Signal-Level Cooperative Spatial Multiplexing for Uplink Throughput Enhancement in MIMO Broadband Systems
Hatim Chergui, Tarik Ait Idir, Mustapha Benjillali, Samir Saoudi

To cite this version:
Hatim Chergui, Tarik Ait Idir, Mustapha Benjillali, Samir Saoudi. Signal-Level Cooperative Spatial Multiplexing for Uplink Throughput Enhancement in MIMO Broadband Systems. WCNC 2013 : IEEE Wireless Communications and Networking Conference, Apr 2013, Shanghai, China. IEEE, 2013. <hal-00833891>

HAL Id: hal-00833891
https://hal.archives-ouvertes.fr/hal-00833891
Submitted on 13 Jun 2013

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Signal-Level Cooperative Spatial Multiplexing for Uplink Throughput Enhancement in MIMO Broadband Systems

Hatim Chergui(1,2), Tarik Ait-Idir(1,2), Mustapha Benjillali(3), and Samir Saoudi(2)
(1) ExceliaCom Solutions, Rabat, Morocco
(2) Institut TELECOM/TELECOM Bretagne, UMR CNRS 3192 Lab-STICC, Technopôle Brest-Iroise, France
(3) Communications Systems Department, INPT, Madinat Al Irfane, Rabat, Morocco
Emails: {chergui, aitidir, benjillali}@ieee.org, samir.saoudi@telecom-bretagne.eu

Abstract—In this paper, we address the issue of throughput-efficient half-duplex constrained relaying schemes for broadband uplink transmissions over multiple-input multiple-output (MIMO) channels. We introduce a low complexity signal-level cooperative spatial multiplexing (CM) architecture that allows for the shortening of the relaying phase without resorting to any symbol detection or re-mapping at the relay side. Half-duplex latency is thereby reduced, resulting in a remarkable throughput gain compared to amplify-and-forward (AF) relaying scheme. Surprisingly, we show that CM strategy becomes more powerful in boosting uplink throughput as the relay approaches cell edge.

However, from the complexity viewpoint, bit-level and symbol-level processing are required in the first and second schemes, respectively.

In this paper, we introduce a novel signal-level cooperative spatial multiplexing (CM) scheme for uplink MIMO broadband transmissions. It enables to shorten the time consumed by the relaying phase through packet resizing, without requiring any symbol detection or re-mapping at the relay. Such a strategy turns out to be throughput-efficient over the whole signal-to-noise ratio (SNR) range compared to AF mode, and interestingly, becomes more powerful at cell edge.

The remaining of the paper is organized as follows: In Section II, we introduce the system model whereas we describe the broadcast phase processing in Section III. Section IV details then the building blocks of the relaying scheme while the equivalent MIMO channel derivation and average throughput analysis is conducted in Section V. Section VI is devoted to numerical results. Finally, the paper is concluded in Section VII.

Notational convention:
- Superscripts $^T$ and $^H$ denote transpose, and Hermitian transpose, respectively.
- $E[.]$ is the mathematical expectation, and $[.]$ represents the integer part function.
- $\delta_{tt'}$ is the Kronecker symbol, i.e., $\delta_{tt'} = 1$ for $t = t'$ and $\delta_{tt'} = 0$ for $t \neq t'$.
- $I_N$ is the $N \times N$ identity matrix, and $0_{N \times M}$ denotes an all zero $N \times M$ matrix.
- $U_T$ is the unitary $T \times T$ Fourier matrix whose $(m,n)$-th element is $U_T[m, n] = \frac{1}{\sqrt{T}} e^{-j2\pi mn/T}$, and $j = \sqrt{-1}$.
- $U_{T,N} \triangleq U_T \otimes I_N$, where $\otimes$ denotes the Kronecker product.
- $z^j$ is the block discrete Fourier transform (DFT) transform of $z$ defined as $z^j \triangleq U_{T,N} z$.
- vec$_T \{z_t\} \triangleq [z^T_0, \ldots, z^T_{T-1}]^T$ is the stacked vector linking sub-vectors $z_t (t = 0, \ldots, T - 1)$.

1For CApital EXpenditures and OPerational EXpense, respectively.
II. SYSTEM MODEL

A. Channel Description

We consider a single carrier multi-antenna broadband cooperative uplink transmission involving a \( n_s \) antennas source, a \( n_r \) antennas relay, and a \( n_d \) antennas destination. Communication between each couple of NEs, \( i \in \{s, r\} \) and \( i' \in \{r, d\} \), is established via a wireless link \( ii' \) corrupted by two fading effects:

- Large-scale fading: modeled by the average link loss \( \alpha_{ii'} = d_{ii'}^{-\kappa/2} \) encompassing both free space attenuation and shadowing, where \( d_{ii'} \) is the distance between nodes \( i \) and \( i' \) and \( \kappa \) is the path loss exponent.

- Small-scale fading: where each link \( ii' \) is supposed to be a block fading quasi-static frequency-selective MIMO channel of memory \( L_{ii'} - 1 \) (index \( l = 0, \ldots, L_{ii'} - 1 \)). The \( l \)th path is represented by an independent standard complex Gaussian matrix \( \mathbf{H}_{ii'}^l \in \mathbb{C}^{n_i \times n_{i'}} \). Coefficients thereof have variance \( \frac{1}{L_{ii'}} \) under a normalized equal power-delay profile. Therefore, the total average received power per each receive antenna (at both the relay and the destination) is equal to \( n_s \) when no large scale fading is considered.

B. Cooperation Protocol

The relay transmission is assumed half-duplex, spanning hence two consecutive phases. In this framework, we consider that the cooperation is orthogonal [5], i.e., the source broadcasts the whole data block during the first phase while it remains silent during the second phase when the relay forwards a processed version of the captured packet to the destination.

III. BROADCAST PHASE PROCESSING

A. Signaling Scheme

We restrict the source to operate under the spatial multiplexing (SM) mode. During each broadcast phase, node \( s \) generates a \( n_s \times T \) symbol matrix \( \mathbf{X} \),

\[
\mathbf{X} \triangleq [\mathbf{x}_0, \ldots, \mathbf{x}_{T-1}],
\]

where \( T \) (index \( t = 0, \ldots, T-1 \)) is the total number of channel uses (c.u.), and \( \mathbf{x}_t = [x_{1,t}, \ldots, x_{n_s,t}]^T \in \mathbb{A}^{n_s} \) is the symbol vector at c.u. \( t \), with \( \mathbb{A} \) is the alphabet of normalized constellation symbols. We assume that the source has no channel state information (CSI). Therefore, equal transmit power allocation is the optimal choice [7]. Symbols are considered to be zero-mean and independent in both space and time dimensions (deep interleaving assumption). Their cross-correlation is given by

\[
E[\mathbf{x}_t\mathbf{x}_t^H] = \delta_{tt} \mathbf{I}_{n_s}.
\]

To prevent interblock interference, each packet is preceded by a cyclic prefix (CP) of length \( L_{CP} = \max\{L_{sd}, L_{sr}, L_{rd}\} \).

B. Broadcast Phase Communication Model

At this level, the source proceeds by sending a prefixed version of packet \( \mathbf{x} \) to both the destination and the relay. The corresponding CP-free baseband received signals can be respectively expressed as

\[
y_{d,t} = \alpha_{sd} \sum_{l=0}^{L_{sd}-1} \mathbf{H}_{d,s}^l \mathbf{x}_{(t-l)\bmod T} + \mathbf{n}_{d,t}^{(1)} \in \mathbb{C}^{n_d \times 1},
\]

\[
y_{r,t} = \alpha_{sr} \sum_{l=0}^{L_{sr}-1} \mathbf{H}_{r,s}^l \mathbf{x}_{(t-l)\bmod T} + \mathbf{n}_{r,t} \in \mathbb{C}^{n_r \times 1},
\]

where random vectors \( \mathbf{n}_{d,t}^{(1)} \sim \mathcal{N}(0_{n_d \times 1}, \sigma_d^2 \mathbf{I}_{n_d}) \) and \( \mathbf{n}_{r,t} \sim \mathcal{N}(0_{n_r \times 1}, \sigma_r^2 \mathbf{I}_{n_r}) \) denote the additive thermal noise.

IV. RELAYING PHASE PROCESSING

A. Frequency Domain Transformation

The relaying phase starts by transposing the stacked signal vector \( \mathbf{y}_r \) into the frequency domain. For that end, a block-wise communication model is constructed from (4) as

\[
y_{r} = \alpha_{sr} \mathbf{H}^{sr} \mathbf{x} + \mathbf{n}_r,
\]

where \( \mathbf{H}^{sr} \) is a \( n_rT \times n_sT \) block circulant matrix whose first column is

\[
\begin{bmatrix}
\mathbf{H}_{0}^{sr} & \cdots & \mathbf{H}_{L_{sr}-1}^{sr} \\
0_{n_r \times n_r \times (T-L_{sr})}
\end{bmatrix}
\]

\[
\mathbf{H}^{sr} \text{ can therefore be block diagonalized in the Fourier basis, i.e., } \mathbf{H}^{sr} = \mathbf{U}^{H} \mathbf{C}^{sr} \mathbf{U}^{T}.
\]

where \( \mathbf{C}^{sr} \triangleq \text{diag}\{\mathbf{C}_{1}^{sr}, \ldots, \mathbf{C}_{T-1}^{sr}\} \), and

\[
\mathbf{C}_{l}^{sr} = \sum_{l=0}^{L_{sr}-1} \mathbf{H}_{l}^{sr} \exp \left\{-j \frac{2\pi tl}{T}\right\} \in \mathbb{C}^{n_r \times n_s}
\]

stands for the channel frequency response (CFR) at the \( t \)th subcarrier. Hence, the frequency domain image of (5) is given by

\[
y_{r,t} = \alpha_{sr} \mathbf{C}^{sr} \mathbf{x}_{t} + \mathbf{n}_{r,t} \in \mathbb{C}^{n_r \times 1},
\]

which can be expressed component-wise as

\[
y_{r,t} = \alpha_{sr} \mathbf{C}^{sr}_{t} \mathbf{x}_{t} + \mathbf{n}_{r,t} \in \mathbb{C}^{n_r \times 1}.
\]

According to (7), each matrix \( \mathbf{C}^{sr}_{t} \) is a linear combination of independent standard Gaussian matrices. It follows that it is full rank, i.e., \( \text{rank}(\mathbf{C}^{sr}_{t}) = \min(n_s, n_r) = n_s \).
By invoking (11), we can write the packet of length correspondingly constructed as a multiple of $n$

\[ y'_{r,t} = Q_{r,t}^H \tilde{y}_{r,t}, \]

where the $n_r \times n_s$ matrix $Q_{r,t}$ has orthogonal columns with unit norm and the $n_s \times n_r$ matrix $R_{r,t}$ is upper triangular. Multiplying the received signal $y_{r,t}$ by $Q_{r,t}^H$ yields the sufficient statistic

\[ \tilde{y}_{r,t} = Q_{r,t}^H y_{r,t} = \alpha_{sr} \mathbf{R}_t \tilde{x}_t + \tilde{n}_{r,t} \in \mathbb{C}^{n_r \times 1} \]

for the estimation of transmit vector $x'_t$ at the destination side. Since $Q_r$ is an unitary matrix, the statistical properties of the noise term $\tilde{n}_{r,t} = Q_{r,t}^H y_{r,t}$ are maintained.

### C. Signal-Level Spatial Multiplexing

In the event that only $n_s$ relay antennas are required to forward statistic $y'_{r,t}$ to node $d$, a spatial multiplexing can be performed on the $(n_r - n_s)$ free antennas. It entails simultaneously transmitting $k$ signal vectors of size $n_s \times 1$ to the destination, where

\[ k \triangleq \left\lfloor \frac{n_r}{n_s} \right\rfloor. \]

The transmission unit of node $r$ hence becomes a short packet of $k n_s \times T_k$ signal samples, where actually, the new packet length $T_k = \frac{T_k}{T_k}$ is an integer since $T$ is supposed to be a multiple of $n_r$. The $t^{th}$ subcarrier signal $y'_{r,t}$ is correspondingly constructed as

\[ \tilde{y}_{r,t} = \begin{bmatrix} y_{r,k^{(t-1)}}, & \cdots, & y_{r,k^{(t)}} \end{bmatrix}^T \in \mathbb{C}^{kn_s \times 1}. \]

By invoking (11), we can write

\[ \tilde{y}_{r,t} = \alpha_{sr} \mathbf{R}_t \tilde{x}_t + \tilde{n}_{r,t}, \quad t = 0, \ldots, T_k - 1 \]

with $x'_t = \begin{bmatrix} x_{r,t}, & \cdots, & x_{r,k^{(t-1)}} \end{bmatrix}^T \in \mathbb{C}^{kn_s \times 1}$, $\mathbf{R}_t = \text{diag} \begin{bmatrix} \mathbf{R}_{r,t}, & \cdots, & \mathbf{R}_{r,k^{(t-1)}} \end{bmatrix} \in \mathbb{C}^{kn_s \times kn_s}$, and $\tilde{n}_{r,t} = \begin{bmatrix} \tilde{n}_{r,k^{(t-1)}}, & \cdots, & \tilde{n}_{r,k^{(t)}} \end{bmatrix}^T \in \mathbb{C}^{kn_s \times 1}$.

The relay performs time domain conversion of the stacked signal $y'_{r,t} = \text{vec}_{T_k} \begin{bmatrix} \tilde{y}_{r,t} \end{bmatrix}$ via the application of a $T_k$-point inverse DFT as

\[ \tilde{y}_r = \mathbf{U}_{T_k,n_s}^H \tilde{y}_r' \]

The resulting $kn_s \times 1$ single carrier signal at channel use $t$ is then normalized using its conditional covariance matrix,

\[ \mathbf{H}_{l}^{sr} = \mathbf{E} \begin{bmatrix} \tilde{y}_{r,l} \tilde{y}_{r,l}^H \end{bmatrix} \in \mathbb{C}^{kn_s \times kn_s}. \]

Given the aforementioned assumption of deep space time interleaving, and the independence between symbols and noise vectors, (17) yields a developed expression of (19)

\[ \mathbf{H}_{l}^{sr} = \mathbf{H}_{l}^{sr} + \sigma^2 \mathbf{I}_{kn_s}. \]

By considering the Cholesky factorization $\mathbf{H}_{l}^{sr} = \mathbf{\Gamma H}_{l}^{sr}$, the normalization consists on left multiplying $\tilde{y}_{r,l}$ by $\mathbf{\Gamma}^{-1}$.

### D. Relaying Phase Communication Model

During the second phase, termed also "relaying phase", the normalized signal vector is mapped to $kn_s$ relay antennas and transmitted towards node $d$. In the simplest case, these active antennas are selected according to a fixed mapping matrix,

\[ \mathbf{M} = \begin{bmatrix} \mathbf{I}_{kn_s} \\ 0_{(n_r - kn_s) \times kn_s} \end{bmatrix}, \]

which is the strategy here, since the problem of antennas selection is out of the scope of this paper. At the receiver side, the obtained signal after the elimination of CP is consequently expressed as

\[ y_{d,t}^{(2)} = \alpha_{rd} \sum_{l=0}^{L_1-1} \mathbf{H}_{t}^{rd} \mathbf{M}^{-1} \tilde{y}_{r,t(l-1)} + \tilde{n}_{d,t}^{(2)} \in \mathbb{C}^{n_d \times 1}, \]
where \( \tilde{n}^{(2)}_{d,t} \sim \mathcal{N} \left( 0, \sigma^2 \mathbf{I}_{M_B} \right) \) denotes the additive Gaussian noise. By invoking (17) and (22), the sampled \( n_{d,t} \times 1 \) signal vector \( y^{(2)}_{d,t} \) can be further developed as
\[
y^{(2)}_{d,t} = \alpha_{rd} \sum_{l=0}^{L_{rd}-1} H^{rd}_l \tilde{x}_{(t-l)\text{mod}T_k} + \tilde{n}^{(2)}_{d,t},
\] (23)
with \( L_{rd} = T_k + L_{rd} - 1 \), and
\[
H^{rd}_l = \min(l, T_k - 1) \sum_{n=\max(0, l-L_{rd}+1)}^{\min(l, T_k-1)} H^{rd}_{l-n} \mathbf{M}^{-1} \mathbf{H}^{sr}_n \in \mathbb{C}^{n_d \times k_n},
\] (24)
The corresponding noise \( n^{(2)}_{d,t} \) is expressed by
\[
n^{(2)}_{d,t} = \alpha_{rd} \sum_{l=0}^{L_{rd}-1} H^{rd}_l \mathbf{M}^{-1} \tilde{n}_l_{(t-l)\text{mod}T_k} + \tilde{n}^{(2)}_{d,t},
\] (25)
and has conditional covariance matrix \( \mathbf{A}_{|H^{rd}} \) (conditioned upon \( H^{rd} \))
\[
\begin{align*}
\mathbf{A}_{|H^{rd}} &= \sigma^2 \left( \alpha_{rd}^2 \sum_{l=0}^{L_{rd}-1} \mathbf{A}_l \mathbf{A}_l^H + \mathbf{I}_{n_d} \right), \\
\mathbf{A}_l &= H^{rd}_l \mathbf{M}^{-1} - 1.
\end{align*}
\] (26)

V. AVERAGE THROUGHPUT ANALYSIS

In this section, we show that the presented cooperation scheme can be viewed as a transmission over a virtual MIMO channel whose expression is derived in the sequel. The system performance, in terms of average throughput, is then analyzed.

A. Equivalent MIMO Channel

By transposing the received signal packets \( y^{(1)}_d = \text{vec}_T \{ y^{(1)}_{d,t} \} \) and \( y^{(2)}_d = \text{vec}_{T_k} \{ y^{(2)}_{d,t} \} \) to the frequency domain,
\[
\begin{align*}
y^{(1)}_d &= \mathbf{U}_{T,n_d} y^{(1)}_d, \\
y^{(2)}_d &= \mathbf{U}_{T_k,n_d} y^{(2)}_d,
\end{align*}
\] (27)
we get the following subcarriers communication models
\[
\begin{align*}
y^{(1)}_{d,t} &= \alpha_{sd} \mathbf{C}^{sd}_t \mathbf{x}_t' + n^{(1)}_{d,t}, t = 0, \ldots, T - 1, \\
y^{(2)}_{d,t} &= \alpha_{rd} \alpha_{sd} \mathbf{C}^{sr_d}_t \mathbf{x}_t' + n^{(2)}_{d,t}, t = 0, \ldots, T_k - 1,
\end{align*}
\] (28)
where \( \{ \mathbf{C}^{sd}_t \} \) and \( \{ \mathbf{C}^{sr_d}_t \} \) correspond to the CFRs of \( \{ \mathbf{H}^{sd}_t \} \) and \( \{ \mathbf{H}^{sr_d}_t \} \), respectively. To unify the channel inputs in (28), each \( k \) consecutive observations of \( y^{(1)}_d \) are limped into one stacked vector
\[
\mathbf{y}^{(1)}_d = \alpha_{sd} \mathbf{C}^{sd}_{t,k} \mathbf{x}_t' + \mathbf{n}^{(1)}_{d,t}, t = 0, \ldots, T_k - 1, 
\] (29)
with
\[
\begin{align*}
\mathbf{y}^{(1)}_d &\triangleq \left[ y^{(1)}_{d,k+1}^T, \ldots, y^{(1)}_{d,k(T+1)-1}^T \right]^T \in \mathbb{C}^{k n_d}, \\
\mathbf{C}^{sd}_{t,k} &\triangleq \text{diag} \left( \mathbf{C}^{sd}_k, \ldots, \mathbf{C}^{sd}_{k(T+1)-1} \right) \in \mathbb{C}^{k n_d \times k n_d}, \\
\mathbf{n}^{(1)}_{d,t} &\triangleq \left[ n^{(1)}_{d,k+1}^T, \ldots, n^{(1)}_{d,k(T+1)-1}^T \right]^T \in \mathbb{C}^{k n_d}.
\end{align*}
\] (30)

Noise \( \mathbf{n}^{(2)}_{d,t} \) is colored, having the same covariance matrix \( \mathbf{A}_{|H^{rd}} \). Consequently, we rather consider the Cholesky decomposition based whitened signal \( \Omega^{-1} y^{(2)}_d \) in the equivalent channel derivation, where \( \mathbf{A}_{|H^{rd}} = \sigma^2 \Omega^{H} \).

Based on (28) and (29), the considered relaying system can be represented by a virtual \( (k + 1) n_d \times k_n s \) MIMO channel whose expression at the \( t \)th subcarrier \( (t = 0, \ldots, T_k - 1) \) is given by
\[
\begin{bmatrix}
\mathbf{y}^{(1)}_{d,t} \\
\Omega^{-1} y^{(2)}_{d,t}
\end{bmatrix}
= \begin{bmatrix}
\alpha_{sd} \mathbf{C}^{sd}_{t,k} \Omega^{-1} \\
\alpha_{rd} \alpha_{sd} \mathbf{C}^{sr_d}_{t,k} \Omega^{-1}
\end{bmatrix}
\mathbf{x}^t + \begin{bmatrix}
\mathbf{n}^{(1)}_{d,t} \\
\Omega^{-1} \mathbf{n}^{(2)}_{d,t}
\end{bmatrix}.
\] (31)

B. Average Throughput

To characterize the performance of the proposed cooperative spatial multiplexing scheme, average throughput is adopted as a metric. It is commonly a function of the factor \( k \), the target spectral efficiency \( S \), and the received SNR \( \gamma \),
\[
\overline{T}(k, S, \gamma) = \mathbb{E} [s],
\] (32)
where \( s \) is a random variable (RV) taking values \( S \) and 0 with probabilities \( 1 - P_{out}(k, S, \gamma) \) (in case of successful packet decoding) and \( P_{out}(k, S, \gamma) \) (when the decoding outcome is erroneous), respectively. Thus,
\[
\mathbb{E} [s] = S \left( 1 - P_{out}(k, S, \gamma) \right),
\] (33)
where \( P_{out}(k, S, \gamma) \) is the transmission’s outage probability. It is defined in terms of the mutual information of the above equivalent MIMO channel (31) as
\[
P_{out}(k, S, \gamma) = \Pr \left\{ \frac{1}{k + 1} I(C, \gamma) < S \right\}. 
\] (34)
The \( \frac{1}{k + 1} \) distortion factor in (34) results from the fact that one channel use of the equivalent MIMO channel corresponds to \( k + 1 \) effective c.u. of the system. The mutual information \( I(C, \gamma) \) can be approximated by assuming a Gaussian input alphabet,
\[
I(C, \gamma) \approx \frac{1}{T_k} \sum_{t=0}^{T_k-1} \log_2 \left( \det \left( \mathbf{I}_{(k+1)n_d} + \frac{\gamma}{n_s} \mathbf{C}^H_t \mathbf{C}_t \right) \right).
\] (35)

VI. SIMULATION RESULTS

A. Simulation Settings

In this section, average throughput performance of the presented signal-level cooperative spatial multiplexing scheme is evaluated via Monte-Carlo simulations. As a benchmark, we consider the half-duplex orthogonal amplify-and-forward (AF) relaying function, that actually, presents the same constraints as our system while being also signal-level oriented. To ensure a fair comparison, nodes of both systems must perceive the same...
SNRs. Let $\gamma_{i'\ell}$ denote the average SNR per receive antenna over link $i'\ell$. CM and AF SNR measurements are similar for links $sd$ and $sr$, i.e., $\gamma_{sd}^{CM} \approx \gamma_{sd}^{AF} = \frac{\alpha_{sr}^{n_{s,r}}}{\sigma^2}$, $i' \in \{r,d\}$, while they differ for link $rd$

$$\gamma_{rd}^{CM} = \frac{\alpha_{rd}^{n_{r,d}}}{\sigma^2} \leq \frac{\alpha_{rd}^{n_{r,d}}}{\sigma^2} = \gamma_{rd}^{AF}.$$  

To balance the relay-destination links, we increase the average transmit power of CM by a factor $\frac{\alpha_{rd}^{n_{r,d}}}{\sigma^2}$. In all simulation scenarios, the source node is equipped with a single antenna ($n_s = 1$) since it is the typical uplink transmission scheme in MIMO broadband systems (e.g., LTE). Links $sd$, $sr$, and $rd$ have the same length $L_{sd} = L_{sr} = L_{rd} = 3$. The path loss exponent is set to $\kappa = 3$, and $T = 128$ c.u. The average throughput we are computing corresponds to a target spectral efficiency $S$ of $n_s$ (bit/s/Hz).

### B. Performance Analysis

1) **Average throughput versus SNR:** It is noteworthy that the relay is located at the midpoint between nodes $s$ and $d$ so that the performance behaviour can be relatively decorrelated with node $r$ position. In the case of antennas configuration $(n_s, n_r, n_d) = (1, 2, 2)$, the CM scheme shrinks the relaying phase duration to the half ($k = 2$) thus leading to a gain of 3 to 4 dB compared to AF over the entire SNR range. Such a difference becomes more accentuated when $(n_s, n_r, n_d) = (1, 3, 3)$. In Fig. 4, a 4 to 5 dB gap is observed between CM and AF since the first relay performs a spatial multiplexing on its 3 antennas ($k = 3$). The CM throughput saturates at $-9$ dB ($\bar{T} = 1$), whereas AF’s one reaches only $0.1$ bit/s/Hz.

2) **Average throughput versus distance:** Let us now focus on the medium SNR region, where average throughput trends can be concisely evaluated for various relay locations. Fig. 5 shows that CM is mostly throughput-efficient than AF, and increases as node $r$ moves away from the source. The rationale behind it is that the signal-level spatial multiplexing is sensitive to the $rd$ link. Insofar that the decorrelation between channel matrix $H^{rd}$ elements starts to be weaker in the surroundings of the source node ($d_{sr} < 0.3$), the spatial multiplexing becomes impractical compared to AF strategy. Consequently, CM turns out to be an efficient relaying function for uplink throughput enhancement at cell edge.

### VII. Conclusion

In this paper, a new low complexity signal-level cooperative spatial multiplexing scheme for uplink broadband MIMO channels has been presented. It enables to dramatically reduce the half-duplex latency in relay-aided systems, leading thereby to a great throughput enhancement, especially when the relay is at cell edge.

### REFERENCES


