Cross-Layer Based Transmit Antenna Selection for Decision-Feedback Detection in Correlated Ricean MIMO Channels

Hassan A. Abou Saleh and Walaa Hamouda, *Senior Member, IEEE*

***Abstract*—In this paper, we investigate a cross-layer transmit antenna selection (AS) approach for the decision-feedback detector (DFD) over spatially correlated flat Ricean fading multiple-input multiple-output (MIMO) channels. Closed-form expressions for the system throughput with both perfect and imperfect channel estimation are derived. Considering a training-based channel estimation technique, we show that the capacity-based AS is more robust to imperfect channel estimation. However, in all cases, the cross-layer AS delivers higher throughput gains than the capacity-based AS.**

***Index Terms*—Correlated fading, multiple-input multiple-output (MIMO), cross-layer, antenna selection (AS).**

I. INTRODUCTION

THE ultimate objectives of new wireless communication systems are to accommodate the quality of service (QoS) and rate requirements set by forthcoming applications like multimedia messaging service, video chat, and other streaming services. To this end, the new emerging wireless technologies adopt multiple-input multiple-output (MIMO) systems [1]. Recently, many detectors have been proposed to exploit the high spectral efficiency of MIMO systems, among which is the decision-feedback detector (DFD), also known as the vertical Bell labs layered space-time (VBLAST) [2]. Using ordered successive interference cancelation (OSIC), the DFD can reap a large fraction of the high spectral efficiency of a MIMO system.

The dramatic performance enhancement of multiple-antenna systems comes with an increased hardware complexity, e.g., analog radio frequency (RF) chains, low-noise amplifiers (LNAs), etc. This complexity problem can be mitigated using antenna selection (AS) at the transmitter and/or receiver. With AS, a small number of analog RF chains are multiplexed between a much larger number of transmit/receive antennas. AS for spatial multiplexing systems was first presented in [3]. More specifically, the authors show that feeding back an optimal subset of transmit antennas often increases system capacity over the case of no feedback. In [4], the authors present an AS approach that aims at minimizing the system error rate for linear receivers.

In the aforementioned works, the authors study AS from a physical layer standpoint (e.g., capacity and error probability criteria). However, in practice, link quality is determined by both physical and data-link layers. In [5], the authors investigate the performance of a cross-layer design employing automatic-repeat-request (ARQ) and transmission control protocol (TCP) based on the VBLAST architecture over Rayleigh fading channels. A cross-layer approach that combines AS and adaptive modulation, in Rayleigh fading channels, is investigated in [6], in which a hybrid automatic-repeat-request (H-ARQ) technique is used at the data-link layer to improve the link throughput. Based on the zero-forcing (ZF) detection, the authors in [7] propose a family of multiuser scheduling methods that take into consideration the packet throughput in upper-layer protocols. However, it is important to mention that the works in [5]–[7] relied on assumptions that are too optimistic to be practical: $i)$ uncorrelated signal propagation paths; $ii)$ absence of direct-path propagation; $iii)$ channel state information (CSI) perfectly known at the receiver. Only more recently, researchers realized the importance of those issues, where measurement results indicate that channels suffer from correlation [8]. Thus, the independent Rayleigh fading model assumed in [5]–[7] is not suitable in practice especially for systems that have poor scattering conditions and/or insufficient spacing between adjacent antennas. Note that, in our work, we restrict our attention to the exponential correlation model [9]. The latter is physically realistic since correlation decreases with increasing distances between antennas.

Motivated by the observations given above, in this paper, we extend the works in [5]–[7] to spatially correlated Ricean MIMO channels and pilot-aided channel estimation. Closed-form expression for the system throughput, with both perfect and imperfect CSI at the receiver, are derived. Our results reveal that the capacity-based AS is less sensitive to channel estimation errors than the cross-layer approach. However, in all cases, the cross-layer AS approach is able to deliver higher throughput gains than the capacity-based approach.

The remainder of the paper is organized as follows. The system model is introduced in Section II. The performance analysis of the cross-layer AS is presented in Section III. Simulation results for the link level performance are discussed in Section IV. Finally, conclusions are outlined in Section V.

II. SYSTEM MODEL

We consider a point-to-point single-user MIMO wireless packet switched communication system with M transmit and N $(N \geq M)$ receive antennas, and a $1 : K$ $(K \leq M)$ spatial multiplexer as shown in Fig. 1. For the sake of simplicity (i.e., reduced delay and buffer requirements), a go-back-n (GBN) protocol [10] is adopted at the link level. At the receiver end, a DFD is employed to cancel interference and improve detection of the transmitted packets.

We assume transmissions are organized in frames, all of fixed predefined length L. At the transmitter, the incoming

Manuscript received September 14, 2008; revised November 25, 2008; accepted November 27, 2008. The associate editor coordinating the review of this letter and approving it for publication was Y. J. Zhang.

The authors are with the Department of Electrical and Computer Engineering, Concordia University, Montréal, Quebec, H3G 1M8, Canada (e-mail: h_abousa@encs.concordia.ca; hamouda@ece.concordia.ca).

Digital Object Identifier 10.1109/TWC.2009.081235

$$\begin{aligned}\eta\left(\mathbf{H}_p\right) &= K\cdot\frac{1-\mathrm{PER}\left(\mathbf{H}_p\right)}{1+\left(W-1\right)\mathrm{PER}\left(\mathbf{H}_p\right)}\\ &= K\cdot\frac{\left[\prod_{i=1}^{K}\left(1-Q\left(\sqrt{2\,r_{i,i}^2\,\gamma_0}\right)\right)\right]^{L/K}}{\left[1+\left(W-1\right)\left(1-\left[\prod_{i=1}^{K}\left(1-Q\left(\sqrt{2\,r_{i,i}^2\,\gamma_0}\right)\right)\right]^{L/K}\right)\right]},\end{aligned} \tag{8}$$

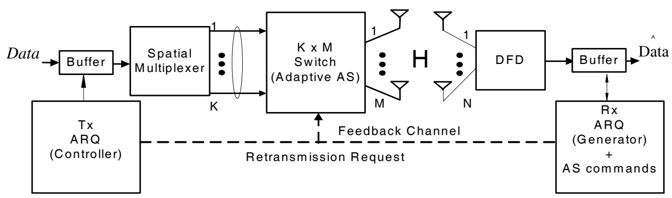

Fig. 1. Block diagram of the communication system model.

data is fed into a spatial multiplexer that splits the input data streams among the K active antennas out of the M possible ones. The optimal subset $p \in P$ of size K is determined at the receiver and conveyed to the transmitter through, low-bandwidth, zero-delay and error-free, feedback channel. The latter assumption may not always hold true, and can lead to a performance degradation compared with ideal channels. Note that P is given by

$$P=\left\{\binom{M}{K};\ \text{for } K=1,2,\ldots,M\right\}. \tag{1}$$

Let $\mathbf{H}$ denote the $N\times M$ channel matrix, and $\mathbf{H}_p$ denote the $N\times K$ channel submatrix corresponding to optimal transmit antennas in p. The corresponding sampled received baseband signal is given by

$$\mathbf{y}=\mathbf{H}_p\,\mathbf{\Pi}\,\mathbf{x}+\mathbf{n}, \tag{2}$$

where $\mathbf{y}\in\mathcal{C}^{N\times 1}$ is the received signal, and $\mathbf{H}_p\in\mathcal{C}^{N\times K}$ is the spatially correlated Ricean channel matrix. We assume that the fading process is sufficiently slow, and hence considered constant for the duration of a frame. $\mathbf{\Pi}\in\mathcal{R}^{K\times K}$ is a channel-dependent permutation matrix corresponding to the greedy QR detection ordering [11], and $\mathbf{x}\in\mathcal{C}^{K\times 1}$ is the information symbol vector. The receiver noise $\mathbf{n}\sim\mathcal{CN}\left(0,N_0\,\mathbf{I}_N\right)$ consists of independent circularly symmetric zero-mean complex Gaussian entries of variance N_0, where $\mathbf{I}_N$ is an identity matrix of size N.

To focus on the impact of spatial correlation on the cross-layer transmit AS approach, we assume that fading is only transmit correlated (e.g., indoor environments). The Ricean channel matrix $\mathbf{H}_p$, that contains transmit antenna correlation but no receive correlation, is given by [12]

$$\mathbf{H}_p=\sqrt{\frac{\kappa}{\kappa+1}}\,\mathbf{\Psi}+\sqrt{\frac{1}{\kappa+1}}\,\mathbf{H}_w\,{\mathbf{R}_t}^{1/2}, \tag{3}$$

where κ and $\mathbf{R}_t$ are the Ricean factor and the $K\times K$ transmit correlation matrix, respectively. The $N\times K$ matrix $\mathbf{H}_w$ consists of independent and identically distributed (i.i.d.) circularly symmetric Gaussian random variables with zero-mean and unit-variance $\sim N\left(0,1\right)$. The line-of-sight (LOS) component $\mathbf{\Psi}$ is an $N\times K$ matrix of all ones.

III. Adaptive Cross-layer Transmit Antenna Selection Approach

In this section, a detailed analysis on the throughput performance of the cross-layer AS, with both perfect and imperfect CSI at the receiver, is presented. Before proceeding further it is important to keep in mind that the capacity-based AS is based on the general capacity formula [3]

$$C\left(\mathbf{H}_p\right)=\log_2\det\left[\mathbf{I}_K+\frac{\gamma}{K}\mathbf{H}_p{}^H\mathbf{H}_p\right],\quad \text{bits/s/Hz}, \tag{4}$$

where $\gamma=\mathbb{E}\left[\mathbf{x}^H\mathbf{x}\right]/N_0$, is the signal-to-noise ratio (SNR) per receive antenna, $\mathbf{I}_K$ denotes an identity matrix of size K, $\left(\cdot\right)^H$ stands for Hermitian transpose, and $\det\left(\cdot\right)$ stands for determinant.

A. Performance Analysis with Perfect Channel Estimation

Here we assume perfect CSI is available at the receiver while performing AS. Also, a ZF detector is used to suppress interference [2]. Now if the previous decisions are correct (i.e., no propagation of error), the DFD decouples the MIMO channel into a set of K parallel SISO virtual subchannels. Thus, one can show that the output SNR of the ith substream is given by

$$\gamma_i=r_{i,i}^2\,\gamma_0,\quad \text{for}\quad i=1,2,\ldots,K, \tag{5}$$

where $\gamma_0=\mathbb{E}\left[\mathbf{x}^H\,\mathbf{x}\right]/K\,N_0$ is the average normalized received SNR at each receive antenna. Thus, the output SNRs of the substreams are determined by the diagonal entries of the matrix $\mathbf{R}$, which in turn depends on $\mathbf{\Pi}$. Using (5), and assuming binary phase-shift keying (BPSK) transmission, the symbol-error rate (SER) of the ith layer, conditioned on having correctly detected all previous symbols, is given by

$$\mathrm{SER}_i=Q\left(\sqrt{2\,r_{i,i}^2\,\gamma_0}\right),\quad \text{for}\quad i=1,2,\ldots,K, \tag{6}$$

where $Q\left(\cdot\right)$ represents the Gaussian Q-function. Now from the fact that each information packet contains L/K symbols, the uncoded packet-error rate (PER) can be written as

$$\mathrm{PER}\left(\mathbf{H}_p\right)=1-\left[\prod_{i=1}^{K}\left(1-\mathrm{SER}_i\right)\right]^{L/K}. \tag{7}$$

The link layer throughput is measured as the effective number of correctly received bits at the link layer per channel use [10].

$$\eta\left(\hat{\mathbf{H}}_p\right) = K \cdot \frac{\left[\prod_{i=1}^{K}\left(1-Q\left(\sqrt{\frac{2\,\hat{r}_{i,i}^2\,\lambda}{\lambda\sum_{j=1}^{K}|\Omega_{i,j}|^2+N_0}}\right)\right)\right]^{L/K}}{\left[1+(W-1)\left(1-\left[\prod_{i=1}^{K}\left(1-Q\left(\sqrt{\frac{2\,\hat{r}_{i,i}^2\,\lambda}{\lambda\sum_{j=1}^{K}|\Omega_{i,j}|^2+N_0}}\right)\right)\right]^{L/K}\right)\right]}. \tag{17}$$

Now having obtained an expression for the PER as in (7), the instantaneous throughput, of the selected system can be expressed as in (8), where W is the window size of the GBN protocol. Note that (8) can be easily extended to other modulation schemes. However, it is worth noting that for a coded system different throughput expression would result. Based on (8), the receiver selects the optimal subset $p \in P$ and conveys the AS commands to the transmitter. It is instructive now to see the behavior of (8) at high SNR asymptote. Thus, for SNR $\rightarrow \infty$ we have

$$\eta_\infty = \lim_{\gamma_0\rightarrow\infty} \eta = K. \tag{9}$$

Inspection of (9) reveals that in order to achieve the maximum throughput value M $(K \le M)$, the transmitter must select all the M available antennas. We stress that, even with high spatial correlation (e.g., ≥ 0.8), the transmitter is expected to select the M antennas.

B. Performance Analysis with Imperfect Channel Estimation

In the previous section, perfect CSI is assumed at the receiver while performing AS. The effect of imperfect channel estimation on the system performance is now investigated. In what follows, we assume that a time frame is composed of L_t pilot symbols intervals and L_d data symbols (payload) intervals. Following the approach in [13], one can obtain a maximum-likelihood (ML) estimate of $\mathbf{H}$. This estimate of $\mathbf{H}$ can be written as

$$\hat{\mathbf{H}} = \mathbf{H} + \mathbf{\Delta H}, \tag{10}$$

where $\mathbf{\Delta H}$ represents the estimation error matrix. Thus, with AS, we have

$$\hat{\mathbf{H}}_p = \mathbf{H}_p + \mathbf{\Delta H}_p, \tag{11}$$

where $\mathbf{\Delta H}_p$ represents the estimation error matrix corresponding to optimal transmit antennas in p. Therefore, the corresponding sampled received baseband signal can be written as

$$\mathbf{y} = \mathbf{H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x} + \mathbf{n}. \tag{12}$$

Having obtained the ML estimate $\hat{\mathbf{H}}_p$, the receiver uses $\hat{\mathbf{H}}_p$ for detection. Thus, the receiver, first performs a QR factorization of the estimated channel matrix $\hat{\mathbf{H}}_p$ followed by nulling and cancelation. The estimated greedy QR ordered DFD can be represented by applying the QR decomposition to $\hat{\mathbf{H}}_p$ with its columns permuted, i.e., $\hat{\mathbf{H}}_p\hat{\mathbf{\Pi}} = \hat{\mathbf{Q}}\,\hat{\mathbf{R}}$ where $\hat{\mathbf{\Pi}}$ is a permutation matrix $\left(\hat{\mathbf{\Pi}}\,\text{is a function of}\,\hat{\mathbf{H}}_p\right)$. The transmitted symbols are then detected at the receiver as follows. Multiplying both sides of (12) by $\hat{\mathbf{Q}}^H$ yields

$$\begin{aligned}
\tilde{\mathbf{y}} &= \hat{\mathbf{Q}}^H\left(\mathbf{H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}+\mathbf{n}\right)\\
&= \hat{\mathbf{Q}}^H\left[\left(\hat{\mathbf{H}}_p-\mathbf{\Delta H}_p\right)\hat{\mathbf{\Pi}}\,\mathbf{x}+\mathbf{n}\right]\\
&= \hat{\mathbf{Q}}^H\left[\hat{\mathbf{H}}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}-\mathbf{\Delta H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}+\mathbf{n}\right]\\
&= \hat{\mathbf{Q}}^H\,\hat{\mathbf{H}}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}-\hat{\mathbf{Q}}^H\,\mathbf{\Delta H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}+\tilde{\mathbf{n}}\\
&= \hat{\mathbf{Q}}^H\,\hat{\mathbf{Q}}\,\hat{\mathbf{R}}\,\mathbf{x}-\hat{\mathbf{Q}}^H\,\mathbf{\Delta H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}+\tilde{\mathbf{n}}\\
&= \hat{\mathbf{R}}\,\mathbf{x}-\hat{\mathbf{Q}}^H\,\mathbf{\Delta H}_p\,\hat{\mathbf{\Pi}}\,\mathbf{x}+\tilde{\mathbf{n}}.
\end{aligned} \tag{13}$$

Let $\mathbf{\Omega} = \hat{\mathbf{Q}}^H\,\mathbf{\Delta H}_p\,\hat{\mathbf{\Pi}}$ denote a $K \times K$ matrix. Then the received vector $\tilde{\mathbf{y}}$, can be expressed as

$$\begin{bmatrix}\tilde{y}_1\\ \vdots\\ \tilde{y}_K\end{bmatrix} = \begin{bmatrix}\hat{r}_{1,1}-\Omega_{1,1} & \dots & \hat{r}_{1,K}-\Omega_{1,K}\\ \vdots & \ddots & \vdots\\ -\Omega_{K,1} & \dots & \hat{r}_{K,K}-\Omega_{K,K}\end{bmatrix}\begin{bmatrix}x_1\\ \vdots\\ x_K\end{bmatrix}+\begin{bmatrix}\tilde{n}_1\\ \vdots\\ \tilde{n}_K\end{bmatrix}. \tag{14}$$

Assuming that all previous decisions are correct, the different substreams can be expressed as

$$\tilde{y}_i = \hat{r}_{i,i}\,x_i - \sum_{j=1}^{K}\Omega_{i,j}\,x_j + \tilde{n}_i, \quad \text{for} \quad i = 1,2,\dots,K, \tag{15}$$

where $\hat{r}_{i,i}$ is the (i,i)th entry of $\hat{\mathbf{R}}$. Assuming no error propagation from previous stages, the signal-to-noise-plus-interference ratio (SNIR) for the ith substream is given by

$$\xi_i = \frac{\hat{r}_{i,i}^2\,\lambda}{\lambda\sum\limits_{j=1}^{K}|\Omega_{i,j}|^2+N_0}, \tag{16}$$

where $\lambda = \mathbb{E}\left[\mathbf{x}^H\,\mathbf{x}\right]/K$ is the average energy per symbol at the transmitter. From (16), the instantaneous throughput with imperfect channel estimation can be expressed as in (17). Note that, regardless of its simplicity, the computational complexity to choose optimal antennas for both perfect and imperfect CSI, may be high when the number of transmit antennas is large.

IV. Simulation Results

Performance results are reported in terms of the throughput versus E_s/N_0 in dB. In the following, a system with M transmit and N receive antennas is referred to as an $M \times N$ system. Henceforth, we consider: $i)$ 4×4 MIMO system; $ii)$ GBN window with $W = 4$ packets; $iii)$ frame duration of 2 ms; $iv)$ frame length is $L = 180$ symbols; $v)$ Ricean factor is set to $\kappa = 3$ dB; $vi)$ exponential correlation model [9]. The

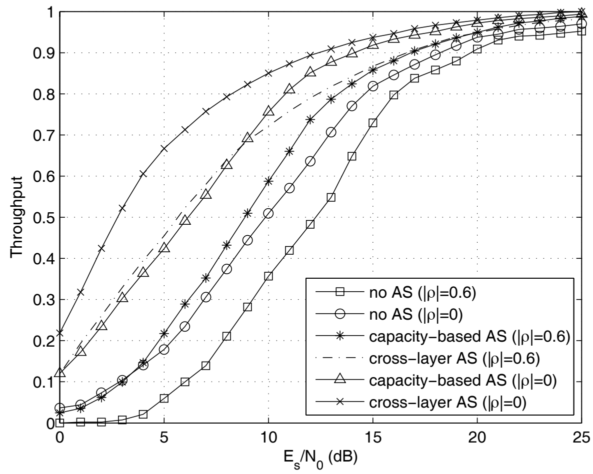

Fig. 2. Normalized throughput performance of a 4×4 system performing both cross-layer and capacity-based AS. $\kappa = 3\ dB$, exponential correlation model, BPSK constellations.

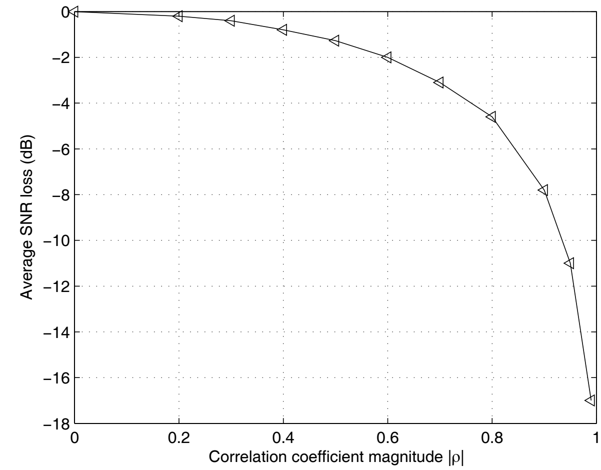

Fig. 3. Average SNR loss due to spatial correlation for a 4×4 system employing cross-layer AS. $\kappa = 3\ dB$, exponential correlation model, BPSK constellations.

entries of the transmit correlation matrix, $\mathbf{R}_t$, are given by

$$[\mathbf{R}_t]_{i,j} = \begin{cases} \rho^{j-i}, & i \leq j \\ [\mathbf{R}_t]^*_{j,i}, & i > j, \end{cases} \tag{18}$$

where $(\cdot)^*$ denotes complex conjugate and ρ is the complex correlation coefficient of neighboring transmit branches ($|\rho| \leq 1$).

A. Perfect Channel Estimation

Fig. 2 shows the system performance with both cross-layer and capacity-based AS approaches. We consider two correlation settings: $i)$ $|\rho| = 0$ (uncorrelated case); $ii)$ $|\rho| = 0.6$. We plot along an additional curve, as a benchmark, for the same system with no AS. It can be noticed that the performance of the cross-layer AS is significantly better than the capacity-based one. In fact, the throughput gain is large at moderate SNRs. Inspection of Fig. 2 reveals that the cross-layer AS is more robust to the effect of spatial correlation at low SNRs ($[0-7]$ dB). In this case the performance degradation is about 2 dB for the cross-layer AS, whereas it is about 3 dB for the capacity-based one.

Fig. 3 shows the average SNR loss due to spatial correlation for the 4×4 MIMO system performing cross-layer AS. Note that the average SNR loss, for a predefined throughput η and correlation values $|\rho|$, is defined as: $\text{loss}\,(\text{dB}) = \text{SNR}\,(|\rho| = x) - \text{SNR}\,(|\rho| = 0)$. For instance, the average SNR loss for $\eta = 0.5$ with $|\rho| = 0.4$ is about 1 dB. It can be seen that the average SNR loss increases with the correlation coefficients $|\rho|$, and the loss rate reaches 3 dB when $|\rho|$ increases up to 0.7. Also as shown the average SNR loss increases steeply when correlation exceeds $|\rho| = 0.8$.

In Fig. 4, the usage rate of each antenna combination of both cross-layer and capacity-based AS is shown. In these results, we consider three correlation settings: $i)$ $|\rho| = 0$; $ii)$ $|\rho| = 0.4$; $iii)$ $|\rho| = 0.9$. An inspection of Fig. 4 discloses qualitatively different behaviors for the cross-layer AS at moderate SNRs (e.g., $[0-12]$ dB). More precisely, the rate of usage of each antenna combination with high spatial correlation of $|\rho| = 0.9$

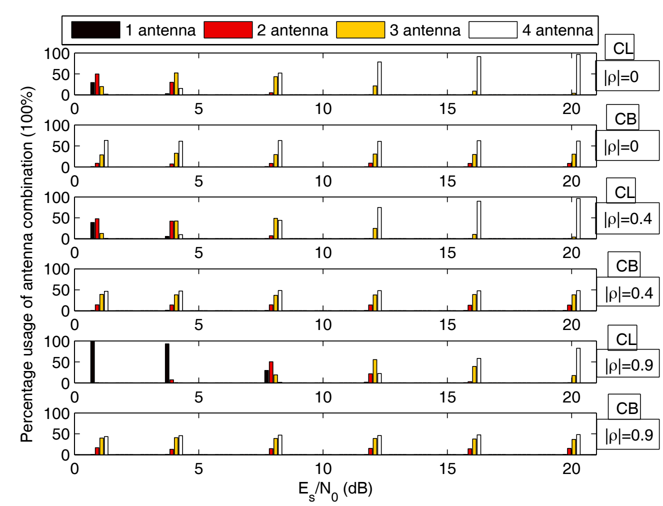

Fig. 4. Usage rate of transmit antenna combination, active antenna K, of a 4×4 system performing cross-layer (CL) and capacity-based (CB) AS. $\kappa = 3\ dB$, exponential correlation model, BPSK constellations.

(this corresponds to a severe lack of angular spread or closely spaced antennas) reveals different behavior than that with moderate spatial correlation of $|\rho| = 0, 0.4$. For instance, at high spatial correlation (i.e., $|\rho| = 0.9$), the one antenna case is the dominant one where it reaches approximately 100% with $|\rho| = 0.9$. A primary reason for the difference can be explained intuitively as follows. At high spatial correlation and at moderate SNRs, the cross-layer AS tends to choose the minimum number of antennas in an attempt to reduce the effect of spatial correlation as possible. Whereas, at high SNRs (e.g., $\geq 16\,$dB), the usage rate behavior is slightly affected by spatial correlation where the four antenna combination is the most employed. It is worth noting that this observation conforms with $\eta_\infty = K$ given in (9). As for the capacity-based AS, one can directly notice that at low/high SNR, the capacity-based AS exhibits approximately the same usage rate behavior with four antenna combination being dominant. It follows that the usage rate of each antenna combination, for the capacity-

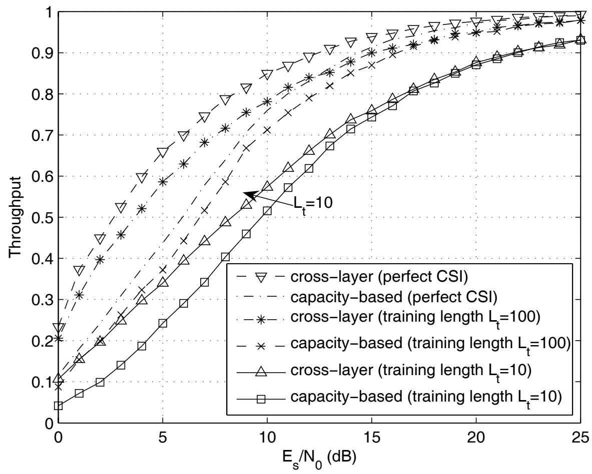

Fig. 5. Comparison of the impact of imperfect channel estimation on a 4×4 system employing both cross-layer (CL) and capacity-based (CB) AS, with various training-sequence length settings. $\kappa = 3\ dB$, uncorrelated case ($|\rho| = 0$), BPSK constellations.

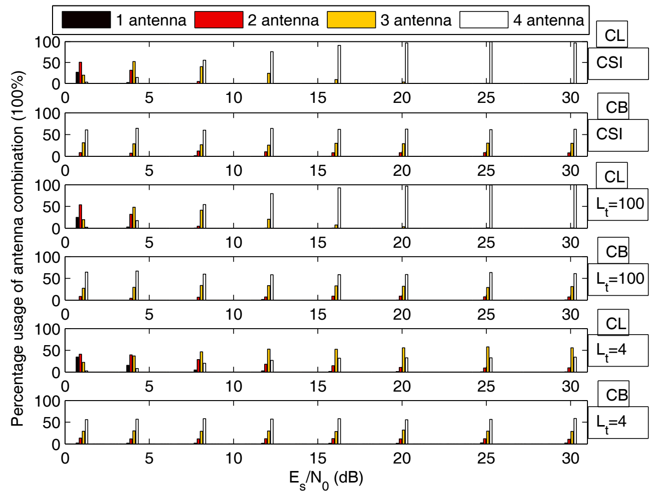

Fig. 6. Usage rate of transmit antenna combination, active antenna K, of a 4×4 system performing both cross-layer (CL) and capacity-based (CB) AS with various training-sequence length settings. $\kappa = 3\ dB$, uncorrelated case ($|\rho| = 0$), BPSK constellations.

based AS, is slightly affected by spatial correlation. It can be seen that the existence of spatial correlation ($|\rho| > 0$) slightly decreases the usage rate of the four antenna combination at moderate SNRs. This ties well with intuition since the presence of spatial correlation can raise the possibility of moderately to severely ill-conditioned channel matrix, i.e., rank-deficient channel matrix $\mathbf{H}$ $(\text{rank}(\mathbf{H}) < \min(N, M))$. Now, keep in mind the fact that the optimal choice of K transmit antennas that maximizes the channel capacity results in a channel matrix that is full rank $(\text{rank}(\mathbf{H}_p) = K)$ [3]. Thus, this explains the decrease in the usage rate of the four antenna combination. Note that in the limit $|\rho| \to 1$ (i.e., keyhole channel), the best strategy is to select only the antenna with the highest channel gain.

B. Imperfect Channel Estimation

Here, we investigate the impact of imperfect CSI on the cross-layer AS. To isolate the effects of spatial correlation, we consider independent Ricean flat fading channels (i.e., $|\rho| = 0$). We stress that in simulations, training symbols are not counted in the throughput computation.

Fig. 5 depicts the throughput performance with both cross-layer and capacity-based AS. We consider two training-sequence lengths: $i)$ $L_t = 10$ symbols; $ii)$ $L_t = 100$ symbols. As a benchmark, we plot along curves of both cross-layer and capacity-based AS, for the case of perfect CSI at the receiver. It can be observed that both cross-layer and capacity-based AS, with $L_t = 100$ symbols, exhibit a very close performance to that with perfect CSI. Thus a longer training-sequence yields a higher throughput. Decreasing the training-sequence length from $L_t = 100$ to $L_t = 10$ symbols, increases the SNR loss to about 5 dB and 3 dB for cross-layer and capacity-based AS, respectively. Examining Fig. 5 reveals that capacity-based AS is more tolerant/robust to imperfect CSI. For instance, for $\eta = 0.5$ with $L_t = 10$ symbols, the SNR loss is about 5 dB and 3 dB for cross-layer and capacity-based AS, respectively.

The rate of usage of each antenna combination, with imperfect channel estimation, of both cross-layer and capacity-based AS is depicted in Fig. 6. With this setting, the rate of usage of the cross-layer AS with $L_t = 100$ exhibits a similar behavior to that with perfect CSI, whereas for $L_t = 4$ symbols, the three antenna combination is the most employed over the range of SNRs. However, in contrast to the cross-layer AS, the capacity-based AS is independent of the reliability of the channel estimates obtained using different training-sequence lengths, and somehow similar to that with perfect CSI. Note that the four antenna combination is again the most adopted in this approach over all SNRs. Thus, unlike the cross-layer AS approach, the antenna usage rate of the capacity-based AS is less affected by the nonideal channel conditions considered here (i.e., spatial correlation and imperfect channel estimation). However, in all cases, the cross-layer AS approach is still able to achieve a better throughput performance than the capacity-based AS.

V. Conclusions

We investigated the performance of a cross-layer AS approach for the DFD in MIMO systems. We have considered a spatially correlated flat Ricean fading MIMO model, which is known more accurately to model real-world wireless environments. Closed-form expressions for the instantaneous system throughput, with both perfect and imperfect channel estimation, are derived. Furthermore, it has been shown that the capacity-based AS is more robust to nonideal channel conditions such as spatial correlation and imperfect channel estimation. However, in all cases, the cross-layer AS approach is able to outperform the capacity-based AS.

References

[1] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Commun.*, vol. 6, pp. 311-335, Nov. 1998.

[2] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture," *Electron. Lett.*, vol. 92, pp. 14-16, Jan. 1999.

[3] D. A. Gore, R. U. Nabar, and A. Paulraj, "Selecting an optimal set of transmit antennas for a low rank matrix channel," in *Proc. IEEE ICASSP'00*, Istanbul, Turkey, June 2000, pp. 2785-2788.

[4] R. W. Health, S. Sandhu, and A. Paulraj, "Antenna selection for spatial multiplexing systems with linear receivers," *IEEE Commun. Lett.*, vol. 5, pp. 142-144, Apr. 2001.

[5] A. Milani, V. Tralli, and M. Zorzi, "Improving protocol performance in BLAST-based wireless systems using channel adaptive antenna selection," in *Proc. IEEE VTC'02*, Birmingham, UK, May 2002, pp. 409-413.

[6] J. L. Vicario, M. A. Lagunas, and C. Anton-Haro, "A cross-layer approach to transmit antenna selection," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 1993-1997, Aug. 2006.

[7] H. Zhang and H. Dai, "Delay constrained multiuser scheduling schemes based on upper-layer performance," in *Proc. IEEE WCNC'06*, Las Vegas, NV USA, Apr. 2006, pp. 1130-1135.

[8] J. P. Kermoal, L. Schumacher, K. Ingemann, P. E. Mogensen, and F. Frederiksen, "A stochastic MIMO radio channel model with experimental validation," *IEEE J. Select. Areas Commun.*, vol. 20, pp. 1211-1226, Aug. 2002.

[9] S. Loyka, "Channel capacity of MIMO architecture using the exponential correlation matrix," *IEEE Commun. Lett.*, vol. 5, pp. 369-371, Sept. 2001.

[10] S. Lin, D. Costello, and M. Miller, "Automatic-repeat-request error-control schemes," *IEEE Commun. Mag.*, vol. 22, pp. 5-17, Dec. 1984.

[11] Y. Jiang and M. K. Varanasi, "The effect of ordered detection and antenna selection on diversity gain of decision feedback detector," in *Proc. IEEE ICC'07*, Glasgow, Scotland, June 2007, pp. 5383-5388.

[12] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge, UK: Cambridge Univ. Press, 2003.

[13] T. L. Marzetta, "BLAST training: estimating channel characteristics for high capacity space-time wireless," in *Proc. 37th Annual Allerton Conference Commun., Control, Computing*, Monticello, IL, Sept. 1999, pp. 958-966.