose and conjugate transpose, respectively. $\mathrm{E}[\cdot]$ denotes expectation.

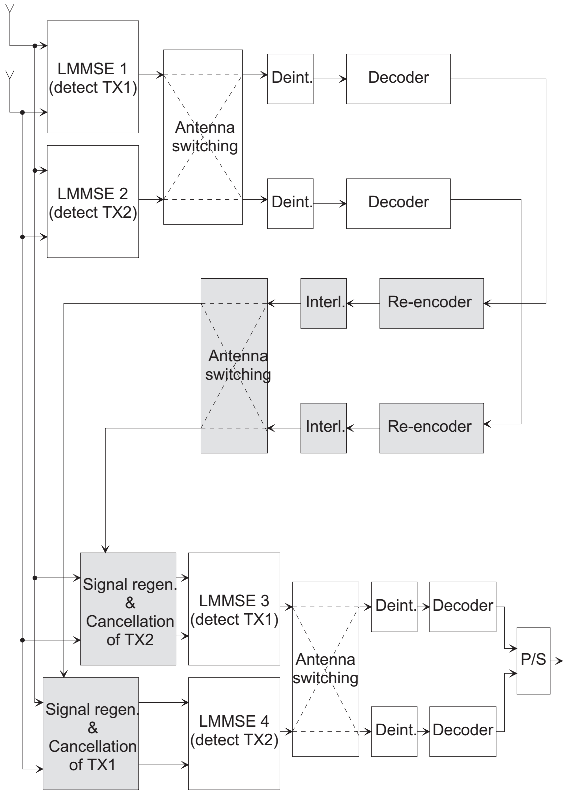

Figure 4: Receiver for layered scheme 2 using antenna switching.

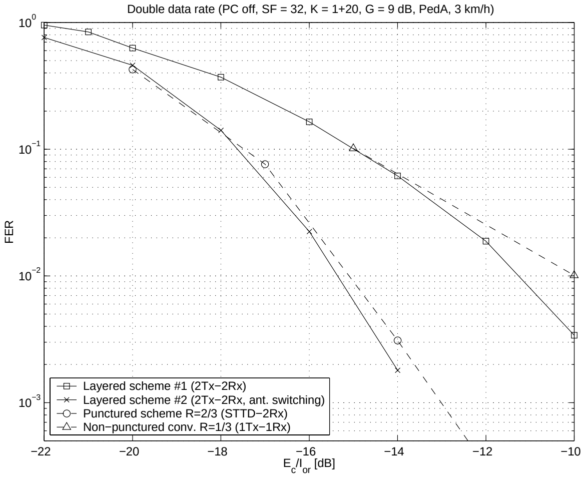

Figure 5: Performance of layered and diversity MIMO schemes in ITU pedestrian A channel.

and receive antennas were assumed to be uncorrelated. QPSK modulation was used in all test cases.

The simulation results are presented as frame error rates (FER) as a function of E_c/I_{or}, where E_c is the transmission power of the desired user and I_{or} is the total transmission power of the base station. The total transmission power was assumed to be fixed and divided between the common pilot channel, the desired user and 20 interfering users. In case of dual-antenna transmission, the transmit power is divided between the antennas so that the total power is not increased compared to single-antenna transmission. The common pilot channel was allocated 10 % of the total transmission power, and it is used for channel estimation in all the test cases. Complex channel coefficients corresponding to each multipath and each transmit-receive antenna pair is estimated by averaging the ”raw” common pilot channel estimates over the time period corresponding to three slots (3 x 0.67 ms). The desired user uses spreading factor 32 while all the interfering users are assumed to be low data rate users with spreading factor of 256.

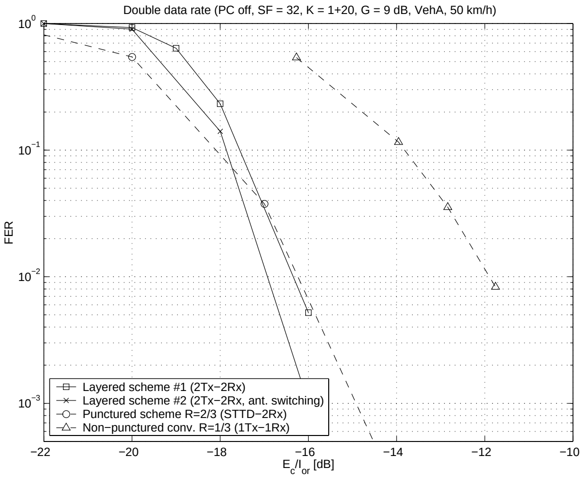

Figure 6: Performance of layered and diversity MIMO schemes in ITU vehicular A channel.

A geometry parameter, G, used in the simulations was defined as

$$G = \frac{I_{or}}{I_{non-or} + N}, \tag{8}$$

where I_{or} is again the signal power from the desired base station, I_{non-or} represents the signal power received from adjacent cells and N is the thermal noise power. The value of G can be related to the user’s position in the cell; a large value indicates that the serving BS is dominating in the received signal and thus the distance to the BS is small. It is expected that high data rate services are possible only at a sufficiently small distance from the BS corresponding to a large G. This is why value $G = 9$ dB has been used. In the simulations the denominator of (8) was modelled as white Gaussian noise which is a good approximation when the number of interfering signal sources with similar power levels is high.

Fig. 5 shows the performance of the layered schemes and the punctured diversity scheme in the two-path pedestrian channel. All the techniques result in double data rate compared to the conventional single-antenna transmission which is also included in the figure. No power control has been used in the simulations. The punctured diversity scheme seems to offer the double data rate with approximately the same transmission power than the best layered scheme, but with significantly lower complexity. The effect of transmit antenna hopping used in layered scheme 2 is clearly visible. Without hopping the lack of transmit diversity degrades the performance of layered scheme 1 since the pedestrian channel offers almost no multipath diversity. Its performance is however similar to single-antenna transmission which offers only half of the data rate. This is actually an expected result since the FER performance is dominated by the frame errors occurring in the detection of the stronger transmit antenna (which is first selected by the receiver). The reason for this is that, when detecting the stronger transmit antenna, the dual-antenna LMMSE suppresses the signal from the other transmit antenna but, at the same time, loses in the receive diversity order. Thus the stronger layer is in effect detected in a (1, 1) ”MIMO” channel, and the total FER should be close to a conventional SISO system. Transmit antenna switching is applied in LS2 to fight against this phenomenon so that some degree of transmit diversity is obtained to partially overcome the lack of receive diversity.

Fig. 6 illustrates the performance in the five-path vehicular channel. Since the multipath diversity order due to the channel is high, the transmit antenna switching is not giving much gain. Layered scheme 2 is however still better than the scheme 1 because its LMMSE reception combined with interference cancellation is more efficient. Even though the transmit diversity used with the punctured scheme provides only moderate additional gain with high order of multipath diversity, the punctured scheme can achieve a performance comparable to the layered schemes with significantly lower receiver complexity. It should be noted that if a dual-antenna LMMSE was used with the punctured diversity scheme instead of a dual-antenna RAKE, the punctured scheme is expected to outperform the other techniques with the tested system parameters.

IV SUMMARY

We have studied different techniques to increase the user data rate in WCDMA FDD downlink by using (2, 2) MIMO antenna configuration. So-called layered schemes transmit parallel data streams from the transmit antennas, while the proposed diversity scheme relies on the high transmit and receive diversity gain to overcome the loss due to weak channel encoding and the possibly used higher-order modulation.

The results show that the punctured diversity MIMO scheme achieves a similar or better performance than the layered MIMO schemes although it requires a significantly lower receiver complexity. This indicates that it is beneficial to increase the channel encoding rate to increase the data rate whenever it is possible. The layered schemes suffer from the fact that suppression of interfering layers causes loss of diversity order, and one of the layers have to be detected practically without any receive diversity. This layer dominates in the total frame error rate performance. It was also indicated that by using transmit antenna switching it is possible to alleviate the lack of transmit diversity suffered by the basic layered scheme.

With all the studied MIMO techniques it is possible to at least double the user data rate achieved in SISO systems without any need for increasing the transmission power and thus interference to other users.

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