Link Adaptation Mechanism Based on Cross Layer Design for MIMO Systems

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Abstract—In this paper, we present and analyze a novel link layer transmission strategy for wireless networks using multiple input multiple output (MIMO) technology at the physical layer. When the channel state information (CSI) is available at the transmitter (CSIT), we present an adaptation algorithm that selects the appropriate orthogonal sub-channels of the MIMO link to use in order to increase the link layer throughput while maintaining an acceptable frame loss rate. Computer simulations show that the proposed adaptation technique provides a significant performance improvement achieved by designing MIMO-aware link layer algorithms.

Index Terms—Cross layer, Link adaptation, MIMO systems

I. INTRODUCTION

Wireless communication systems using multiple antennas, MIMO, are considered one of the best approaches for providing high data rate wireless links and are presently at the leading edge of wireless systems research. MIMO is prominently regarded as a technology of choice for future commercial wireless networks such as IEEE 802.11, IEEE 802.16, cellular third generation (3G) systems, etc [1].

Since the pioneering work on MIMO wireless systems that predicted a remarkable spectral efficiency [2], [3], research has been mostly focused on the development of physical layer algorithms and coding techniques for reaching the theoretical MIMO capacity [3], [5]. However, wireless communication systems generally consist of several layers, and the use of multiple antennas does not affect only the physical and coding layers, but also impacts the higher layers. By designing algorithms for every layer taking advantage of the multiple antennas, one can envision that the global performance of the wireless system will improve significantly. In this paper, we present a new link adaptation technique based on cross layer design in order to exploit the multiple antennas for improving the error control link layer performance.

In the literature, some approaches for combining an automatic repeat request (ARQ) procedure with multiple antenna technology have been proposed, some of which attempt to improve the physical layer performances by introducing a relatively complex ARQ procedure at the symbol level [8]. In [9], the authors propose to combine ARQ with multidimensional trellis coded modulation. Other schemes have been developed in the particular context of implementing MIMO in 3G cellular wireless networks [10]. In [11], we have defined new strategies for transmitting a frame, encoded using a hybrid ARQ-FEC (Forward Error Correcting) error control coding strategy [7], horizontally or vertically from the antenna array when the CSI is available only at the receiver (CSIR). In this paper, we consider a MIMO system where the CSI is perfectly known at both the transmitter (CSIT) and at the receiver (CSIR). However, in real systems where the CSI available at the transmitter is imperfect [4], the performance of our proposed technique represents an upper bound.

In this paper, we assume the use of a type-I hybrid ARQ-FEC [7]. When the transmitter knows perfectly the channel state, using singular value decomposition (SVD), the MIMO channel can be decomposed into orthogonal sub-channels [6]. Our proposed adaptation technique uses the appropriate number of orthogonal sub-channels for transmission while maintaining an acceptable frame loss rate (FLR) with the objective of improving the link throughput, defined as the rate of frames received correctly at the link level.

The paper is structured as follows. The system model is given in Section II. We present in Section III the novel frame level transmission technique. Simulation results illustrating the performance of the proposed technique are shown in Section IV. The paper is concluded in Section V.

II. SYSTEM MODEL

A. Channel Model

We consider a wireless link model with $M_T$ transmit antennas and $M_R$ receive antennas. The $M_R \times M_T$ channel matrix $H = [h_{i,j}]$ describes the channel. The flat fading coefficient $h_{i,j}$ represents the complex path gain from transmit antenna $j$ to receive antenna $i$. In Section IV, we assume for simulation purpose that the $h_{i,j}$’s are independent identically distributed (i.i.d.) zero mean complex Gaussian random variables, circularly symmetric distributed with unit variance. The received $M_R \times 1$ vector $r$ can be written as:

$$ r = Hs + w, \quad (1) $$

where $s$ is the $M_T \times 1$ transmitted vector and $w$ is the $M_R \times 1$ additive white circularly symmetric complex Gaussian noise vector associated with the transmission of $s$. The covariance matrix of the noise is $N_0 I_{M_R}$ where $I_{M_R}$ is the $M_R \times M_R$ identity matrix. We assume that an independent noise vector $w$ is observed for each transmitted vector.

Let $T_f$ be the time required for transmitting one frame on a single-input single-output (SISO) link. We assume that
of generality, that $\mathbf{H}$ matrix whose diagonal elements $\sigma$ conjugate of a matrix $\mathbf{M}$ have the same error rate denoted by the number of errors is not larger than the error correcting (considering the worst case) by the FEC decoder only when the number of errors is not larger than the error correcting capability of the code denoted by $t$. Assuming that all the bits have the same error rate denoted by $P$, the frame error rate (FER) is given by: $\text{FER} = 1 - \sum_{i=0}^{\sigma} \binom{N}{i} (1 - P)^{N-i} P^i$.

Whenever the ARQ system fails to detect an erroneous frame, we have a non-detectable error event. However, the probability of non-detectable errors is assumed to be quite negligible. When a frame is sent $U$ times without success, then no further retransmissions are attempted and the frame is considered lost. Note that the channel changes also for the retransmitted frames.

### III. Adaptive Transmission Technique

In [11], we have investigated the error performance at frame level for a MIMO system using a hybrid ARQ-FEC scheme with no CSIT. By developing variants of layered space time techniques [3], an encoded frame can be sent entirely from one antenna (horizontal transmission) or it can be divided into $M_T$ sub-frames and each sub-frame sent using one of the $M_T$ antennas (vertical transmission). We have showed that using the vertical transmission gives better error performances for moderate and high SNR (Signal to Noise Ratio). When a limited binary feedback is available, a selection criterion have been proposed in order to choose between the two techniques.

Assuming perfect CSIT, an SVD decomposition of the MIMO channel provides $R_H$ orthogonal sub-channels where $R_H$ is the rank of the channel matrix $\mathbf{H}$ [4]. Therefore, $\mathbf{H} = \mathbf{U} \mathbf{A} \mathbf{V}^H$ where the $M_R \times M_R$ matrix $\mathbf{U}$ and the $M_T \times M_T$ matrix $\mathbf{V}$ are unitary matrices, $\mathbf{V}^H$ is the transpose conjugate of a matrix $\mathbf{V}$ and $\mathbf{A}$ is a $M_R \times M_T$ diagonal matrix whose diagonal elements $\sigma_1, \ldots, \sigma_{R_H}$ are the real nonnegative singular values of $\mathbf{H}$. We assume, without loss of generality, that $\sigma_1 \geq \ldots \geq \sigma_{R_H} \geq 0$.

By sending independent data across each of the parallel channels, the MIMO channel supports $R_H$ times the data rate of a SISO system. Note that the $j$th sub-channel transmission capacity depends on its associated gain $\sigma_j$. Similar to [11], an encoded frame can be sent entirely over one sub-channel (horizontally) or it can be divided into $R_H$ sub-frames and sent vertically over the non-correlated $R_H$ sub-channels. The analysis presented in [11] can be extended to a MIMO system with CSIT. Consequently, we expect that vertical transmission outperforms the horizontal transmission for moderate to high SNR. In this paper, we introduce a new strategy that selects the appropriate sub-channels for transmitting vertically a frame in order to increase the link throughput. The physical throughput, defined as the number of frames sent during $T_f$, can be increased by transmitting over all the sub-channels; whereas, the BER is decreased by sending a single data stream on the sub-channel having the largest gain. However, the link throughput defined as the number of frames received correctly at the link layer during $T_f$, is BER-dependent. It is increased by finding a trade-off between the physical throughput and the error rate.

Let $BER^{(M)}$ be the average BER when the $M$ sub-channels having the largest gains are used. The proposed algorithm attempts to find the highest number of sub-channels, $M_{opt} = 1, \ldots, R_H$ that can be used while satisfying $BER^{(M_{opt})} \leq \frac{f}{U}$. The rational behind this constraint is that if $\frac{f}{U}$, the ratio between the correcting capability of the FEC code and the FEC codeword length, is higher than the BER, most of the frames sent using the vertical transmission will be received correctly. Then, the FEC and thus the frame loss rate (FLR) will have acceptable small values.

Let $\rho_i$ be the energy allocated to the $i$th ($1 \leq i \leq R_H$) sub-channel. The bit error rate for data transmitted over the $i$th sub-channel, $P_i$, using coherent detection and Binary Phase Shift Keying (BPSK) modulation is given by [12]:

$$P_i = Q\left(\sqrt{\frac{2\rho_i\sigma_i^2}{N_0}}\right).$$

(2)

Using the typical approximation of the function $Q(x)$, we obtain from the equation (2):

$$BER^{(M)} \approx \frac{1}{2M} \sum_{m=1}^{M} \exp\left(-\frac{\rho_i\sigma_i^2}{N_0}\right).$$

(3)

The transmit energy allocated during one symbol period, $E_s$, can be optimally distributed across the sub-channels to minimize the $BER^{(M)}$ for a fixed $M$ [6]. If there is no worst-case BER constraints in the system, then $BER^{(M)}$ can be minimized when $\rho_i$, $1 \leq i \leq M$, is given by [6]:

$$\rho_i = N_0 \frac{\log(\sigma_i) - \mu}{\sigma_i},$$

(4)

where $\mu$ is chosen to satisfy the power constraint, i.e., $\sum_{i=1}^{M} \rho_i = E_s$.

To find the value of $M_{opt}$, first, the algorithm considers $M = R_H$ and calculates the corresponding $BER^{(M)}$ using (3). If the constraint $BER^{(M)} \leq \frac{f}{U}$ is satisfied, then, the algorithm selects $M_{opt} = M$. Alternatively, if $BER^{(M)} > \frac{f}{U}$, the algorithm decreases $M$ by one and recalculates the new $BER^{(M)}$. The algorithm continues this operation until $M_{opt}$ is found. If $M$ reaches 1 without satisfying the bit error rate constraint, then the transmitter sends a single frame over the sub-channel having the largest gain.
Fig. 1 presents a diagram of the proposed adaptation strategy. After the FEC encoder, each frame is segmented into $M_{opt}$ sub-frames and transmitted vertically over the $M_{opt}$ sub-channels with the largest gains. The frames are reassembled at the reception before being sent to the FEC decoder. Next, the error detecting code decides whether the frame is received correctly or erroneously.

IV. SIMULATIONS RESULTS

In this section, simulation results are presented showing the performance improvement obtained with our proposed technique. We consider a $4 \times 4$ MIMO system with perfect CSIT and CSIR. The performances are calculated as a function of the signal to noise ratio at the transmission defined as: $SNR = \frac{E_s}{N_0}$. For simulation purpose, we assume a rich scattering environment leading to $R_H = \min(M_R, M_T)$.

Fig. 2 shows the FER using horizontal or vertical transmission. The curves $M = 2, 3, 4$ correspond to a fixed number of sub-channels (the most dominant) used simultaneously. The curve $M_{opt}$ illustrates the FER obtained when $M$ is selected adaptively according to the algorithm described in Section III. We notice that the vertical transmission outperforms the horizontal one for FER $< 20\%$. Note that this high FER can be reached only when $M = 4$. As $M$ gets larger, the error rate is higher and consequently the gap between the vertical and the horizontal transmission is more significant. The difference is also significant when $M$ is adapted ($M_{opt}$) to increase the link throughput. It is interesting to notice that FER increases with SNR for low SNR in the curves corresponding to $M_{opt}$. This is due to the fact that when the SNR increases, $M_{opt}$ increases to improve the link throughput. Hence the system increases its physical throughput at the cost of higher FER.

Frame loss rate (FLR) is defined as the rate of frames transmitted $U$ times without success. We consider $U = 3$.

From Fig. 3, we notice that when the extended Golay Code $[N = 24, K = 12, t = 3]$ is used, the proposed strategy achieves better link throughput (Fig. 3.a) while maintaining FLR $< 2 \times 10^{-4}$ (Fig. 3.b) which is acceptable for most of the wireless data applications. Similar results are observed (Fig. 4.a) using the extended Hamming code $[N = 24, K = 19, t = 1]$. Some FLR curves do not appear in figures 3.b and 4.b because FLR values are smaller than $10^{-5}$.

V. CONCLUSION

We have investigated new frame-level transmission strategy efficiently adapted for a MIMO wireless system using a hybrid ARQ-FEC coding scheme. When the channel is perfectly known at the transmitter, MIMO channel can be de-
composed into orthogonal sub-channels. We have presented a transmission scheme that increases the link throughput by adapting appropriately the number of used sub-channels while maintaining an acceptable frame loss rate. Simulation results showed that the rate of correctly-received frames increases while the frame loss rate is kept significantly small with our proposed transmission strategy.

Future work will investigate the impact of CSIT imperfection as well as multiuser scheduling on the proposed strategy.

REFERENCES