Effect of MIMO Wireless Channels on TCP

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***Abstract*— Multiple-input multiple-output (MIMO) wireless communication systems that employ multiple transmit and receive antennas can provide very high-rate data transmissions without increase in bandwidth or transmit power. For this reason MIMO technologies are considered as a key ingredient in the next generation wireless systems, where provision of reliable data services for TCP/IP applications such as wireless multimedia or Internet is of extreme importance. However, while the performance of TCP has been extensively studied over different wireless links, little attention has been paid to the impact of MIMO systems on TCP. This paper provides an investigation on the performance of modern TCP systems when used over wireless channels that employ MIMO technologies. In particular we focus on two representative categories of MIMO systems, namely the BLAST systems and the space-time block coding (STBC) systems, and how the ARQ and packet combining techniques impact on the overall TCP performance. We also study the effect of antenna correlation on the TCP throughput under various conditions. Keywords: TCP/IP, MIMO, BLAST, space-time block coding, ARQ, packet combining, antenna correlation.**

I. Introduction

The use of multiple transmit and receive antennas in wireless communication systems together with the recently developed space-time coding and signal processing techniques, has been shown to provide dramatic capacity increase over the traditional single-input single-output (SISO) channels, especially over rich scattered environments [7]. This potential gain in link throughput and network capacity makes such multiple-input multiple-output (MIMO) systems ideal candidate as the core technology for the next generation broadband wireless communication systems. As the majority of Internet services such as FTP, web or e-mail are provided by TCP, it is essential for any present and future wireless access to provide better support to TCP services in terms of reliability, throughput and delay. However, while the performance of TCP has been extensively studied over different wireless links [6], little research has been made on the behavior of TCP over MIMO systems.

TCP was originally designed to operate over wired networks where the main cause of packet loss is congestion. When used over wireless networks, with typically high frame error rate (FER), the performance of TCP is severely affected [3], [5]. While the use of ARQ mechanisms effectively mitigate the impact of losses on TCP, they also introduce delay and rate variation due to the retransmissions [5], producing a negative impact on TCP. Therefore, although ARQ mechanisms may improve TCP performance by reducing the observed FER, a solution in which the channel does not appear as highly variable is preferred from the TCP standpoint.

MIMO systems offer a flexible way of using the antenna diversity to trade off throughput for stability. The Bell-Labs layered space-time (BLAST) system [7] transmits different symbols from all transmitting antennas simultaneously, and is aimed at high data-rate transmissions. On the other hand, different space-time coding (STC) systems [1] exploit the transmission diversity by sending the same symbols from different transmit antennas, thus increasing the reliability at the expense of throughput. Depending on the quality of the channel (its signal-to-noise ratio or SNR), from the TCP perspective it may be preferable to reduce the channel throughput while improving its FER than to activate a retransmission mechanism on a channel with high throughput but also high error rate.

In this paper we use the above reasoning to investigate the impact of the use of different MIMO schemes on TCP systems. The remainder of this paper is organized as follows. In Section II we describe the two types of MIMO systems considered in this paper. In Section III, we discuss the local retransmission mechanisms with packet combining over MIMO channels. In Section IV, we describe the simulation setup. In Section V, we present the simulation results and our analysis, including the effects of antenna correlation on TCP under various conditions. Section VI concludes the paper by identifying the key variables that affect performance and hence constitute the basis for a cross-layer design.

II. MIMO Systems

A. The BLAST System

In the BLAST architecture, a single data stream is split into n_T sub-streams that are encoded separately and transmitted simultaneously from n_T transmit antennas. The signals received by the n_R receive antennas are processed to separate the streams and recover the original data. The input-output signal relationship in a BLAST system is expressed as

$$\boldsymbol{y} = \sqrt{\frac{\rho}{n_T}}\boldsymbol{H}\boldsymbol{s} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{y} = [y_1, y_2, ..., y_{n_R}]^T$ is the $(n_R \times 1)$ received symbol vector, $\boldsymbol{s} = [s_1, s_2, ..., s_{n_T}]^T$ is the $(n_T \times 1)$ transmitted signal vector with $s_i \in \mathcal{A}$, where $\mathcal{A}$ is a finite constellation signal set with unit energy ($E\left\{|s_i|^2\right\} = 1$), and $\boldsymbol{n}$ is the $(n_R \times 1)$ received noise vector with $n_i \sim \mathcal{N}_c(0, 1)$. The signal-to-noise ratio ρ is independent of the number of transmit antennas. The

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channel is represented by a $(n_R \times n_T)$ matrix $\boldsymbol{H}$, where h_{ij} represents the complex gain of the channel between the j-th transmit antenna and the i-th receive antenna. For the rest of the discussion we will assume that the MIMO channel matrix $\boldsymbol{H}$ it is known at the receiver but not at the transmitter.

The optimal BLAST detection scheme is the maximum likelihood detector (ML) given by

$$\hat{\boldsymbol{s}}_{ML} = \arg \min_{\boldsymbol{s} \in \mathcal{A}^{n_T}} \left\| \boldsymbol{y} - \sqrt{\frac{\rho}{n_T}} \boldsymbol{H}\boldsymbol{s} \right\|^2, \qquad (2)$$

which has a computational complexity $\mathcal{O}\left(|A|^{n_T}\right)$ that grows exponentially with the number of transmit antennas n_T.

A lower complexity receiver is the MMSE detector with ordered interference cancellation. In this scheme, a symbol with the highest SNR is detected using a linear MMSE filter, and then subtracted from the received signals. Such a procedure is repeated until all the transmitted symbols are detected as follows [4]:

$\bar{\boldsymbol{H}} = \boldsymbol{H}$
$\boldsymbol{r} = \boldsymbol{y}$
for $i = 1 : n_T$ **do**
  $\boldsymbol{\Omega} = \left(\frac{\rho}{n_T}\bar{\boldsymbol{H}}^H\bar{\boldsymbol{H}} + \boldsymbol{I}\right)^{-1}$ *(MMSE criterion)*
  $k_i = \arg\min\{\boldsymbol{\Omega}_{j,j}\}$ *($k_i \sim$ min SNR symbol index)*
  $\boldsymbol{w} = (\bar{\boldsymbol{H}}\boldsymbol{\Omega})(:, k_i)$ *($\boldsymbol{w}$ is the nulling vector)*
  $z_{k_i} = \boldsymbol{w}^H\boldsymbol{r}$ *(nulling operation)*
  $\hat{s}_k = \mathcal{Q}_{\mathcal{A}}(z_{k_i})$
  $\boldsymbol{r} = \boldsymbol{r} - \sqrt{\frac{\rho}{n_R}}\boldsymbol{H}(:, k_i)\hat{s}_k$ *(cancellation operation)*
  $\bar{\boldsymbol{H}} =$ remove column k_i from $\bar{\boldsymbol{H}}$
end for

B. Space-time Block Coding

In the space-time coded (STC) MIMO systems [1], [11], instead of transmitting different symbols, the same symbols are transmitted through different antennas to increase diversity. A space-time block code is represented by the matrix $\mathcal{C}_{m,n_T}$, where the rows represent the n_T transmit antennas and the columns represent the number of time slots that the block takes to be transmitted. In what follows we consider three STBC systems with rate $1/2$, 1 and 2 respectively with four transmit antennas. The half-rate orthogonal code employs a $\mathcal{C}_{8,4}$ transmission matrix, hence transmitting four symbols in eight transmissions. The received signal at antenna i over the eight transmissions is given by

$$\begin{bmatrix} y_{i,1} \\ y_{i,2} \\ y_{i,3} \\ y_{i,4} \\ y_{i,5} \\ y_{i,6} \\ y_{i,7} \\ y_{i,8} \end{bmatrix} = \sqrt{\frac{\rho}{4}} \underbrace{\begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix}}_{\boldsymbol{C}_{8,4}} \begin{bmatrix} h_{i,1} \\ h_{i,2} \\ h_{i,3} \\ h_{i,4} \end{bmatrix} + \begin{bmatrix} n_{i,1} \\ n_{i,2} \\ n_{i,3} \\ n_{i,4} \\ n_{i,5} \\ n_{i,6} \\ n_{i,7} \\ n_{i,8} \end{bmatrix},$$

$$i = 1, 2, ..., n_R. \qquad (3)$$

Note that (3) can be rewritten as

$$\underbrace{\begin{bmatrix} y_{i,1} \\ y_{i,2} \\ y_{i,3} \\ y_{i,4} \\ y_{i,5}^* \\ y_{i,6}^* \\ y_{i,7}^* \\ y_{i,8}^* \end{bmatrix}}_{\boldsymbol{y}_i} = \sqrt{\frac{\rho}{4}} \underbrace{\begin{bmatrix} h_{i,1} & h_{i,2} & h_{i,3} & h_{i,4} \\ -h_{i,2} & h_{i,1} & -h_{i,4} & h_{i,3} \\ -h_{i,3} & h_{i,4} & h_{i,1} & -h_{i,2} \\ -h_{i,4} & -h_{i,4} & h_{i,2} & h_{i,1} \\ -h_{i,1}^* & -h_{i,2}^* & -h_{i,3}^* & -h_{i,4}^* \\ -h_{i,2}^* & h_{i,1}^* & -h_{i,4}^* & h_{i,3}^* \\ h_{i,3}^* & -h_{i,4}^* & -h_{i,1}^* & h_{i,2}^* \\ h_{i,4}^* & h_{i,3}^* & -h_{i,2}^* & -h_{i,1}^* \end{bmatrix}}_{\bar{\boldsymbol{H}}_i} \underbrace{\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}}_{\boldsymbol{s}_i} + \underbrace{\begin{bmatrix} n_{i,1} \\ n_{i,2} \\ n_{i,3} \\ n_{i,4} \\ n_{i,5}^* \\ n_{i,6}^* \\ n_{i,7}^* \\ n_{i,8}^* \end{bmatrix}}_{\boldsymbol{n}_i},$$

$$i = 1, 2, ..., n_R. \qquad (4)$$

The matrix $\bar{\boldsymbol{H}}_i$ is orthogonal, i.e. $\bar{\boldsymbol{H}}_i^H\bar{\boldsymbol{H}}_i = \sum_{k=1}^{4} |h_{i,k}|^2 \boldsymbol{I}_4$. Hence, at the receiver, the symbols are detected by a simple linear detector $\hat{\boldsymbol{s}} = \mathcal{Q}_A(\boldsymbol{z})$, where

$$\boldsymbol{z} = \sum_{i=1}^{n_R} \bar{\boldsymbol{H}}_i^H \boldsymbol{y}_i. \qquad (5)$$

A rate-1 orthogonal code does not exist for four transmit antennas [11]. However a rate-1 quasi-orthogonal scheme [9] is given by the following transmission matrix

$$\boldsymbol{C}_{4,4} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \\ s_3 & -s_4 & -s_1 & s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix}. \qquad (6)$$

The received signal at the i-th receive antenna for the four transmissions is

$$\begin{bmatrix} y_{i,1} \\ y_{i,2} \\ y_{i,3} \\ y_{i,4} \end{bmatrix} = \sqrt{\frac{\rho}{4}} \boldsymbol{C}_{4,4} \begin{bmatrix} h_{i,1} \\ h_{i,2} \\ h_{i,3} \\ h_{i,4} \end{bmatrix} + \begin{bmatrix} n_{i,1} \\ n_{i,2} \\ n_{i,3} \\ n_{i,4} \end{bmatrix}, i = 1, 2, ..., n_R, \qquad (7)$$

that can be rewritten as

$$\underbrace{\begin{bmatrix} y_{i,1} \\ y_{i,2}^* \\ y_{i,3} \\ y_{i,4}^* \end{bmatrix}}_{\boldsymbol{y}_i} = \sqrt{\frac{\rho}{4}} \underbrace{\begin{bmatrix} h_{i,1} & h_{i,2} & h_{i,3} & h_{i,4} \\ -h_{i,2}^* & h_{i,1}^* & -h_{i,4}^* & h_{i,3}^* \\ h_{i,3} & -h_{i,4} & -h_{i,1} & h_{i,2} \\ h_{i,4}^* & h_{i,3}^* & -h_{i,2}^* & -h_{i,1}^* \end{bmatrix}}_{\bar{\boldsymbol{H}}_i} \underbrace{\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}}_{\boldsymbol{s}_i} + \underbrace{\begin{bmatrix} n_{i,1} \\ n_{i,2} \\ n_{i,3} \\ n_{i,4} \end{bmatrix}}_{\boldsymbol{n}_i},$$

$$i = 1, 2, ..., n_R, \qquad (8)$$

The decision statistic at the receiver antenna is given by [8]

$$\boldsymbol{z}_i = \bar{\boldsymbol{H}}_i^H \boldsymbol{y}_i = \sqrt{\frac{\rho}{4}} \bar{\boldsymbol{H}}_i^H \bar{\boldsymbol{H}}_i \boldsymbol{s} + \bar{\boldsymbol{H}}_i^H \boldsymbol{n}_i = \sqrt{\frac{\rho}{4}} \boldsymbol{\Omega}_i \boldsymbol{s} + \boldsymbol{w}_i, \quad i = 1, 2, ..., n_R, \qquad (9)$$

with

$$\bar{\boldsymbol{\Omega}}_i = \begin{bmatrix} \gamma_i & 0 & \alpha_i & 0 \\ 0 & \gamma_i & 0 & -\alpha_i \\ -\alpha_i & 0 & \gamma_i & 0 \\ 0 & \alpha_i & 0 & \gamma_i \end{bmatrix}, \quad \gamma_i = \sum_{j=1}^{4} |h_{i,j}|^2,$$

$$\alpha_i = 2j\Im(h_{i,1}^* h_{i,3} + h_{i,4}^* h_{i,2}), \qquad (10)$$

and $\boldsymbol{w}_i \sim \mathcal{N}_c(0, \bar{\boldsymbol{\Omega}})$. We can group the statistics in (9) to form two 2×2 BLAST systems defined by

$$\begin{bmatrix} z_{i,1} \\ z_{i,3} \end{bmatrix} = \sqrt{\frac{\rho}{2}} \begin{bmatrix} \gamma_i & \alpha_i \\ -\alpha_i & \gamma_i \end{bmatrix} \begin{bmatrix} s_1 \\ s_3 \end{bmatrix} + \begin{bmatrix} w_{i,1} \\ w_{i,3} \end{bmatrix},$$

$$\text{and} \quad \begin{bmatrix} z_{i,4} \\ z_{i,2} \end{bmatrix} = \sqrt{\frac{\rho}{2}} \begin{bmatrix} \gamma_i & \alpha_i \\ -\alpha_i & \gamma_i \end{bmatrix} \begin{bmatrix} s_4 \\ s_2 \end{bmatrix} + \begin{bmatrix} w_{i,4} \\ w_{i,2} \end{bmatrix}, \quad i = 1, 2, ..., n_R. \quad (11)$$

The systems in (11) can be decoded using the ML detector in (2) or the MMSE detector with ordered interference cancellation described in Section II-A.

Finally we consider a rate-2 system by combining STBC and BLAST together [12]. For a symbol set $\boldsymbol{s} = [s_1, s_2, s_3, s_4]^T$, two antennas can be used to transmit $\bar{\boldsymbol{s}}_1 = [s_1, s_2]^T$ and the other two antennas to transmit $\bar{\boldsymbol{s}}_2 = [s_3, s_4]^T$ both using the rate-1 Alamouti code [1] as follows

$$\begin{bmatrix} y_{i,1} \\ y_{i,2} \end{bmatrix} = \sqrt{\frac{\rho}{2}} \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_{i,1} \\ h_{i,2} \end{bmatrix} + \sqrt{\frac{\rho}{2}} \begin{bmatrix} s_3 & s_4 \\ -s_4^* & s_3^* \end{bmatrix} \begin{bmatrix} h_{i,3} \\ h_{i,4} \end{bmatrix} + \begin{bmatrix} w_{i,1} \\ w_{i,2} \end{bmatrix}, i = 1, 2, ..., n_R. \quad (12)$$

The received signal at the i-th receive antenna after the two separate transmissions is given by [8]

$$\underbrace{\begin{bmatrix} y_{i,1} \\ y_{i,2}^* \end{bmatrix}}_{\boldsymbol{y}_i} = \sqrt{\frac{\rho}{2}} \underbrace{\begin{bmatrix} h_{i,1} & h_{i,2} \\ h_{i,2}^* & -h_{i,1}^* \end{bmatrix}}_{\bar{\boldsymbol{H}}_{i,1}} \underbrace{\begin{bmatrix} s_1 \\ s_2 \end{bmatrix}}_{\bar{\boldsymbol{s}}_1} + \sqrt{\frac{\rho}{2}} \underbrace{\begin{bmatrix} h_{i,3} & h_{i,4} \\ h_{i,4}^* & -h_{i,3}^* \end{bmatrix}}_{\bar{\boldsymbol{H}}_{i,2}} \underbrace{\begin{bmatrix} s_3 \\ s_4 \end{bmatrix}}_{\bar{\boldsymbol{s}}_2} + \begin{bmatrix} w_{i,1} \\ w_{i,2}^* \end{bmatrix}, i = 1, 2, ..., n_R. \quad (13)$$

This can be expressed as a BLAST system for n_R receive antennas of the form

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{n_R} \end{bmatrix}}_{\boldsymbol{y}} = \sqrt{\frac{\rho}{2}} \underbrace{\begin{bmatrix} \bar{\boldsymbol{H}}_{1,1} & \bar{\boldsymbol{H}}_{1,2} \\ \bar{\boldsymbol{H}}_{2,1} & \bar{\boldsymbol{H}}_{2,2} \\ \vdots & \vdots \\ \bar{\boldsymbol{H}}_{n_R,1} & \bar{\boldsymbol{H}}_{n_R,2} \end{bmatrix}}_{\bar{\boldsymbol{H}}} \underbrace{\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}}_{\boldsymbol{s}} + \underbrace{\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{n_R} \end{bmatrix}}_{\boldsymbol{w}}. \quad (14)$$

Again the received signal in (14) can be detected using the ML detector in (2), or the MMSE detector with ordered cancellation described in Section II-A.

III. ARQ WITH PACKET COMBINING FOR MIMO

A common way to hide losses from TCP is to use a local retransmission mechanism just below the IP level in the wireless link. These link layer protocols use the available time of the generous TCP time-out values to retransmit the lost frames, and also fragment the TCP segments because the FER of the channel heavily depends on the frame size. The local retransmission mechanism usually implements a form of automatic-repeat request (ARQ) error detection. The basic ARQ protocols work as follows: when a frame is received it is first checked for errors, and if the frame contains errors it is discarded and a retransmission is requested. A further benefit from the local retransmission mechanism is the fact that it is transparent to higher layers, in particular to TCP. Packet combining can be employed in conjunction with ARQ. The idea is that instead of discarding the old packets that contain errors, the soft decision statistics obtained for every ARQ retransmission are coherently combined symbol by symbol, resulting in a gain of effective SNR. We next discuss the packet combining techniques for the MIMO systems described in Section II.

First consider the BLAST system (1) with ML detection (2). Suppose that the symbol vector $\boldsymbol{s}$ is transmitted by the ARQ protocol L times. Then we have

$$\boldsymbol{y}(l) \; = \; \sqrt{\frac{\rho}{n_T}} \boldsymbol{H}(l)\boldsymbol{s} + \boldsymbol{n}(l), \quad l = 1, 2, ..., L, \quad (15)$$

where $\boldsymbol{y}(l)$, $\boldsymbol{H}(l)$ and $\boldsymbol{n}(l)$ are the received signal, the MIMO channel value and the receiver noise corresponding to the l-th retransmission respectively. Then the ML decision rule based on the L received signals is given by

$$\hat{\boldsymbol{s}}_{ML} \; = \; \arg \min_{\boldsymbol{s} \in \mathcal{A}^{n_T}} \sum_{l=1}^{L} \left\| \boldsymbol{y}(l) - \sqrt{\frac{\rho}{n_T}} \boldsymbol{H}(l)\boldsymbol{s} \right\|^2. \quad (16)$$

On the other hand, when the MMSE detection with ordered interference cancellation is employed, we denote the decision statistic corresponding to the i-th symbol s_i and the l-th transmission as $z_i(l)$ (line 7 of the algorithm in Section II-A). Then the combined decision statistic is given by $z_i = \sum_{l=1}^{L} \omega_i(l) z_i(l)$.

Two packet combining schemes are in order. In equal gain combining, we simply set $\omega_i(l) = 1$ for all $l = 1, 2, ..., L$. In a maximal ratio combining, on the other hand, the combining weight $\omega_i(l)$ is proportional to the signal-to-noise ratio, i.e.

$$\omega_i(l) = \frac{1}{\{\boldsymbol{\Omega}_{k_i,k_i}\}} \quad (17)$$

where $\boldsymbol{\Omega}$ and k_i are specified by lines 4 and 5 of the MMSE algorithm.

Now we turn to the space-time coding schemes discussed in Section II-B. For the half-rate code $\boldsymbol{C}_{8,4}$, we denote the decision statistics vector given by (5) and corresponding to the l-th retransmission as $\boldsymbol{z}(l)$. Then the combined decision statistic vector is given by $\boldsymbol{z} = \sum_{l=1}^{L} \omega(l) \boldsymbol{z}(l)$, and the combining weight $\omega(l)$ for the l-th retransmission is given by

$$\omega(l) \; = \; \sum_{i=1}^{n_R} \sum_{k=1}^{4} |h_{i,k}(l)|^2, \quad l = 1, 2, ..., L. \quad (18)$$

For the rate-1 code $\boldsymbol{C}_{4,4}$, the decision statistics per antenna obtained in (11) define two different 2×2 BLAST systems, and the combining can be performed separately for each as in the BLAST scheme described in (17). Similarly, the rate-2 code defined by the equivalent BLAST system in (14) can be combined following the scheme in (17).

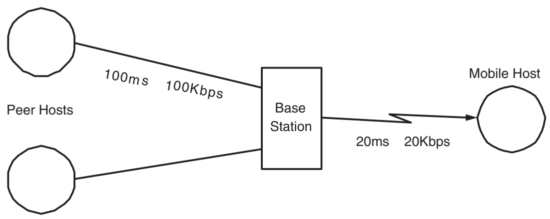

Fig. 1. Network scenario used in our simulations.

IV. Simulation Setup

We consider the scenario depicted in Fig. 1, in which a large data file is transferred via File Transfer Protocol (FTP) from a fixed node to a mobile host. The fixed links have a delay of 100ms representing (more than) one non-congested hop. The experiments were performed using the ns-2 simulator [10].

A typical TCP/IP/LL/RLP stack is used on the wireless link between the Radio Network Controller (RNC) and the Mobile Host (MH). We do not consider the multiuser scenario in which the medium is shared and a complex MAC protocol is needed. The TCP implementation selected is Reno with selective acknowledgement. The size of the data segment is 600 bytes. The LL in our scenario implements the segmentation and retransmission (acknowledgement). The LL maximum frame size is 1500 bytes in order to support the maximum allowed TCP segment. The LL does not have fragmentation or retransmission capabilities. The RLP layer implements an pure NACK selective acknowledgment hybrid ARQ type I protocol that performs retransmissions, fragmentation and reassembly. The RLP frame size is 30 bytes, so typically a TCP segment will need 20 RLP frames to be completely transmitted. The selective repeat ARQ protocol requires buffering both in the sender and in the receiver. Moreover the receiver has a timeout for every missing frame. The retransmission timeout accounts for buffering and segmentation delays, and it is typically set to the time needed for sending 4 RLP frames. A loss is detected when a non-consecutive RLP frame is received or a timeout for a frame occurs. In case of loss, a NACK for the missing frame is sent back to the sender, which proceeds to a retransmission. This process continues until the correct frame is received or a maximum number of timeout expiration n per frame is reached (n ranges from 3 to 10 retransmissions). If after the n attempts an RLP frame is still missing the RLP layer does not pass any of the fragments to the link layer, and discards them silently. The link layer would eventually re-send the missing fragments or will eventually let the TCP layer handle the loss. RLP also sends periodically ACK packets to free buffers from the sender.

For the combining to be effective certain fields of the frames need to be heavily protected to avoid corruption, particularly the sequence number. Otherwise the receiver would be unable to tell with which frame the newly received frame is combined. We assume that a strong forward-error-correction (FEC) code is applied to the RLP headers so the sequence information and the packet type can always be recovered. For the physical layer we consider MIMO systems with $n_T = 4$ transmit and $n_R = 4$ receive antennas signaling over a quasi-static flat-fading channel with quadrature phase shift keying (QPSK) modulation in a rich-scattering indoor wireless environment. Therefore, the BLAST system has a spectral efficiency of 8 bits/sec/Hz. The STBC systems have different spectral efficiencies depending on its rate: the half rate orthogonal code has a spectral efficiency of 1 bit/sec/Hz, the rate-1 quasi-orthogonal code has a spectral efficiency of 2 bits/sec/Hz, and the rate-2 group Alamouti scheme has a spectral efficiency of 4 bits/sec/Hz. To account for that difference in spectral efficiency the wireless link is 20kbps for the BLAST schemes, 10kbps for the rate-2 STBC, 5kbps for the rate-1 STBC code and 2.5kbps for the half-rate STBC code. By using higher constellations in STBC we would be able to increase its throughput at the cost of higher error rate, and hence losing its main difference with BLAST. We will show that the spectral efficiency or the BER cannot be taken alone as performance metrics from the user point of view, but the TCP throughput itself determines the goodput that the user will experience.

V. Results

The performance measurement is the end-to-end throughput of TCP during a 100-second FTP transmission. In the cases in which the ARQ protocol is not active, the TCP segments are still fragmented at the RNC. The TCP throughput when the ARQ retransmission mechanism of the RLP layer is not activated is shown in Fig. 2. Here, the effect of the difference on spectral efficiency for the different channels on the overall TCP performance is noticeable. For a SNR of 20dB and above the BLAST MMSE channel is preferable because the low FER observed. However the quality of the BLAST channel drops significantly in the 15-20dB range in favor of the more reliable STBC channels. The most reliable channel is the orthogonal half rate STBC, which allows TCP to have the maximum available throughput with a SNR as low as 1dB. Above SNR 7db the quasi-orthogonal STBC rate-1 and the STBC rate-2 offer the same TCP throughput, but the higher spectral efficiency of the STBC rate-2 receiver makes it preferable in terms of TCP throughput. Figure 3 shows the TCP throughput when ARQ is used for 10 maximum retransmissions. The drop in BLAST MMSE occurs in the SNR range of 12-16dB, meaning a consistent 4dB gain. In the STBC systems the drop in throughput is smoother when ARQ is activated. The reliability difference between the three systems is nulled by the retransmission mechanism for lower SNR values and practically above 3dB the rate-2 STBC system achieves the best results.

The effect of combining is shown in Figure 4 for max. 10 retransmissions. We observe that by using combining the TCP performance is improved in all systems. However the gain is clearly superior in the BLAST MMSE receiver, in which the gain ranges from 1dB to a significant 10dB gain. The throughput difference for STBC systems is, however, negligible above 5dB and the SNR gain rarely surpasses 2dB.

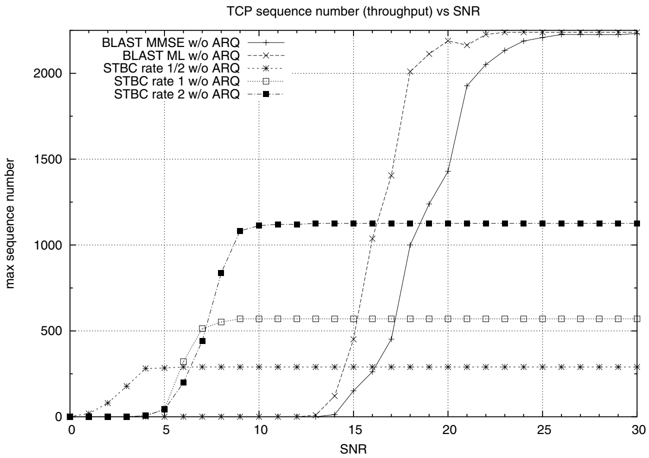

Fig. 2. TCP throughput vs. SNR without ARQ.

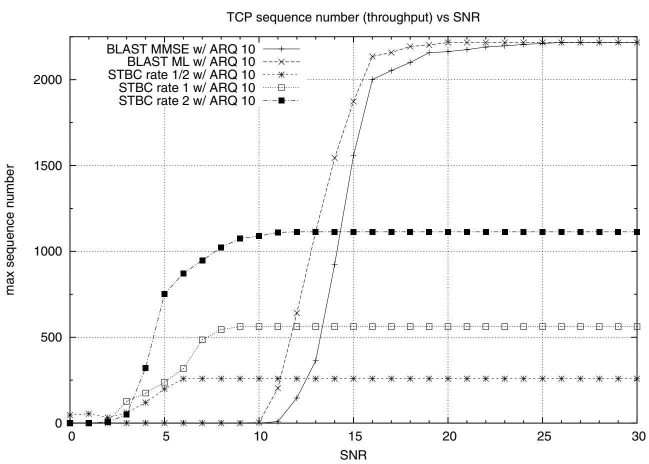

Fig. 3. TCP throughput with ARQ, without combining 10 retransm.

Interestingly the performance of a BLAST MMSE receiver with combining outperforms the half-rate STBC for all SNR values, and for a normal range of operation, with SNR in the range of 15-25dB, the BLAST MMSE system outperforms the rest of the receivers.

A. Effects of Channel Correlation on TCP Performance

Assuming no line of sight between transmit and receiver antennas and assuming the signals encounter a cluster of scatters on its way to the receiver, as showed in [2], for small angular spread, the correlation matrix for the receiver can be approximated as

$$[\boldsymbol{R}_r]_{i,j} \approxeq e^{-\jmath 2\pi(j-i)d\cos(\bar{\phi}_o^R)} e^{\frac{1}{2}[2\pi(j-i)d\sin(\bar{\phi}_o^R)\delta_o^T]}, \quad i,j = 1,2,...,n_R, \quad (19)$$

assuming equal antenna spacing d and normalized signal power $|\beta| = 1$. Here, d is the distance between antennas measured in wavelengths (λ), the angular spread δ_o^R of the arrival incident waves (δ_o^T for transmit antennas) and the mean angle $\bar{\phi}_o^R$ of the arrival incident waves ($\bar{\phi}_o^T$ for the transmit antennas). A similar expression for (19) is obtained

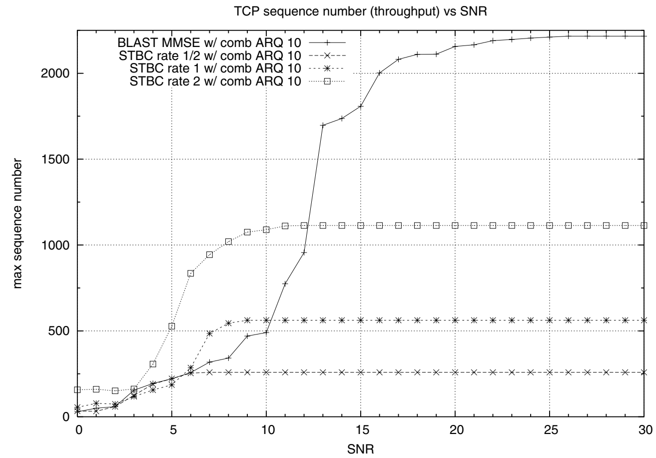

Fig. 4. TCP throughput with ARQ, combining for 10 max retransm.

for the correlation matrix of the transmit antennas $\boldsymbol{R}_t$. Assuming correlation at both the transmitter and the receiver, the MIMO channel response matrix can be expressed as $\boldsymbol{H} = \boldsymbol{R}_r^{1/2}\boldsymbol{H}_w\boldsymbol{R}_t^{1/2}$, where $\boldsymbol{H}_w$ is an $n_T \times n_R$ matrix containing i.i.d. $\mathcal{N}_c(0,1)$ random variables; $\boldsymbol{R}_r$ and $\boldsymbol{R}_t$ represent the $(n_R \times n_R)$ and $(n_T \times n_T)$ covariance matrices defined in (19) that induce the receive and transmit correlations respectively.

Following the correlation model previously described, we consider two different correlation scenarios (urban and rural) detailed in [4]. The exact parameters are shown in Table I.

Scenario	δ_o^T	ϕ_o^T	δ_o^R	ϕ_o^R	d
Urban	7^o	84^o	7^o	60^o	0.5λ
Rural	2^o	84^o	2^o	60^o	0.5λ

TABLE I

Fig. 5 shows the effect of the correlation in the TCP throughput when ARQ is not used. As expected the performance of MIMO channels in correlated conditions is worse than the uncorrelated case, and it has a significant impact on the TCP performance, mainly in the less reliable BLAST schemes. The STBC receivers, however, behave better than the BLAST systems but suffer a significatively reduction of SNR gain. The rural correlation is higher compared to the urban correlation, and so the expected result is a reduction in the TCP.

Fig. 6 shows the TCP performance in a urban correlated scenario for different MIMO schemes when the maximum number of ARQ retransmissions is 3. As expected, the ARQ mechanism improve the TCP throughput compared to the case when no ARQ is used. The most noticeable improvement occurs in the BLAST systems while the benefit for the STBC receivers is minor. As expected, the benefit obtained by the ARQ is inversely proportional to the reliability of the MIMO scheme.

Fig. 7 shows the effect of the packet combining on the systems without combining showed in Fig. 6. Unlike the uncorrelated case, the benefit obtained through combining is minimal for STBC systems and larger for BLAST systems. The hostile MIMO correlated channels allow the retrans-

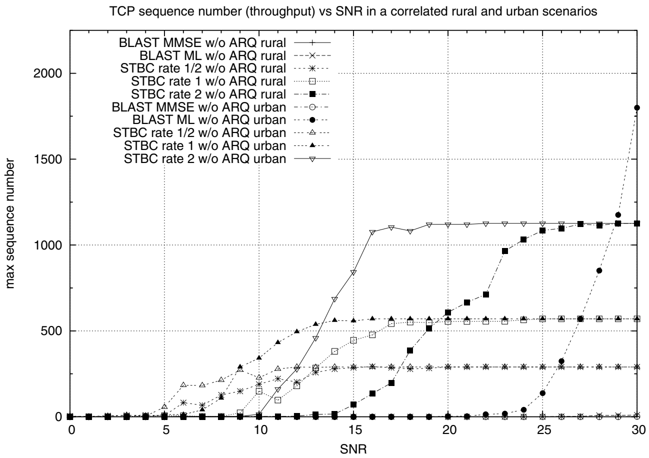

Fig. 5. TCP throughput without ARQ and with correlated antennas.

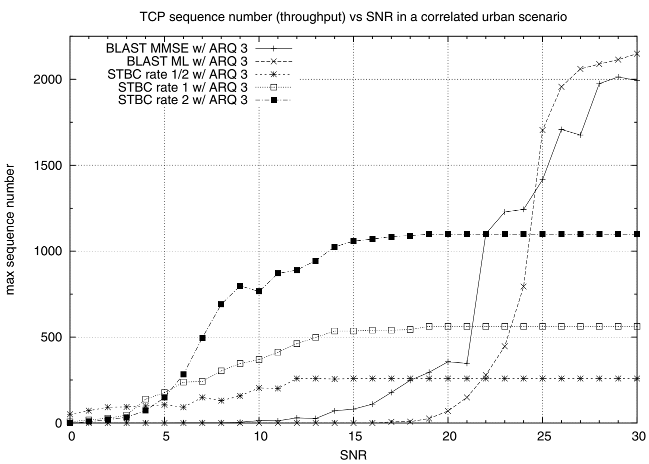

Fig. 6. TCP throughput with ARQ and correlated antennas for the urban scenario. The maximum number of retransmissions is 3.

mission mechanism just little room for improvement. It is interesting to note, however, that the combining effectively improves the TCP throughput. As in the previous section, the less reliable BLAST systems take more advantage than the STBC systems.

VI. Conclusions

In this paper we have investigated the effect of MIMO channels in modern TCP systems. We showed that TCP can benefit from the better reliability of the STBC systems for low to modest SNR 20dB. However at higher SNR the BLAST system outperforms the STBC systems. The results obtained show that the packet combining method significantly improves the performance of the MMSE BLAST receiver (more than 10dB at times), outperforming the quasi-orthogonal rate-1 STBC for all SNR values when the MIMO channels are uncorrelated. From a cross-layer design perspective, it shows that space-time coding can be used instead of an RLP protocol to improve TCP performance under poor channel conditions are bad (SNR before 12dB), but when channel conditions improve a switch to BLAST scheme with RLP

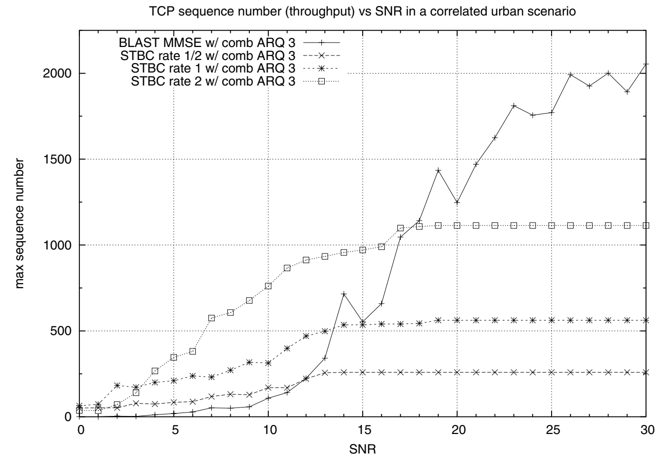

Fig. 7. TCP throughput with combining ARQ and correlated antennas for the urban scenario. The maximum number of retransmissions is 3.

is preferred. In addition we observed that when the MIMO channels are correlated, the more reliable STBC systems are always preferable. The ARQ retransmission mechanisms together with the packet combining significantly improves the performance of TCP under correlated channels for BLAST systems, offering a minor improvement for the more reliable STBC systems. As a major point, our investigation shows that when regarding application performance, the common approach of simply increasing spectral efficiency does not necessary result in an increment of the TCP throughput.

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