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► **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. hal-00833891

HAL Id: hal-00833891

<https://hal.science/hal-00833891v1>

Submitted on 13 Jun 2013

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Signal-Level Cooperative Spatial Multiplexing for Uplink Throughput Enhancement in MIMO Broadband Systems

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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.

I. INTRODUCTION

In 4G heterogeneous networks (HetNets) and beyond [1], the concept of relaying is a paramount feature insofar that deploying relays in a broadband wireless communication network might drive far-reaching gains in terms of coverage, capacity, and consequently CAPEX and OPEX¹ cost savings. This is because a relay is designed to be power-efficient, running low-complexity signal processing schemes by which it serves as an artificial source of spatial diversity to other network elements (NEs) [2]. In this context, amplify-and-forward (AF) is considered as the simplest relaying strategy, since it processes received packets at the signal level by merely amplifying and retransmitting them to the destination.

A common limitation to all relaying schemes is that *full-duplex* mode, in which a relay can simultaneously transmit and receive, is infeasible due to practical design constraints [3]. Relays are therefore operating in *half-duplex* mode, thus leading to a great throughput loss. To sidestep such a drawback, several relaying strategies have been introduced. Hence, it has been shown that when adopting channel dependant modulations in both source and relay nodes, throughput can be improved in coded cooperative systems [4]. Also, by letting a detect-and-forward (DetF) relay use a modulation whose order is higher than the one at the source, relaying phase duration has been reduced in [5], resulting thereby in interesting throughput gains.

However, from the complexity viewpoint, bit-level and symbol-level processings 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.
- $E[\cdot]$ is the mathematical expectation, and $[\cdot]$ represents the integer part function.
- $\delta_{tt'}$ is the Kronecker symbol, i.e., $\delta_{tt'} = 1$ for $t = t'$ and $\delta_{tt'} = 0$ for $t \neq t'$.
- \mathbf{I}_N is the $N \times N$ identity matrix, and $\mathbf{0}_{N \times M}$ denotes an all zero $N \times M$ matrix.
- \mathbf{U}_T is the unitary $T \times T$ Fourier matrix whose (m, n) -th element is $\mathbf{U}_T[m, n] = \frac{1}{\sqrt{T}} e^{-j2\pi mn/T}$, and $j = \sqrt{-1}$. $\mathbf{U}_{T,N} \triangleq \mathbf{U}_T \otimes \mathbf{I}_N$, where \otimes denotes the Kronecker product.
- \mathbf{z}' is the block discrete Fourier transform (DFT) transform of \mathbf{z} defined as $\mathbf{z}' \triangleq \mathbf{U}_{T,N} \mathbf{z}$.
- $\text{vect}_T \{\mathbf{z}_t\} \triangleq [\mathbf{z}_0^T, \dots, \mathbf{z}_{T-1}^T]^T$ is the stacked vector limping sub-vectors \mathbf{z}_t ($t = 0, \dots, T - 1$).

¹For CAPital EXpenditures and OPERational EXpense, respectively

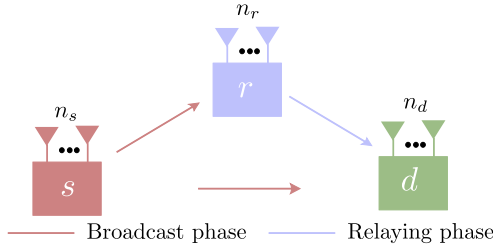


Figure 1. Orthogonal cooperation

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 ($n_d \geq n_r \geq n_s$). 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, with $d_{ii'}$ is the distance between nodes i and i' and κ 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 $l = 0, \dots, L_{ii'} - 1$). The l th path is represented by an independent standard complex Gaussian matrix $\mathbf{H}_l^{ii'} \in \mathbb{C}^{n_i \times n_{i'}}$. Coefficients thereof have variance $1/L_{ii'}$ 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} ,

$$\mathbf{X} \triangleq [\mathbf{x}_0, \dots, \mathbf{x}_{T-1}], \quad (1)$$

where T (index $t = 0, \dots, T-1$) is the total number of channel uses (c.u.), and $\mathbf{x}_t = [x_{1,t}, \dots, x_{n_s,t}]^T \in \mathcal{A}^{n_s}$ is the symbol vector at c.u. t , with \mathcal{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 [?]. Symbols are considered to be zero-mean and independent in both space and time dimensions (deep interleaving assumption). Their cross-correlation is given by

$$\mathbb{E} [\mathbf{x}_t \mathbf{x}_{t'}^H] = \delta_{tt'} \mathbf{I}_{n_s}. \quad (2)$$

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

$$\mathbf{y}_{d,t}^{(1)} = \alpha_{sd} \sum_{l=0}^{L_{sd}-1} \mathbf{H}_l^{sd} \mathbf{x}_{(t-l) \bmod T} + \mathbf{n}_{d,t}^{(1)} \in \mathbb{C}^{n_d \times 1}, \quad (3)$$

$$\mathbf{y}_{r,t} = \alpha_{sr} \sum_{l=0}^{L_{sr}-1} \mathbf{H}_l^{sr} \mathbf{x}_{(t-l) \bmod T} + \mathbf{n}_{r,t} \in \mathbb{C}^{n_r \times 1}, \quad (4)$$

where random vectors $\mathbf{n}_{d,t}^{(1)} \sim \mathcal{N}(\mathbf{0}_{n_d \times 1}, \sigma^2 \mathbf{I}_{n_d})$ and $\mathbf{n}_{r,t} \sim \mathcal{N}(\mathbf{0}_{n_r \times 1}, \sigma^2 \mathbf{I}_{n_r})$ 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

$$\mathbf{y}_r = \alpha_{sr} \mathbf{H}^{sr} \mathbf{x} + \mathbf{n}_r, \quad (5)$$

where \mathbf{H}^{sr} is a $n_r T \times n_s T$ block circulant matrix whose first column is

$$\left[\mathbf{H}_0^{srT}, \dots, \mathbf{H}_{L_{sr}-1}^{srT}, \mathbf{0}_{n_s \times n_r(T-L_{sr})} \right]^T \quad (6)$$

\mathbf{H}^{sr} can therefore be block diagonalized in the Fourier basis, i.e., $\mathbf{H}^{sr} = \mathbf{U}_{T,n_r}^H \mathbf{C}^{sr} \mathbf{U}_{T,n_s}$ where $\mathbf{C}^{sr} \triangleq \text{diag} \{ \mathbf{C}_0^{sr}, \dots, \mathbf{C}_{T-1}^{sr} \}$, and

$$\mathbf{C}_t^{sr} = \sum_{l=0}^{L_{sr}-1} \mathbf{H}_l^{sr} \exp \left\{ -j \frac{2\pi t l}{T} \right\} \in \mathbb{C}^{n_r \times n_s} \quad (7)$$

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

$$\mathbf{y}'_r = \alpha_{sr} \mathbf{C}^{sr} \mathbf{x}' + \mathbf{n}'_r \in \mathbb{C}^{n_r T}, \quad (8)$$

which can be expressed component-wise as

$$\mathbf{y}'_{r,t} = \alpha_{sr} \mathbf{C}_t^{sr} \mathbf{x}'_t + \mathbf{n}'_{r,t} \in \mathbb{C}^{n_r \times 1}. \quad (9)$$

According to (7), each matrix \mathbf{C}_t^{sr} is a linear combination of independent standard Gaussian matrices. It follows that it is full rank, i.e., $\text{rank}(\mathbf{C}_t^{sr}) = \min(n_s, n_r) = n_s$.

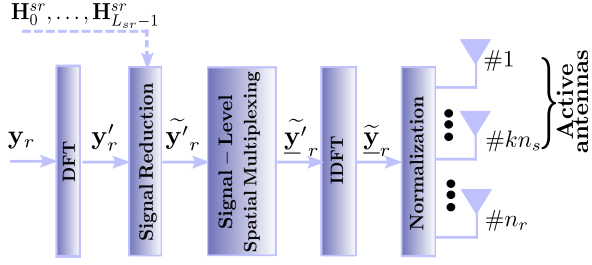


Figure 2. Relaying phase processing

B. Signal Reduction

By the QR decomposition technique [6], the CFR \mathbf{C}_t^{sr} can be written as

$$\mathbf{C}_t^{sr} = \mathbf{Q}_t \mathbf{R}_t, \quad (10)$$

where the $n_r \times n_s$ matrix \mathbf{Q}_t has orthogonal columns with unit norm and the $n_s \times n_s$ matrix \mathbf{R}_t is upper triangular. Multiplying the received signal $\mathbf{y}'_{r,t}$ by \mathbf{Q}_t^H yields the sufficient statistic

$$\tilde{\mathbf{y}}'_{r,t} = \mathbf{Q}_t^H \mathbf{y}'_{r,t} = \alpha_{sr} \mathbf{R}_t \mathbf{x}'_t + \tilde{\mathbf{n}}'_{r,t} \in \mathbb{C}^{n_s \times 1} \quad (11)$$

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

C. Signal-Level Spatial Multiplexing

In the extent that only n_s relay antennas are required to forward statistic $\tilde{\mathbf{y}}'_{r,t}$ 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

$$k \triangleq \left\lfloor \frac{n_r}{n_s} \right\rfloor. \quad (12)$$

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

$$\tilde{\mathbf{y}}'_{r,t} \triangleq \left[\tilde{\mathbf{y}}'_{r,kt}, \dots, \tilde{\mathbf{y}}'_{r,k(t+1)-1} \right]^T \in \mathbb{C}^{kn_s \times 1}. \quad (13)$$

By invoking (11), we can write

$$\tilde{\mathbf{y}}'_{r,t} = \alpha_{sr} \mathbf{R}_t \mathbf{x}'_t + \tilde{\mathbf{n}}'_{r,t}, \quad t = 0, \dots, T_k - 1 \quad (14)$$

with

$$\begin{cases} \mathbf{x}'_t & \triangleq \left[\mathbf{x}'_{kt}, \dots, \mathbf{x}'_{k(t+1)-1} \right]^T \in \mathbb{C}^{kn_s}, \\ \mathbf{R}_t & \triangleq \text{diag} \{ \mathbf{R}_{kt}, \dots, \mathbf{R}_{k(t+1)-1} \} \in \mathbb{C}^{kn_s \times kn_s}, \\ \tilde{\mathbf{n}}'_{r,t} & \triangleq \left[\tilde{\mathbf{n}}'_{r,kt}, \dots, \tilde{\mathbf{n}}'_{r,k(t+1)-1} \right]^T \in \mathbb{C}^{kn_s}. \end{cases} \quad (15)$$

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

$$\tilde{\mathbf{y}}_r = \mathbf{U}_{T_k, kn_s}^H \tilde{\mathbf{y}}'_r. \quad (16)$$

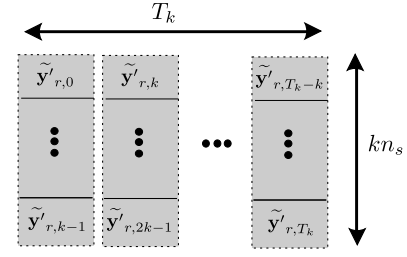


Figure 3. $kn_s \times T_k$ signal packet resulting from spatial multiplexing

The resulting $kn_s \times 1$ single carrier signal at channel use t is given by

$$\tilde{\mathbf{y}}_{r,t} = \alpha_{sr} \sum_{l=0}^{T_k-1} \tilde{\mathbf{H}}_l^{sr} \tilde{\mathbf{x}}_{(t-l) \bmod T_k} + \tilde{\mathbf{n}}_{r,t} \in \mathbb{C}^{kn_s}, \quad (17)$$

where $\tilde{\mathbf{x}} = \mathbf{U}_{T_k, kn_s}^H \mathbf{x}'$ is affected by AWGN noise $\tilde{\mathbf{n}}_r = \text{vec}_{T_k} \{ \tilde{\mathbf{n}}_{r,t} \}$. Due to the above QR decomposition, the energy of the equivalent source-relay multipath channel $\tilde{\mathbf{H}}^{sr}$ is dispersed over T_k virtual paths. The l th path can be explicated as

$$\tilde{\mathbf{H}}_l^{sr} = \sum_{t=0}^{T_k-1} \mathbf{R}_t \exp \left\{ j \frac{2\pi t l}{T_k} \right\} \in \mathbb{C}^{kn_s \times kn_s}. \quad (18)$$

The time domain signal $\tilde{\mathbf{y}}_{r,t}$ is then normalized using its conditional covariance matrix,

$$\Xi_{|\tilde{\mathbf{H}}^{sr}} = \mathbb{E} \left[\tilde{\mathbf{y}}_{r,t} \tilde{\mathbf{y}}_{r,t}^H \mid \{ \tilde{\mathbf{H}}_l^{sr} \} \right]. \quad (19)$$

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

$$\Xi_{|\tilde{\mathbf{H}}^{sr}} = \alpha_{sr}^2 \sum_{l=0}^{T_k-1} \tilde{\mathbf{H}}_l^{sr} \tilde{\mathbf{H}}_l^{srH} + \sigma^2 \mathbf{I}_{kn_s}. \quad (20)$$

By considering the Cholesky factorization $\Xi_{|\tilde{\mathbf{H}}^{sr}} = \mathbf{\Gamma} \mathbf{\Gamma}^H$, the normalization consists on left multiplying $\tilde{\mathbf{y}}_{r,t}$ 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,

$$\mathbf{M} = \begin{bmatrix} \mathbf{I}_{kn_s} \\ \mathbf{0}_{(n_r - kn_s) \times kn_s} \end{bmatrix}, \quad (21)$$

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

$$\mathbf{y}_{d,t}^{(2)} = \alpha_{rd} \sum_{l=0}^{L_{rd}-1} \mathbf{H}_l^{rd} \mathbf{M} \mathbf{\Gamma}^{-1} \tilde{\mathbf{y}}_{r,(t-l) \bmod T_k} + \tilde{\mathbf{n}}_{d,t}^{(2)} \in \mathbb{C}^{n_d \times 1}, \quad (22)$$

where $\tilde{\mathbf{n}}_{d,t}^{(2)} \sim \mathcal{N}(\mathbf{0}_{M_R \times 1}, \sigma^2 \mathbf{I}_{M_R})$ denotes the additive Gaussian noise. By invoking (17) and (22), the sampled $n_d \times 1$ signal vector $\mathbf{y}_{d,t}^{(2)}$ can be further developed as

$$\mathbf{y}_{d,t}^{(2)} = \alpha_{sr} \alpha_{rd} \sum_{l=0}^{L_{srd}-1} \mathbf{H}_l^{srd} \tilde{\mathbf{x}}_{(t-l) \bmod T_k} + \mathbf{n}_{d,t}^{(2)}, \quad (23)$$

with $L_{srd} = T_k + L_{rd} - 1$, and

$$\mathbf{H}_l^{srd} = \sum_{n=\max(0, l-L_{rd}+1)}^{\min(l, T_k-1)} \mathbf{H}_{l-n}^{rd} \mathbf{M} \mathbf{\Gamma}^{-1} \tilde{\mathbf{H}}_n^{sr} \in \mathbb{C}^{n_d \times kn_s}. \quad (24)$$

The corresponding noise $\mathbf{n}_{d,t}^{(2)}$ is explicated by

$$\mathbf{n}_{d,t}^{(2)} = \alpha_{rd} \sum_{l=0}^{L_{rd}-1} \mathbf{H}_l^{rd} \mathbf{M} \mathbf{\Gamma}^{-1} \tilde{\mathbf{n}}_{r,(t-l) \bmod T_k} + \tilde{\mathbf{n}}_{d,t}^{(2)}, \quad (25)$$

and has conditional covariance matrix $\Lambda_{|\mathbf{H}^{rd}}$ (conditioned upon \mathbf{H}^{rd})

$$\begin{cases} \Lambda_{|\mathbf{H}^{rd}} = \sigma^2 \left(\alpha_{rd}^2 \sum_{l=0}^{L_{rd}-1} \Lambda_l \Lambda_l^H + \mathbf{I}_{n_d} \right), \\ \Lambda_l = \mathbf{H}_l^{rd} \mathbf{M} \mathbf{\Gamma}^{-1}. \end{cases} \quad (26)$$

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 $\mathbf{y}_d^{(1)} = \text{vec}_T \left\{ \mathbf{y}_{d,t}^{(1)} \right\}$ and $\mathbf{y}_d^{(2)} = \text{vec}_{T_k} \left\{ \mathbf{y}_{d,t}^{(2)} \right\}$ to the frequency domain

$$\begin{cases} \mathbf{y}'_d^{(1)} = \mathbf{U}_{T, n_s} \mathbf{y}_d^{(1)} \\ \mathbf{y}'_d^{(2)} = \mathbf{U}_{T_k, kn_s} \mathbf{y}_d^{(2)}, \end{cases} \quad (27)$$

we get the following subcarriers communication models

$$\begin{cases} \mathbf{y}'_{d,t}^{(1)} = \alpha_{sd} \mathbf{C}_t^{sd} \mathbf{x}'_t + \mathbf{n}'_{d,t}^{(1)}, t = 0, \dots, T-1 \\ \mathbf{y}'_{d,t}^{(2)} = \alpha_{sr} \alpha_{rd} \mathbf{C}_t^{srd} \mathbf{x}'_t + \mathbf{n}'_{d,t}^{(2)}, t = 0, \dots, T_k-1, \end{cases} \quad (28)$$

where $\{\mathbf{C}_t^{sd}\}$ and $\{\mathbf{C}_t^{srd}\}$ correspond to the CFRs of $\{\mathbf{H}_t^{sd}\}$ and $\{\mathbf{H}_l^{srd}\}$, respectively. To unify the channel inputs in (28), each k consecutive observations of $\mathbf{y}'_d^{(1)}$ are limped into one stacked vector

$$\underline{\mathbf{y}}'_{d,t}^{(1)} = \alpha_{sd} \underline{\mathbf{C}}_t^{sd} \underline{\mathbf{x}}'_t + \underline{\mathbf{n}}'_{d,t}^{(1)}, t = 0, \dots, T_k-1, \quad (29)$$

with

$$\begin{cases} \underline{\mathbf{y}}'_{d,t}^{(1)} \triangleq \left[\mathbf{y}'_{d,kt}^{(1)\top}, \dots, \mathbf{y}'_{d,k(t+1)-1}^{(1)\top} \right]^\top \in \mathbb{C}^{kn_d}, \\ \underline{\mathbf{C}}_t^{sd} \triangleq \text{diag} \left\{ \mathbf{C}_{kt}^{sd}, \dots, \mathbf{C}_{k(t+1)-1}^{sd} \right\} \in \mathbb{C}^{kn_d \times kn_s}, \\ \underline{\mathbf{n}}'_{d,t}^{(1)} \triangleq \left[\mathbf{n}'_{d,kt}^{(1)\top}, \dots, \mathbf{n}'_{d,k(t+1)-1}^{(1)\top} \right]^\top \in \mathbb{C}^{kn_d}. \end{cases} \quad (30)$$

Noise $\mathbf{n}'_{d,t}^{(2)}$ is colored, having the same covariance matrix $\Lambda_{|\mathbf{H}^{rd}}$ as $\mathbf{n}_{d,t}^{(2)}$. Consequently, we rather consider the Cholesky decomposition based whitened signal $\Omega^{-1} \mathbf{y}'_{d,t}^{(2)}$ in the equivalent channel derivation, where $\Lambda_{|\mathbf{H}^{rd}} = \sigma^2 \Omega \Omega^H$.

Based on (28) and (29), the considered relaying system can be represented by a virtual $(k+1)n_d \times kn_s$ MIMO channel whose expression at the t^{th} subcarrier ($t = 0, \dots, T_k-1$) is given by

$$\begin{bmatrix} \underline{\mathbf{y}}'_{d,t}^{(1)} \\ \Omega^{-1} \mathbf{y}'_{d,t}^{(2)} \end{bmatrix} = \underbrace{\begin{bmatrix} \alpha_{sd} \underline{\mathbf{C}}_t^{sd} \\ \alpha_{sr} \alpha_{rd} \Omega^{-1} \mathbf{C}_t^{srd} \end{bmatrix}}_{\mathbf{C}_t} \underline{\mathbf{x}}'_t + \begin{bmatrix} \underline{\mathbf{n}}'_{d,t}^{(1)} \\ \Omega^{-1} \mathbf{n}'_{d,t}^{(2)} \end{bmatrix}. \quad (31)$$

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 \mathcal{S} , and the received SNR γ ,

$$\bar{\mathcal{T}}(k, \mathcal{S}, \gamma) = \mathbb{E}[s], \quad (32)$$

where s is a random variable (RV) taking values \mathcal{S} and 0 with probabilities $1 - P_{out}(k, \mathcal{S}, \gamma)$ (in case of successful packet decoding) and $P_{out}(k, \mathcal{S}, \gamma)$ (when the decoding outcome is erroneous), respectively. Thus,

$$\mathbb{E}[s] = \mathcal{S} (1 - P_{out}(k, \mathcal{S}, \gamma)), \quad (33)$$

where $P_{out}(k, \mathcal{S}, \gamma)$ is the transmission's outage probability. It is defined in terms of the mutual information of the above equivalent MIMO channel (31) as

$$P_{out}(k, \mathcal{S}, \gamma) = \Pr \left\{ \frac{1}{k+1} I(\mathbf{C}, \gamma) < \mathcal{S} \right\}. \quad (34)$$

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 $I(\mathbf{C}, \gamma)$ can be approximated by assuming a Gaussian input alphabet,

$$I(\mathbf{C}, \gamma) \simeq \frac{1}{T_k} \sum_{t=0}^{T_k-1} \log_2 \left(\det \left(\mathbf{I}_{(k+1)n_d} + \frac{\gamma}{n_s} \mathbf{C}_t \mathbf{C}_t^H \right) \right). \quad (35)$$

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 $\gamma_{ii'}$ denote the average SNR per receive antenna over link ii' . CM and AF SNR measurements are similar for links sd and sr , i.e., $\gamma_{si'}^{CM} = \gamma_{si'}^{AF} = \frac{\alpha_{si'} n_s}{\sigma^2}$, $i' \in \{r, d\}$, while they differ for link rd

$$\gamma_{rd}^{CM} = \frac{\alpha_{rd} k n_s}{\sigma^2} \leq \frac{\alpha_{rd} n_r}{\sigma^2} = \gamma_{rd}^{AF}. \quad (36)$$

To balance the relay-destination links, we increase the average transmit power of CM by a factor $\frac{n_r}{k n_s}$.

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 \mathcal{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 \mathbf{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.

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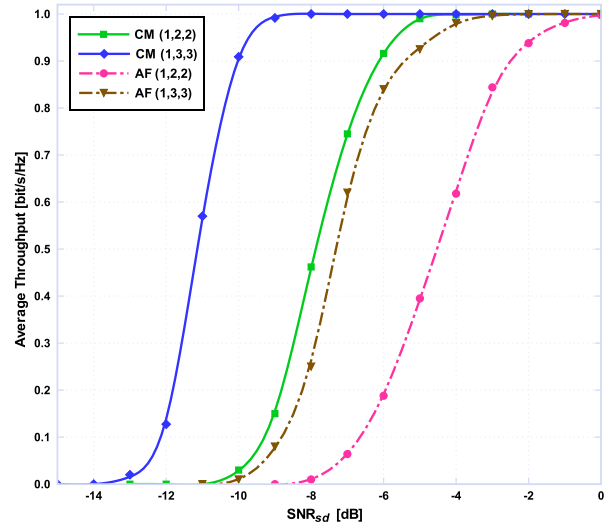


Figure 4. Average Throughput for different antennas triplet (n_s, n_r, n_d) configurations. The relay is at the medium of the source-destination link (i.e., $d_{sr} = 0.5$), $L_{sr} = L_{rd} = L_{sd} = 3$, and $\kappa = 3$.

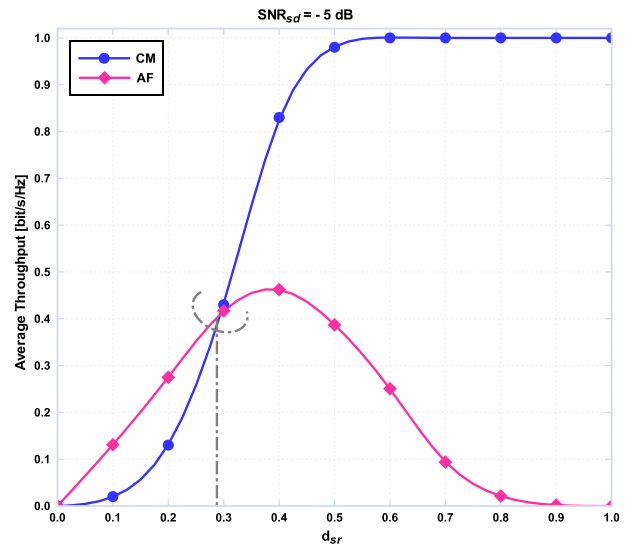


Figure 5. Average Throughput versus d_{sr} at medium SNR, with $(n_s, n_r, n_d) = (1, 2, 2)$, $L_{sr} = L_{rd} = L_{sd} = 3$, and $\kappa = 3$.

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