Link Adaptation Mechanism Based on Cross Layer Design for MIMO Systems

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Abstract—Multiple input multiple output (MIMO) communication systems introduce a new spatial paradigm that can be exploited to improve the performance of higher link layer protocols. In this paper, we are presenting and analyzing a novel link layer transmission strategy for wireless networks using 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 proper orthogonal sub-channels of the MIMO link to be used for increasing the link layer throughput while maintaining an acceptable frame loss rate. The proposed adaptation technique shows a significant performance improvement achieved by designing MIMO-aware link layer algorithms.

I. INTRODUCTION

Wireless communication systems using multiple antennas, MIMO, are considered one of the best approaches for providing high data rate wireless links and therefore they are 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 to reach the theoretical MIMO capacity [3], [4]. 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 define a new link adaptation technique based on cross layer design aiming to exploit the multiple antennas for improving the error control link layer performance.

In the literature, some propositions attempt to combine an automatic repeat request (ARQ) procedure with multiple antenna technology. Various proposals 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 propositions are developed in the particular context of implementing MIMO in 3G cellular wireless networks [10]. In [11], the authors define new strategies for transmitting a frame, encoded using a hybrid ARQ-FEC (Forward Error Correcting) code [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 also perfectly known at the transmitter (CSIT and CSIR). Anyhow, in real systems, the CSI available at the transmitter is imperfect [5]. In this case, the performance of our proposed technique presents an upper bound.

We assume in this paper the use of a type-I hybrid ARQ-FEC [7]. When the transmitter knows perfectly the channel state, the MIMO channel can be decomposed using singular value decomposition (SVD) 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) aims with the goal 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 introduce in Section III a novel frame level transmission technique that enhances the link throughput for a MIMO system with CSIT. 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.) random variables, complex Gaussian zero mean circularly symmetric distribution with unit variance. The received $M_R \times 1$ vector $\mathbf{r}$ can be written as:

$$\mathbf{r} = \mathbf{Hs} + \mathbf{w},$$  \hspace{1cm} (1)

where $\mathbf{s}$ is the $M_T \times 1$ transmitted vector and $\mathbf{w}$ is the $M_R \times 1$ additive white circularly symmetric complex Gaussian noise vector associated with the transmission of $\mathbf{s}$. The covariance matrix of the noise is $\mathbf{N}_0 \mathbf{I}_{M_R}$ where $\mathbf{I}_{M_R}$ is the $M_R \times M_R$ identity matrix. We assume that an independent noise vector $\mathbf{w}$ 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 $T_f$ is smaller than the channel coherence time, so that $H$ is considered constant during $T_f$ but varies every $T_f$. We assume that the channel state information is perfectly known at the transmitter and at the receiver (i.e., CSIT and CSIR).

B. Error Control Model

For controlling the transmission errors, the system model utilizes a type-I hybrid ARQ-FEC with a selective repeat ARQ protocol at the link layer [7]. The link layer data units are encoded with an error detecting code, used by the ARQ procedure, followed by an $(N, K)$ binary FEC code. Those $N$ bits are modulated and transmitted over the MIMO link. An erroneous codeword can be corrected (considering the worst case) by the FEC decoder only when the number of errors is not higher 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:

$$\text{FER} = 1 - \prod_{i=0}^{t} \left(1 - (1 - P)^{N-i} P^i\right).$$

(2)

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 quite negligible. When a frame is sent $U$ times without success, we consider no further retransmissions and that the frame is lost. Note that the channel changes for the retransmitted frames.

III. ADAPTIVE TRANSMISSION TECHNIQUE

In [11], the authors have investigated the error performance at frame level for a MIMO system using a hybrid ARQ-FEC coding 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). The authors showed that using the vertical transmission gives better error performances for moderate and high SNR (Signal to Noise Ratio) values. When a limited binary feedback is available, the authors have proposed a selection criterion 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 $H$ [5]. Therefore, $H = U \Lambda V^H$ where the $M_R \times M_R$ matrix $U$ and the $M_T \times M_T$ matrix $V$ are unitary matrices, $V^H$ is the transpose conjugate of a matrix $V$ and $\Lambda$ 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 $H$. 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 $j^{\text{th}}$ 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 defined as the rate of frames received correctly.

The physical throughput, defined as the number of frames sent during $T_f$, can be increased by sending on 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 tradeoff 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 the following constraint, $BER_M^{(M_{opt})} \leq \frac{1}{N}$. The rational behind this constraint is that if $\frac{1}{N}$, 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 FER and thus the frame loss rate (FLR) will have acceptable small values.

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

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

(3)

Using the typical approximation of the function $Q(x)$, we obtain from the equation (3):

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

(4)

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

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

(5)

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 $BER_M^{(M)}$ using (4). If the constraint $BER_M^{(M)} \leq \frac{1}{N}$ is satisfied, then, the algorithm selects $M_{opt} = M$. Alternatively, if $BER_M^{(M)} > \frac{1}{N}$, the algorithm decreases $M$ by one and recalculates the new $BER_M^{(M)}$. The algorithm continues this operation until $M_{opt}$ is found. If $M$ reaches 1 without satisfying the bit error rate
constraint, 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. The error detecting code within the ARQ procedure decides then 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 in 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 detailed 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 performances of vertical and 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 note that FER increases with SNR for low SNR in the curves corresponding to $M_{opt}$. This is due to the fact that when 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 adaptation 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 noticed when the extended Hamming code $[N = 24, K = 19, t = 1]$ is used from Fig. 4. Some FLR curves does 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 hybrid
ARQ-FEC coding. When the channel is perfectly known at the transmitter, MIMO channel can be decomposed 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 loss rate. Simulation results showed that the rate of correctly-received frames increases while the frame loss rate is kept significantly small with this proposed transmission strategy.

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

REFERENCES


