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# Performance of MUTP-aided MIMO systems over correlated frequency-selective wireless communication channels: a multi-cell perspective

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## Abstract

In this article, we investigate the performance of multiuser transmitter preprocessing (MUTP)-aided multiple-input multiple-output (MIMO) systems in a multi-cell multiuser setting where co-channel interference (CCI) is the major channel impairment, for both uplink (UL) and downlink (DL) transmissions. CCI can considerably reduce data rates resulting in outages in cellular systems, particularly at the cell edges in DL transmission. The MUTP considered in this article is based on singular value decomposition (SVD), which exploits the channel state information (CSI) of all the users at the base stations (BSs) with the aid of BS cooperation, and only the individual users' CSI at the mobile stations (MSs) for both UL and DL transmissions. In particular, in this article, we study the effects of three types of delay spread distributions coupled with different interferer configurations over correlated and uncorrelated frequency-selective channels. Our simulation study shows that SVD-aided MUTP perfectly eliminates CCI with lesser detection complexity under perfect CSI. Also, we provide performance comparisons of SVD-aided MUTP with various precoding techniques widely addressed in literature, and the results show that it provides better achievable symbol error rate (SER) by mitigating multi-stream interference (MSI) and CCI. Further, simulation results demonstrate that compared to equal CCI, the presence of a dominant interferer can lead to more degradation in the system performance in terms of achievable SER while, further degradation results when noise is dominant. Furthermore, this study confirms that imperfect CSI as well as imperfect power control can lead to degradation in the system performance.

**Keywords:** multiple-input multiple-output (MIMO), preprocessing, post-processing, multiuser transmitter preprocessing (MUTP), singular value decomposition (SVD), co-channel interference (CCI), multiuser interference (MUI), multi-stream interference (MSI)

## 1. Introduction

Information theoretic results have shown that significant increase in the capacity of wireless communication systems can be achieved with the aid of multiple antennas at both the transmitters and receivers. The capacity of these multiple antenna systems, also called as multiple-input multiple-output (MIMO) systems, has been shown to grow linearly with small increase in the number of transmit and receive antennas in rich scattering environments, and at sufficiently high signal-to-noise (SNR) ratios [1]. MIMO systems can provide high data rates through spatial multiplexing (invoking Vertical Bell Laboratories

layered space-time architecture (VBLAST) type processing) or considerable diversity using transmit diversity (by exploiting space-time block code type processing) [2]. Much of the research focus has been in the design of single user MIMO systems [3,4], where only multi-stream interference (MSI) is the major channel impairment. In single-cell multiuser MIMO systems, in addition to MSI, multiuser interference (MUI) becomes the dominating channel impairment. In the case of multiuser multi-cell MIMO systems, owing to frequency reuse, co-channel interference (CCI) from other cells becomes the dominating channel impairment. Further, next generation cellular standards like the 3GPP (Third generation partnership project) Long Term Evolution Advanced (LTE-A) aim at exploiting universal frequency reuse in order to

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maximize the area spectral efficiency. However, this could result in high levels of CCI as simultaneous transmission takes place on the same frequency band in the adjacent cells. In this context, the users may synchronously receive their own signals from the serving base station (BS) as well as signals from adjacent co-channel BSs. The signals from the adjacent BSs, namely CCI, can greatly reduce the achievable data rates leading to outages in cellular systems mainly at the cell edges [5-8]. This CCI is asynchronous and is a critical issue that requires serious attention. Hence, disregarding CCI would result in significant degradation in the system performance in terms of achievable symbol error rate (SER). To deal with this interference, multiuser detection (MUD) can be invoked both at the mobile station (MS) and BS [9], but its complexity increases excessively, thus making it impractical for implementation even at the BS, where complexity is acceptable. An alternate way to combat interference is to exploit multiuser transmitter preprocessing (MUTP) at the BS as well as at the MS [3,4,10].

Recently, MUTP that mitigates MUI and CCI has received considerable attention as it facilitates the implementation of less complex and more power efficient MSs. MUTP has been proposed to keep the receiver design simple by moving the required signal processing to the transmitter [10], i.e., signal processing at the BS in the case of DL transmission and at the MS in the case of UL transmission [4]. A comprehensive treatment on transmitter preprocessing, such as transmitter MUD, multiuser transmission (MUT), etc., has been addressed in [10]. As a design choice, in [11] maximum ratio UL transmission scheme was analyzed, by considering the dominant right-hand side (RHS) and left-hand side (LHS) singular eigenvectors for the preprocessing and postprocessing vectors, respectively, to increase the achievable diversity gain. In [3], the multiuser transmission schemes invoke the block diagonalization (BD) method. In some proposed schemes [12,13], it has been demonstrated that dirty paper (DP) precoding could approach the achievable system capacity in various joint transmissions for DL. Furthermore, singular value decomposition (SVD)-assisted space time block coding (STBC) for point-to-point transmission has found many applications [14], while in [4], SVD based MUTP is investigated for flat fading channels. Of late, BS cooperation aided multi-cell multiuser systems have received widespread attention [5-7,12]. The study of [15] presents a detailed survey on multi-cell MIMO cooperation aided wireless networks in the context of inter-cell interference mitigation. The main difference between MUTP aided single cell transmission and multi-cell transmission is that, in the former case BS cooperation is not needed to remove MUI, while in the latter full BS cooperation is required to completely eliminate CCI. The first work in the context of full BS cooperation was investigated by Hanly as stated in

[15], for uplink transmission for a MIMO multiple access channel. In this publication, it was shown that the BSs cooperate to decode each user's symbols. Also, Hanly has shown that, by exploiting interference with the aid of global receivers, interference can be completely eliminated and thus all received signals carry useful information for the global decoder [15]. Further in [15], it is addressed that Hanly et al. have shown that BS cooperation eliminates CCI by invoking optimal power control. In other words, a network of interfering cells has the same per-cell capacity (in numbers of users) as a single, isolated cell. In [16] it is shown in the context of multi-cell MIMO systems, that significant performance gain can be achieved by grouping adjacent cells and by solving the optimal beamforming and power splitting problem jointly. It is demonstrated in [8] that in addition to pairing the adjacent BSs [16], a remarkable improvement in data rates can be achieved if the BSs are synchronized. In [17], BS cooperation approach is proposed to enhance the downlink sum capacity (throughput) with single-input single-output (SISO) systems employed in each cell, by implementing the DP coding (DPC). Also, these cooperative BS-assisted systems have been demonstrated to provide substantial gain in the form of system performance for a multi-cell MIMO system [12]. In [4,18], the performance of MUTP-aided multiuser MIMO systems has primarily been investigated in the context of single cell for DL and UL transmissions in flat-fading channels, respectively.

For cellular systems, two performance metrics namely average cell throughput and user throughput at the cell edges are vital. Improving these measures becomes indispensable in the context of next generation cellular networks. Average cell throughput can be improved by employing relatively simple methods (increasing transmission power), but improving the throughput of the users at cell edges is quite challenging. Furthermore, users at the cell edges experience strong CCI and any increase in the transmission power to improve average cell throughput further creates CCI for cell edge users. Besides this, frequency-selectivity of the channels will severely degrade the system performance resulting in an irreducible bit error rate, thus imposing a limit on the achievable data rates. Thus, improving cell edge throughput becomes imperative in such frequency-selective CCI environments, and that is why interference mitigation techniques have received wide spread attention among research communities in the context of next generation cellular standards.

Hence, in this correspondence, we will be investigating the performance of MUTP-aided MIMO systems in terms of achievable SER in such CCI limited environments with multi-cell cooperation (also called BS cooperation). Specifically, in this contribution we present the performance of joint VBLAST/STBC aided DL and STBC processing aided UL MIMO systems with MUTP in the context of

multi-cell multiuser setting with BS cooperation over correlated and uncorrelated frequency-selective fading for three different delay spread distributions pertaining to LTE standard [19] and flat fading channels.

The rest of the article is organized as follows: Section 2 describes the system model of VBLAST/STBC-aided MIMO system with MUTP for DL and STBC-aided MIMO system with MUTP for UL communications. Section 3 elucidates the performance results of our analysis and in Section 4 conclusions are drawn.

**Notations:** The following notations are adopted for remaining of the article. All boldface capital letters represent a matrix while a lowercase boldface letter denotes a vector.  $(.)^H$  denotes Hermitian transpose while  $(.)^*$  refers to the complex conjugate. Additionally,  $(; \cdot)$  is used to denote row wise concatenation.  $(.)^+$  refers to the Moore-Penrose matrix (pseudo-inverse), while  $\varepsilon\{\cdot\}$  gives the expectation of the argument.  $\text{Trace}\{\cdot\}$  represents the trace of the argument,  $Q(\cdot)$  specifies quantization and  $\|\cdot\|$  denotes the norm operation.

## 2. System configuration

### 2.1 Downlink transmission

Let us consider an  $M$  cell downlink communication system supporting  $K$  users. Figure 1 elucidates a multi-cell MIMO DL communication system with MUTP. Here, the BS employs  $N_t$  transmit antennas and each of the  $K$  users' MS uses  $N_r$  receive antennas. In multi-cell MIMO transmission, the users conflict CCI, as well as MSI and there will be  $(M - 1)N_t$  interfering signals arriving at

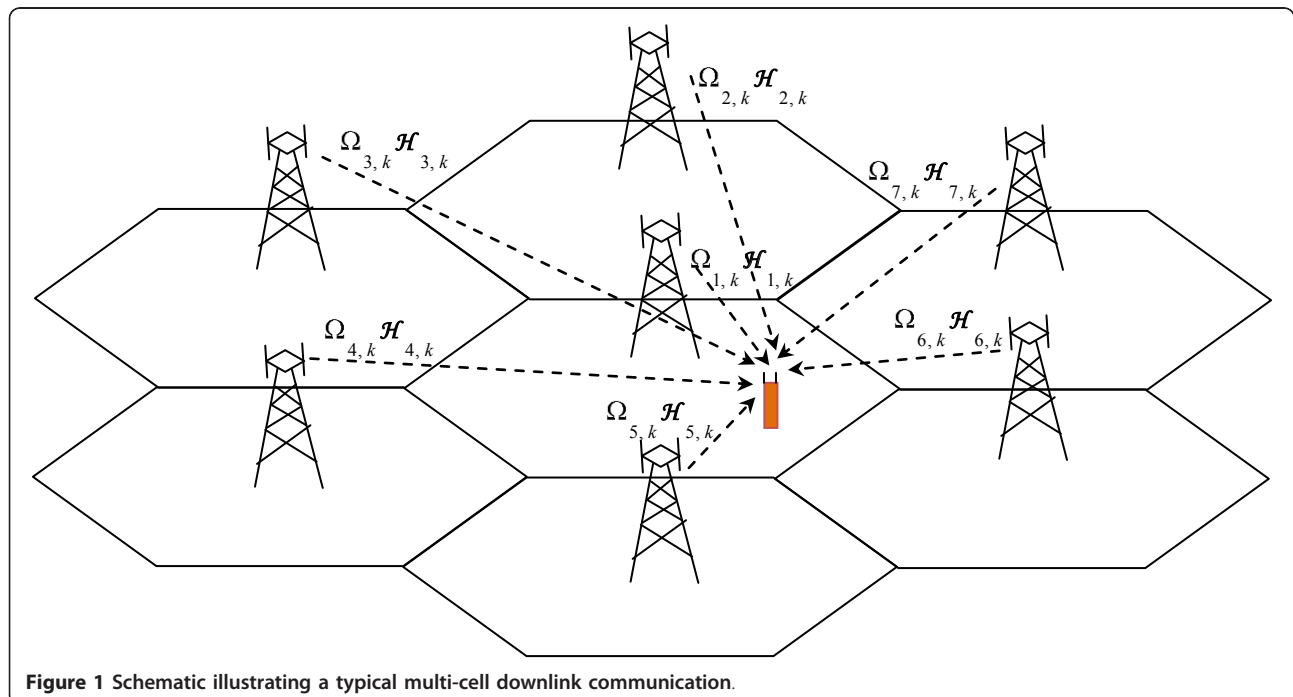
each of the mobile stations (MSs). Though the maximum-likelihood (ML) detector employed at the MS or at the BS offers optimum performance by mitigating the CCI, MUI, and MSI, it often imposes too much computational complexity. To reduce the complexity MUTP can be employed at the BSs [3,4] as well as at the MSs.

In DL transmission, we assume that the BS supports joint VBLAST/STBC processing architecture with MUTP based on SVD technique. The joint VBLAST/STBC technique can be described as follows:

Let  $d_1, d_2, d_3, d_4, d_5$ , and  $d_6$  represent a group of the six symbols in the input data stream to be transmitted. Assuming  $N_t = 4$  and  $N_r = 4$  and invoking joint VBLAST/STBC (STBC is based on Alamouti code [20]) processing, the received matrix after two symbol durations can be described as follows:

$$\underbrace{\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \\ y_{31} & y_{32} \\ y_{41} & y_{42} \end{bmatrix}}_{\mathbf{Y}} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} d_3 & d_5^* \\ d_4 & d_6^* \\ d_1 & -d_2^* \\ d_2 & d_1^* \end{bmatrix}}_{\mathbf{D}} + \underbrace{\begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \\ n_{31} & n_{32} \\ n_{41} & n_{42} \end{bmatrix}}_{\mathbf{N}}$$

where  $\mathbf{Y}$  is an  $(N_r \times 2)$  component received matrix,  $\mathbf{H}$  is an  $(N_r \times N_t)$  small-scale fading channel matrix, and  $\mathbf{D}$  is an  $(N_t \times 2)$  symbol matrix.  $\mathbf{N}$  is the noise matrix, which is assumed to be Gaussian distributed with zero mean and covariance matrix given by  $\sigma^2 \mathbf{I}_{N_r}$ . In this contribution, we evaluate the performance of MUTP-assisted VBLAST/STBC system in frequency-selective fading channels using



**Figure 1** Schematic illustrating a typical multi-cell downlink communication.

LTE channel models for pedestrian (PED), vehicular (VEH), and typical urban (TU) propagation. The channel profiles are detailed in Table 1 [19].

Using the parameters defined in Table 1, the channel impulse response from the  $i$ th transmit antenna to the  $j$ th receive antenna can be expressed as

$$h_{ji}(t) = \sum_{l=1}^L h_{ji}^l \delta(t - \tau_l) \quad (1)$$

where  $h_{ji}^l$  is a complex zero-mean Gaussian random process with variance  $p(\tau_l)$  and  $h_{ji}^l$  is uncorrelated with other paths and channels.  $L$  is the total number of paths between the  $i$ th transmit and the  $j$ th receive antenna.

In the case of single cell, let  $X_k$  be the signal transmitted to the  $k$ th MS which is given by

$$X_k = \mathcal{F}_k \boldsymbol{\gamma}_k D_k \quad k = 1, 2, \dots, K \quad (2)$$

where  $D_k$  is an  $(N_r \times 2)$  component symbol matrix preprocessed before transmission by  $(N_t \times N_r)$  preprocessing matrix  $\mathcal{F}_k = [\boldsymbol{\nu}_{ks}^H]^+$  [4], constituting the signal space component of the decomposed correlated channel matrix  $\mathcal{H}_k$  of size  $(N_r \times N_t)$ , which can be expressed as

$$\mathcal{H}_k = \Omega_k \mathcal{R}_k^{1/2} \mathcal{H}_k' \mathcal{R}_k^{1/2}, \quad k = 1, 2, \dots, K \quad (3)$$

where

$$\mathcal{H}_k' = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r 1} & \dots & \dots & h_{N_r N_t} \end{bmatrix} \text{ denotes the } (N_r \times N_t) \text{ uncor-}$$

related fading co-efficient matrix and  $\mathcal{R}_k^{1/2}$ ,  $\mathcal{R}_k^{1/2}$  are  $(N_r \times N_r)$  receive and  $(N_t \times N_t)$  transmit correlation matrices, respectively.  $\Omega_k$  denotes the large-scale fading co-efficient, that takes into account the effects of path loss and shadowing. Further,  $\boldsymbol{\gamma}_k$  is an  $(N_r \times N_r)$  component diagonal matrix formulating the power normalization co-efficients for normalizing the transmit power associated with the  $k$ th MS. Here, exponential correlation

model is considered as this model is reasonable in the case of uniform linear array [2]. Furthermore, in the case of multi-cell, let the  $(KN_r \times 2)$  component DL symbol matrix transmitted to the  $k$ th MS after two symbol durations by all the BSs be denoted by  $D$ . This is pre-multiplied by an  $(MN_t \times KN_r)$  component preprocessing matrix  $\mathcal{F} = ([\boldsymbol{\nu}_{1s}, \boldsymbol{\nu}_{2s}, \dots, \boldsymbol{\nu}_{Ks}]^H)^+$  of all the users [4] formulated with the aid of BS cooperation, where  $\boldsymbol{\nu}_{ks}^H$  represents the signal space of the decomposed channel matrix  $\mathcal{H}_k$  of the  $k$ th user given by

$$\mathcal{H}_k = [\Omega_{1k} \mathcal{H}_{1k}, \Omega_{2k} \mathcal{H}_{2k}, \dots, \Omega_{Mk} \mathcal{H}_{Mk}] \quad k = 1, 2, \dots, K \quad (4)$$

where  $\mathcal{H}_{mk} = \mathcal{R}_k^{1/2} \mathcal{H}_{mk}' \mathcal{R}_k^{1/2}$ ,  $m = 1, 2, \dots, M$  denotes the  $(N_r \times N_t)$  correlated fading co-efficient matrix that connects the  $m$ th BS and  $k$ th MS. Upon BS cooperation, the transmitted component symbol matrix to the  $k$ th user will be as follows

$$X = \sum_{k=1}^K X_k = \mathcal{F} \boldsymbol{\gamma} D \quad (5)$$

where  $\mathcal{F}$  constitutes the overall preprocessing matrix.  $D = [D_{1k}; D_{2k}; \dots; D_{Mk}]$  denotes the  $(KN_r \times 2)$  component transmitted symbol matrix, transmitted to the  $k$ th MS after two symbol durations. Here,  $\boldsymbol{\gamma} = \text{diag}\{\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \dots, \boldsymbol{\gamma}_K\}$  represents the power control co-efficient matrix formulated for imposing the transmission power constraint. The received signal matrix  $Y_k$  at the  $k$ th MS can be expressed as

$$Y_k = \mathcal{H}_k X + N_k \\ = \underbrace{\mathcal{H}_k X_k}_{\text{Desired Signal}} + \underbrace{\sum_{i=1, i \neq k}^K \mathcal{H}_i X_i}_{\text{CCI}} + N_k, \quad k = 1, 2, \dots, K \quad (6)$$

where  $N_k$  represents the  $(N_r \times 2)$  noise matrix having zero mean and covariance matrix  $\sigma^2 I_{N_r}$ .

**Table 1 Path delays and relative power levels**

Path number ( $l$ )	LTE channel models					
	Extended Pedestrian		Extended Vehicular		Typical Urban	
	Delay	Power	Delay	Power	Delay	Power
	$(\tau_l)(\text{ns})$	$p(\tau_l)(\text{dB})$	$(\tau_l)(\text{ns})$	$p(\tau_l)(\text{dB})$	$(\tau_l)(\text{ns})$	$p(\tau_l)(\text{dB})$
1	0	0	0	0	0	-1
2	30	-1	30	-1.5	50	-1
3	70	-2	150	-1.4	120	-1
4	90	-3	310	-3.6	200	0
5	110	-8	370	-0.6	230	0
6	190	-17.2	710	-9.1	500	0
7	410	-20.8	1090	-7	1600	-3
8			1730	-12	2300	-5
9			2510	-16.9	5000	-7

Upon carrying out SVD on  $\mathcal{H}_k$ , we arrive at

$$\begin{aligned}\mathcal{H}_k &= \mathbf{u}_k [\Lambda_k^{1/2}, \mathbf{0}] \mathbf{v}_k^H = \mathbf{u}_k [\Lambda_k^{1/2}, \mathbf{0}] \begin{bmatrix} \mathbf{v}_{ks}^H \\ \mathbf{v}_{kn}^H \end{bmatrix} \\ &= \mathbf{u}_k \Lambda_k^{1/2} \mathbf{v}_{ks}^H, \quad k = 1, 2, \dots, K\end{aligned}\quad (7)$$

where

$\mathbf{u}_k = (N_r \times N_r)$  unitary matrix,

$\mathbf{v}_k = (MN_t \times MN_t)$  unitary matrix,

$\Lambda_k = (N_r \times MN_t)$  diagonal matrix containing the non-zero eigenvalues of  $\mathcal{H}_k \mathcal{H}_k^H$ ,

$\mathbf{v}_{ks} = (MN_t \times N_r)$  matrix, constituting the eigenvectors corresponding to the non-zero eigenvalues of  $\mathcal{H}_k^H \mathcal{H}_k$ ,

$\mathbf{v}_{kn} = [MN_t \times (MN_t - N_r)]$  matrix, constituting the eigenvectors corresponding to the zero eigenvalues of  $\mathcal{H}_k^H \mathcal{H}_k$ .

Substituting (7) into (6), the received DL signal  $\mathbf{Y}_k$  of the  $k$ th MS can be expressed as

$$\begin{aligned}\mathbf{Y}_k &= \mathbf{u}_k \Lambda_k^{1/2} \mathbf{v}_{ks}^H \mathcal{F} \mathbf{D}_k + \mathbf{N}_k, \quad k = 1, 2, \dots, K \\ &= \mathbf{u}_k \Lambda_k^{1/2} \mathbf{v}_k \mathbf{D}_k + \mathbf{N}_k\end{aligned}\quad (8)$$

The BS transmitter preprocessing matrix  $\mathcal{F}$  is designed so as to effectively mitigate CCI, but there exists MSI, and the postprocessing matrix that completely mitigates the MSI is formulated as [4]

$$\mathcal{G} = [\mathbf{u}_k]^+ \quad (9)$$

Applying this postprocessing matrix to the received matrix yields

$$\mathbf{Y}_k = \mathcal{G} \mathbf{u}_k \Lambda_k^{1/2} \mathbf{v}_k \mathbf{D}_k + \mathcal{G} \mathbf{N}_k, \quad k = 1, 2, \dots, K \quad (10)$$

Substituting the value for  $\mathcal{G}$  from (9), the  $k$ th user's observation matrix can be expressed as

$$\mathbf{Y}_k = \Lambda_k^{1/2} \mathbf{v}_k \mathbf{D}_k + \mathcal{G} \mathbf{N}_k, \quad k = 1, 2, \dots, K \quad (11)$$

Thus the postprocessing matrix  $\mathcal{G}$  mitigates MSI.

In the context of multi-cell DL transmission, power constraints should be considered per BS basis [6] in contrast to single cell DL transmission. If the average transmit power of  $m$ th BS is  $P_m$ , then in order to satisfy the power constraint on per BS basis, we need to have  $\text{Trace} \{ \mathbf{y} \mathbf{y}^H \mathcal{F}_m^H \mathcal{F}_m \} = P_m$ . Here,  $\mathcal{F}_m$  formulates the preprocessing matrix for transmission from the  $m$ th BS to all the MSs. The elements of the received matrix are combined to get the estimates of the transmitted symbols as given below

$$\left. \begin{aligned} \hat{d}_{k1} &= y_{k31} + y_{k42}^* \\ \hat{d}_{k2} &= y_{k41} - y_{k32}^* \\ \hat{d}_{k3} &= y_{k11} \\ \hat{d}_{k4} &= y_{k21} \\ \hat{d}_{k5} &= y_{k12}^* \\ \hat{d}_{k6} &= y_{k22}^* \end{aligned} \right\} \quad (12)$$

$\hat{d}_{ki}$  denotes the  $i$ th estimated symbol of the  $k$ th user,  $y_{kij}$  designates the element in the  $i$ th row and  $j$ th column of the received matrix of the  $k$ th user. Collecting all the estimates of the  $k$ th user symbols,  $\hat{\mathbf{d}}_k$  can be given by

$$\hat{\mathbf{d}}_k = [\hat{d}_{k1}, \hat{d}_{k2}, \hat{d}_{k3}, \hat{d}_{k4}, \hat{d}_{k5}, \hat{d}_{k6}]^T \quad (13)$$

For BPSK modulation,  $Q(\hat{\mathbf{d}}_k)$  gives the detected symbols and, for QAM modulation  $\hat{\mathbf{d}}_k$  for the  $k$ th user is given by

$$\hat{\mathbf{d}}_k = \left[ \frac{\hat{d}_{k1}}{(\lambda_{k33} + \lambda_{k44})}, \frac{\hat{d}_{k2}}{(\lambda_{k33} + \lambda_{k44})}, \frac{\hat{d}_{k3}}{(\lambda_{k11})}, \frac{\hat{d}_{k4}}{(\lambda_{k22})}, \frac{\hat{d}_{k5}}{(\lambda_{k11})}, \frac{\hat{d}_{k6}}{(\lambda_{k22})} \right]^T \quad (14)$$

Symbols are then detected by  $Q(\hat{\mathbf{d}}_k)$ .

## 2.2 Uplink transmission

Figure 2 illustrates a multi-cell MIMO UL communication system with MUTP. Here, we assume that each of the  $K$  users' MS is equipped with  $N_t$  transmit antennas and the BS with  $N_r$  receive antennas. Also, in the context of UL transmission, we assume that MS supports STBC processing [20]. Let  $\mathbf{d}_k = [d_1, d_2, \dots, d_{kN_t}]^T$  denote the  $N_t$  length data symbol vector of the  $k$ th user. Then, by invoking Alamouti code [20] the  $(N_t \times 2)$  component symbol matrix denoted by  $\mathbf{D}_k = [d_1, d_2^*; d_2, -d_1^*]$  will be transmitted to the BS from the  $k$ th MS after two symbol durations. It is premultiplied with an  $(N_t \times N_t)$  component unitary matrix  $\mathbf{v}_k$  of the decomposed correlated channel matrix  $\mathcal{H}_k$ , which is expressed as

$$\mathcal{H}_k = \Omega_k \mathcal{R}_k^{1/2} \mathcal{H}_k' \mathcal{R}_k^{1/2}, \quad k = 1, 2, \dots, K \quad (15)$$

where

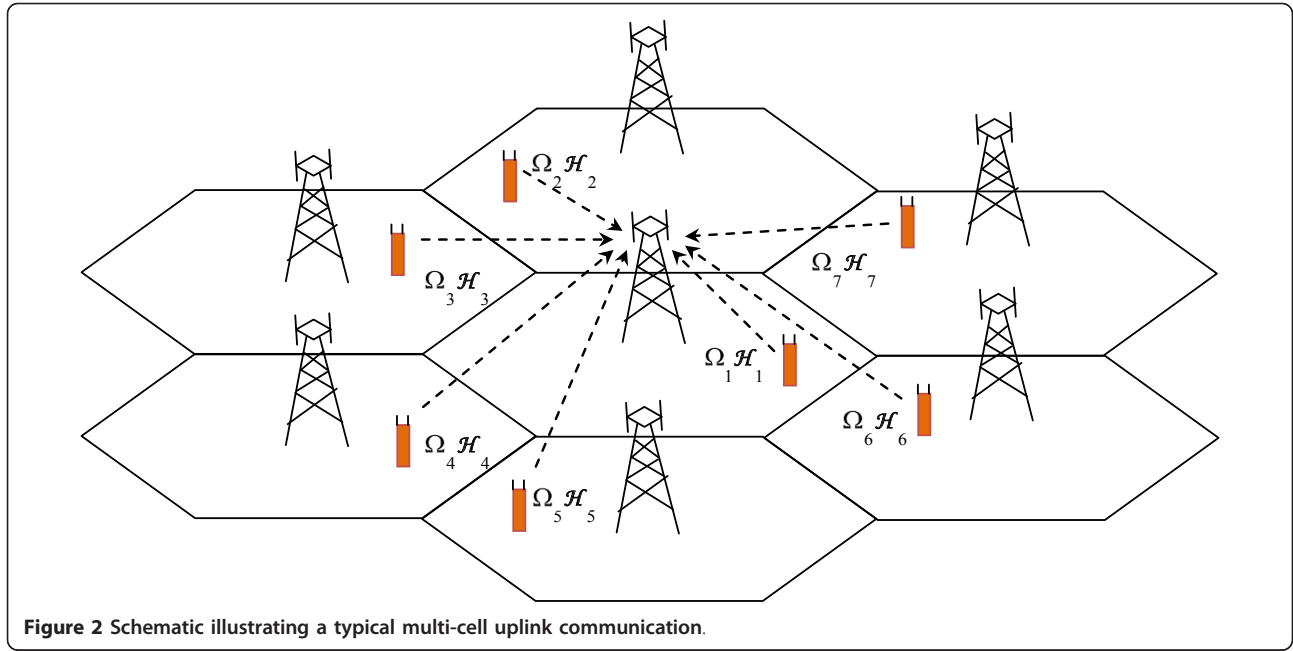
$$\mathcal{H}_k' = \begin{bmatrix} h_{11} & h_{12} & h_{1N_t} \\ h_{21} & . & h_{2N_t} \\ . & . & . \\ h_{N_t1} & . & h_{N_tN_t} \end{bmatrix} \text{ denotes the } (N_r \times N_t) \text{ uncor-}$$

related fading co-efficient matrix and  $\mathcal{R}_k^{1/2}$ ,  $\mathcal{R}_k^{1/2}$  are  $(N_r \times N_r)$  receive and  $(N_t \times N_t)$  transmit correlation matrices, respectively. After transmitter preprocessing, the signal transmitted by the  $k$ th MS is given by

$$\mathbf{X}_k = \mathcal{F}_k \mathbf{v}_k \mathbf{D}_k, \quad k = 1, 2, \dots, K \quad (16)$$

where  $\mathcal{F}_k = \mathbf{v}_k$ ,  $k = 1, 2, \dots, K$  formulates the preprocessing matrix [18] for the  $k$ th user. The  $(N_t \times N_t)$  component diagonal matrix  $\mathbf{v}_k$  constitute the power control co-efficients employed for normalizing the transmission power associated with the  $k$ th MS.





**Figure 2** Schematic illustrating a typical multi-cell uplink communication.

The  $(N_r \times 2)$  component UL received matrix  $\mathbf{Y}$  at the desired BS can be expressed as

$$\begin{aligned} \mathbf{Y} &= \sum_{k=1}^K \mathbf{H}_k \mathbf{X}_k + \mathbf{N} \\ &= \underbrace{\mathbf{H}_k \mathbf{F}_k \boldsymbol{\gamma}_k \mathbf{D}_k}_{\text{Desired Signal}} + \underbrace{\sum_{i=1, i \neq k}^K \mathbf{H}_i \mathbf{F}_i \boldsymbol{\gamma}_i \mathbf{D}_i}_{\text{CCI}} + \mathbf{N} \end{aligned} \quad (17)$$

where  $\mathbf{N}$  is an  $(N_r \times 2)$  noise matrix which is assumed to be zero mean with covariance matrix  $\sigma^2 \mathbf{I}_{N_r}$ . In this article, we assume that the number of receive antenna at the BS is greater than or equal to the total number of antennas employed by all the  $K$  MSs, i.e.,  $N_r \geq KN_t$ . Upon carrying out the SVD on  $\mathbf{H}_k$ , we arrive at

$$\begin{aligned} \mathbf{H}_k &= \mathbf{U}_k \begin{bmatrix} \Lambda_k^{1/2} \\ \mathbf{0} \end{bmatrix} \mathbf{V}_k^H = [\mathbf{u}_{ks} \mathbf{u}_{kn}] \begin{bmatrix} \Lambda_k^{1/2} \\ \mathbf{0} \end{bmatrix} \mathbf{v}_k^H \\ &= \mathbf{u}_{ks} \Lambda_k^{1/2} \mathbf{v}_k^H, \quad k = 1, 2, \dots, K \end{aligned} \quad (18)$$

where

$\mathbf{U}_k = (N_r \times N_r)$  unitary matrix,

$\mathbf{V}_k = (N_t \times N_t)$  unitary matrix,

$\Lambda_k = (N_r \times N_t)$  diagonal matrix containing the  $N_t$  non-zero eigenvalues of  $\mathbf{H}_k \mathbf{H}_k^H$ ,

$\mathbf{u}_{ks} = (N_r \times N_t)$  matrix, denoting the eigenvectors corresponding to the non-zero eigenvalues of  $\mathbf{H}_k \mathbf{H}_k^H$ ,

$\mathbf{u}_{kn} = [N_r \times (N_r - N_t)]$  matrix, denoting the eigenvectors corresponding to the zero eigenvalues of  $\mathbf{H}_k \mathbf{H}_k^H$ .

Upon substituting (18) into (17), the received UL matrix  $\mathbf{Y}$  at the desired BS can be expressed as

$$\mathbf{Y} = \sum_{k=1}^K \mathbf{u}_{ks} \Lambda_k^{1/2} \mathbf{v}_k^H \mathbf{F}_k \boldsymbol{\gamma}_k \mathbf{D}_k + \mathbf{N} \quad (19)$$

Substituting for  $\mathbf{F}_k$  and exploiting the property  $\mathbf{v}_k^H \mathbf{v}_k = \mathbf{I}_{N_t}$ , the UL received signal matrix can be simplified as

$$\mathbf{Y} = \sum_{k=1}^K \mathbf{u}_{ks} \Lambda_k^{1/2} \boldsymbol{\gamma}_k \mathbf{D}_k + \mathbf{N} \quad (20)$$

From the above expression, it can be discerned that the UL transmitter preprocessing matrix  $\mathbf{F}_k$  decouples each of the antenna specific transmitted data symbols of the  $k$ th MS from those of its other antennas. With the aid of BS cooperation, now let us define

$$\begin{aligned} \mathbf{u}_s &= [\mathbf{u}_{1s}, \mathbf{u}_{2s}, \dots, \mathbf{u}_{Ks}] \\ \Lambda^{1/2} &= \text{diag}\{\Lambda_1^{1/2}, \Lambda_2^{1/2}, \dots, \Lambda_K^{1/2}\} \\ \boldsymbol{\gamma} &= \text{diag}\{\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \dots, \boldsymbol{\gamma}_K\} \end{aligned} \quad (21)$$

Using (21) in (20), the received UL matrix  $\mathbf{Y}$  can be expressed as

$$\mathbf{Y} = \mathbf{u}_s \Lambda^{1/2} \boldsymbol{\gamma} \mathbf{D} + \mathbf{N} \quad (22)$$

where  $\mathbf{D}$  denotes the overall data of  $K$  UL users given by  $\mathbf{D} = [\mathbf{D}_1; \mathbf{D}_2; \dots; \mathbf{D}_K]$ . Although, the columns of  $\mathbf{u}_{ks}$  are orthogonal, suggesting that there is no inter antenna interference or MSI, the columns of  $\mathbf{u}_s = [\mathbf{u}_{1s}, \mathbf{u}_{2s}, \dots, \mathbf{u}_{Ks}]$  corresponding to the different UL MSs are not orthogonal and hence there exists CCI. The postprocessing matrix that completely removes the CCI is formulated as [18]

$$\mathcal{G} = [\mathbf{u}_s]^+ \quad (23)$$

Let  $\hat{\mathbf{D}} = \mathcal{G}\mathbf{Y}$  denote the estimates of the  $K$  UL users. Substituting (22) into  $\hat{\mathbf{D}}$  we have

$$\hat{\mathbf{D}} = \mathcal{G}\mathbf{u}_s\mathbf{A}^{1/2}\boldsymbol{\gamma}\mathbf{D} + \mathcal{G}\mathbf{N} \quad (24)$$

Substituting the value for  $\mathcal{G}$  from (23), the overall data estimates of all the MSs can be simplified to

$$\hat{\mathbf{D}} = \mathbf{A}^{1/2}\boldsymbol{\gamma}\mathbf{D} + \mathcal{G}\mathbf{N} \quad (25)$$

Thus the SVD-based matrix  $\mathcal{G}$  removes CCI. To be specific, the estimates of the  $k$ th user's signal is given by

$$\hat{\mathbf{D}}_k = \mathbf{A}_k^{1/2}\boldsymbol{\gamma}_k\mathbf{D}_k + \mathcal{G}_k\mathbf{N}_k, \quad k = 1, 2, \dots, K \quad (26)$$

An important constraint for transmitter preprocessing in UL transmission is to maintain the transmit power of the  $k$ th user before and after preprocessing unaltered. Hence, in order to maintain a constant transmission power,  $\mathcal{F}_k$  should be normalized to satisfy

$$\varepsilon \left\{ \|\mathcal{F}_k\mathbf{D}_k\|^2 \right\} = \varepsilon \left\{ \|\mathbf{D}_k\|^2 \right\} = N_t \quad (27)$$

Alternatively, we can normalize  $\mathcal{F}_k$  to satisfy

$$\text{Trace} \left\{ \|\mathcal{F}_k\|^2 \right\} = \varepsilon \left\{ \|\mathbf{D}_k\|^2 \right\} = N_t \quad (28)$$

The normalization in (28) is based on the assumption  $\varepsilon \left\{ \mathbf{D}_k\mathbf{D}_k^H \right\} = \mathbf{I}_{N_t}$ .

### 3. Performance results

In this section, the simulation results for characterizing the achievable performance of MUTP-assisted MIMO system with joint VBLAST/STBC processing for DL transmission for a multi-cell scenario are presented. Also, the performance results of MUTP-assisted MIMO system with STBC processing for UL transmission are presented. In order to provide a generic framework to deal with MUTP in the context of multi-cell setting, whilst remaining simple enough for analysis and simulation, we assume a model which is characterized by an array of cells. Here, we have taken into account the interference from the first tier. Further, we assume universal frequency reuse. Also, as a first approximation, considering worst case scenario, we deem interference to be Gaussian and hence, interference can be treated as equivalent noise, and the signal-to-interference-plus-noise ratio (SINR) takes the same value as SNR [21]. Furthermore, we assume that all the BSs transmit at the same power. The channel models considered here are based on LTE specifications and the performance is assessed for both correlated and uncorrelated fading channels. Tables 1 and 2 summarize the channel models and simulation parameters, respectively. The

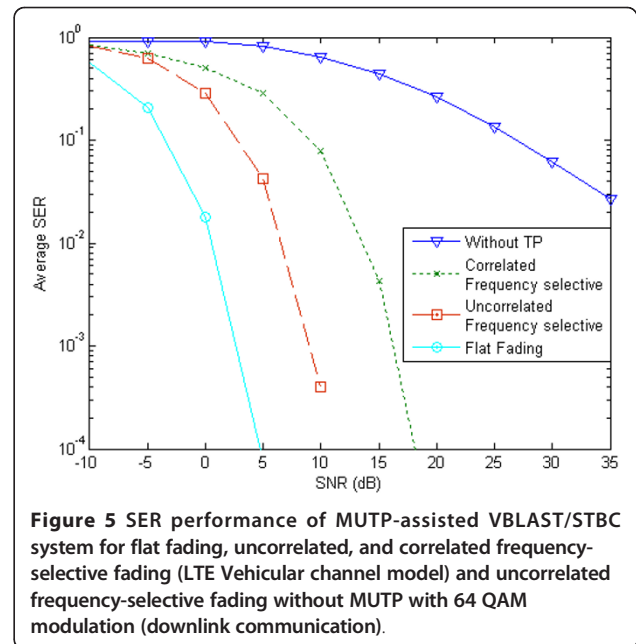
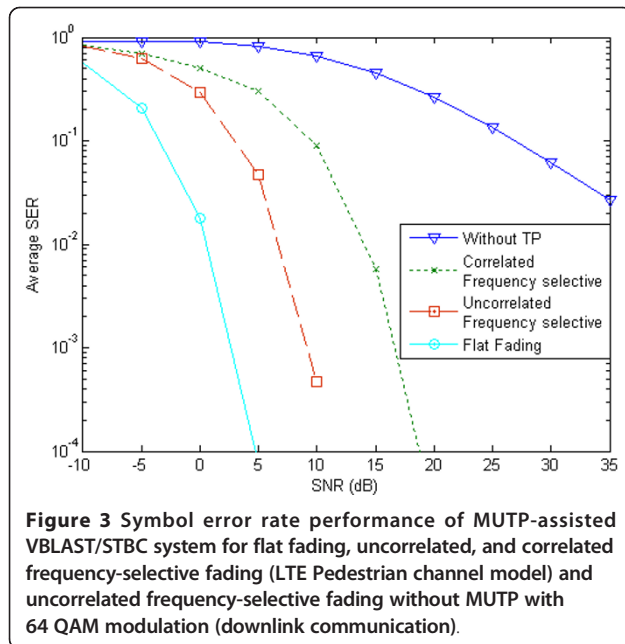
**Table 2 Simulation parameters**

Number of antennas at each BS (DL, UL)	(4, 16)
Number of antennas at each MS (DL, UL)	(4, 2)
Number of co-channel users	6
Channel model	LTE
Scenarios	Pedestrian Typical Urban Vehicular
Modulation technique	64 QAM
Doppler frequency (Hz) (PED/TU/VEH)	5/70/300
Speed (km/h) (PED/TU/VEH)	2.7/40.8/162
Channel bandwidth (MHz)	20
Correlation ( $\rho$ )	0.7
Carrier frequency (GHz)	2
Inter-site distance (m)	2500
Path loss exponent	3.76
Shadowing standard deviation (dB)	8
Power control	Open loop

transmitted signals from the BSs (DL) and MSs (UL) experience free-space path loss, and then undergo path loss according to a power law with path loss exponent 3.7. The multipath propagation is modeled as zero mean complex Gaussian random variable with variance 1/2 per dimension. The standard deviation of log-normal shadow fading is assumed to be 8 dB. The MSs are arbitrarily distributed following a uniform distribution. The modulation technique considered in this study is 64QAM. Further, for transmitter preprocessing to be enabled in the context of multi-cell DL scenario, perfect channel state information (CSI) is assumed to be present at the transmitter with the aid of BS cooperation. Besides, open-loop power control is employed.

Figure 3 illustrates the performance of MUTP-assisted VBLAST/STBC system for extended pedestrian channel model based on LTE specifications for DL transmission. Here, comparisons have been provided for flat fading, uncorrelated frequency-selective and correlated frequency-selective fading with transmitter preprocessing (TP). We have assumed correlation  $\rho = 0.7$  and a Doppler shift of 5 Hz. For comparison, we have assumed uncorrelated frequency-selective fading without MUTP. Monte Carlo simulation trials were carried out so as to evaluate the performance of the system and also for each SNR value, 10,000 channel realizations were employed. It is observed that to achieve a SER of  $10^{-1}$ , a system without TP (zero forcing) over uncorrelated channel requires 25 dB SNR as against the scheme with TP, which requires less than 3 dB in uncorrelated frequency-selective channel.

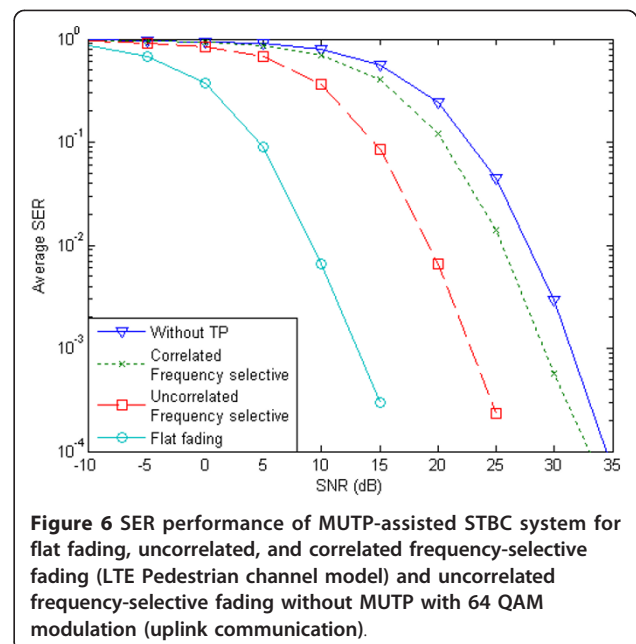
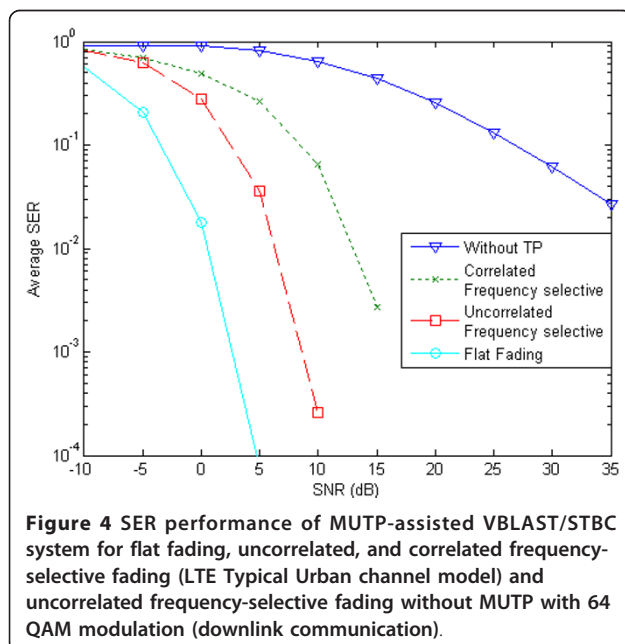
Figures 4 and 5 elucidate the SER performance of MUTP-assisted MIMO system with VBLAST/STBC processing for typical urban and extended vehicular channel



models based on LTE specifications for DL transmission. For typical urban, Doppler frequency of 70 Hz and for vehicular, 300 Hz is assumed with the MS moving at a speed of 40.8 and 162 km/h respectively. MIMO channel models are assumed to be of high correlation with  $\rho = 0.7$ . Our simulation study shows that the system employing TP results in better performance in terms of achievable SER compared to an uncorrelated system without TP. Also, in all the three types of delay spread distributions, system operating over uncorrelated frequency-selective channel with MUTP outperforms the system

over correlated channel with MUTP. Furthermore, in the context of multi-cell MIMO, a system operating over correlated frequency-selective fading with MUTP outperforms a system operating over uncorrelated frequency-selective fading without MUTP by completely mitigating CCI and MSI.

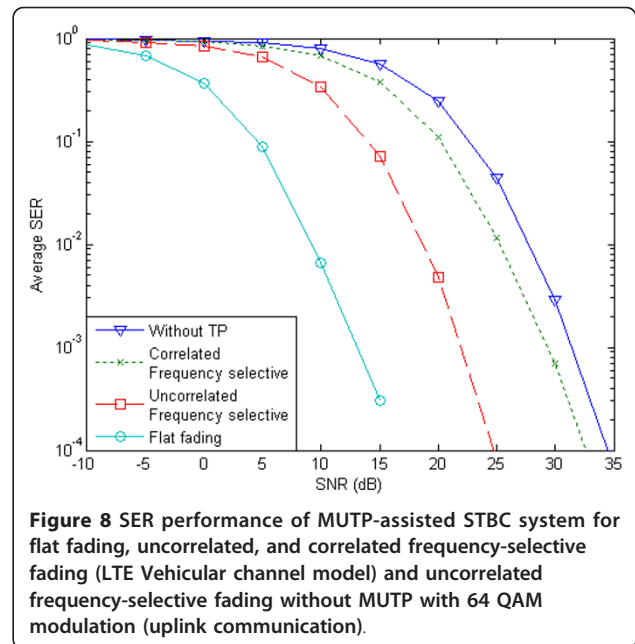
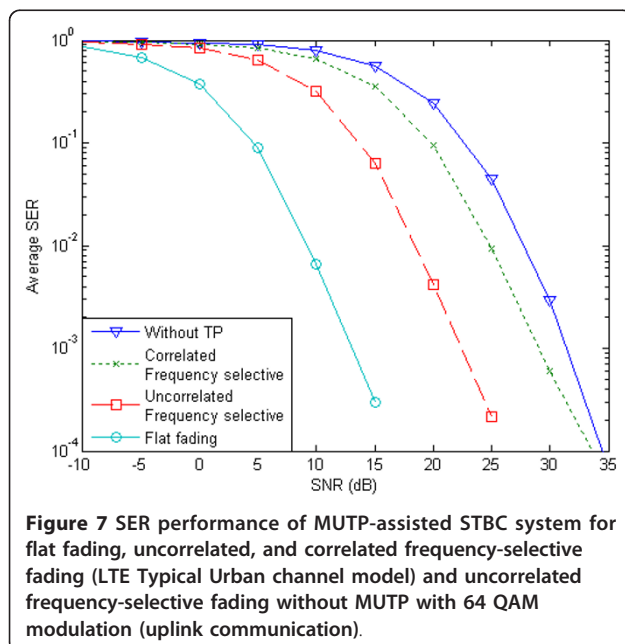
Figure 6 illustrates the performance of MUTP-assisted MIMO system with STBC support for extended pedestrian channel model based on LTE specifications for UL transmission. It is seen that to achieve a SER of  $10^{-3}$ , system



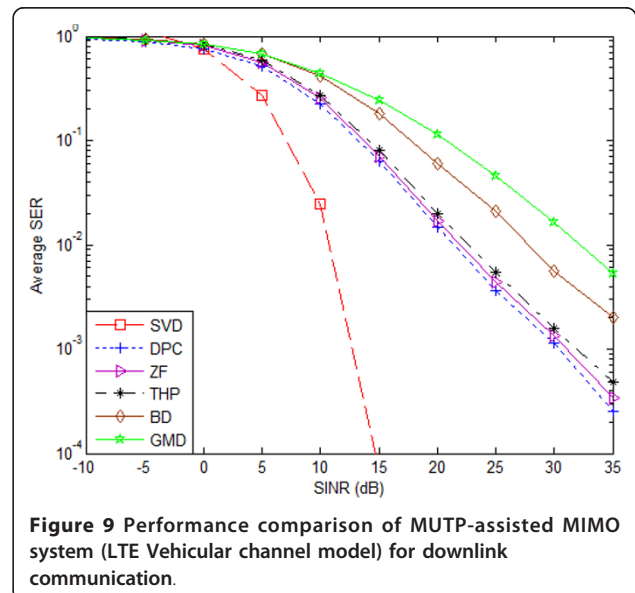


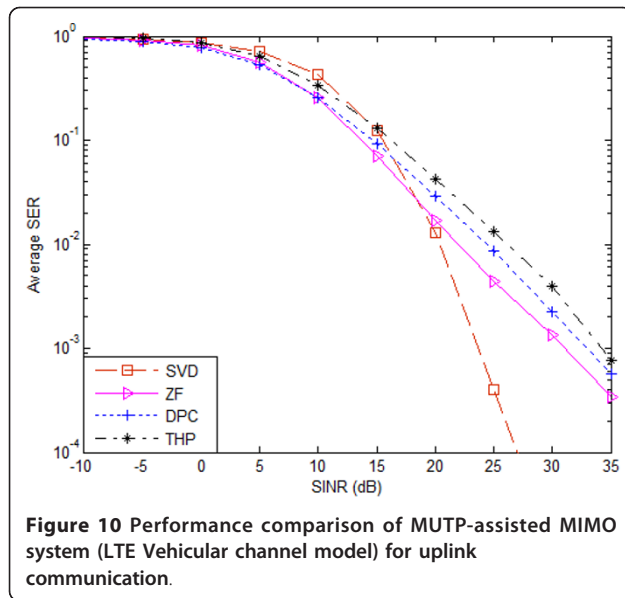
operating over uncorrelated frequency-selective channel requires 5 dB less than the correlated frequency-selective fading channel.

Figures 7 and 8 show the performance of MUTP-assisted MIMO system for typical urban and extended vehicular channel model for UL transmission. It is discerned from simulation results that for a target SER of  $10^{-3}$ , system over uncorrelated frequency-selective fading channel performs better than the system over correlated frequency-selective fading channel, requiring 5 dB lesser SNR. Furthermore, in the context of multi-cell MIMO systems, MUTP based on SVD perfectly eliminates CCI and MSI. Also, MUTP-aided system outperforms system without MUTP. In Figures 9 and 10, we plot the average SER versus SINR for DL and UL transmissions, respectively, assuming different interferer configurations. Here, the simulation results correspond to equal power interferers' scenario [21]. The plots illustrate the performance comparison of SVD-aided MUTP MIMO systems with THP, DPC, ZF, BD, and geometric mean decomposition for DL transmission and THP, ZF, and DPC for UL transmission in uncorrelated frequency-selective channels. It is observed that SVD-based MUTP outperforms other precoding techniques in terms of achievable SER. Further, it can be discerned that performance of the system degrades when equal CCI is considered in contrast to our initial assumption that interference is Gaussian. This can readily be noticed by comparing SVD-aided systems in Figures 5 and 9 for DL and Figures 8 and 10 for UL transmission in the context of uncorrelated vehicular channel model. Figure 11 illustrates the influence of equal CCI, dominant CCI, and dominant noise on the SER performance. For the case

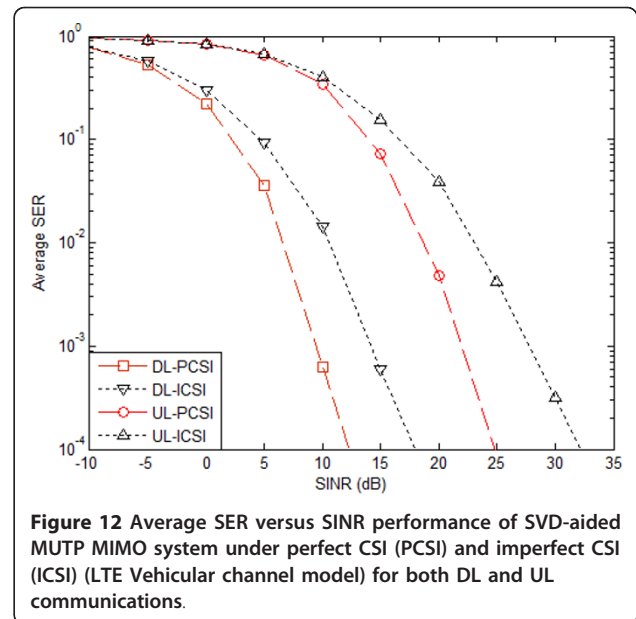


of dominant interferers, we assumed two interferers to be dominant and the rest with equal power. Simulation results show that the existence of highly dominant interferers causes degradation in the system performance compared to low power interferers (equal CCI case). This follows from the fact that a single dominant interferer can have more variations in terms of interference power and therefore, can impact further on the average achievable SER. Furthermore, it is seen that dominant noise results in worst case performance compared to equal and dominant CCI case in the context of MUTP-aided multi-cell MIMO systems.





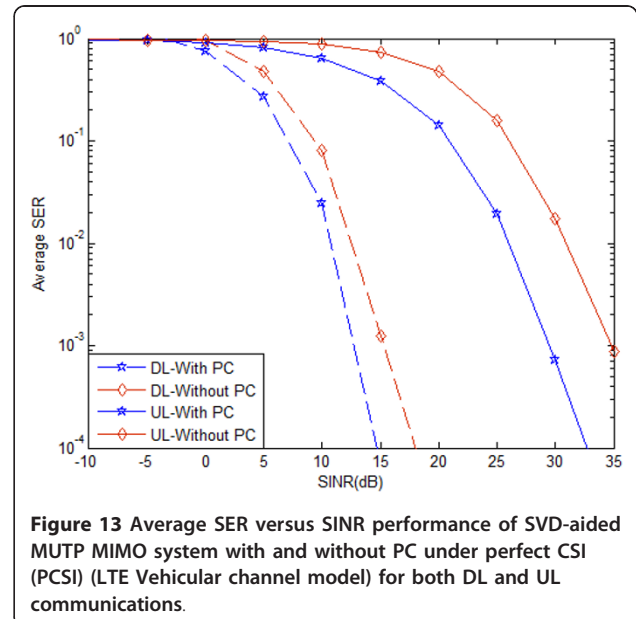
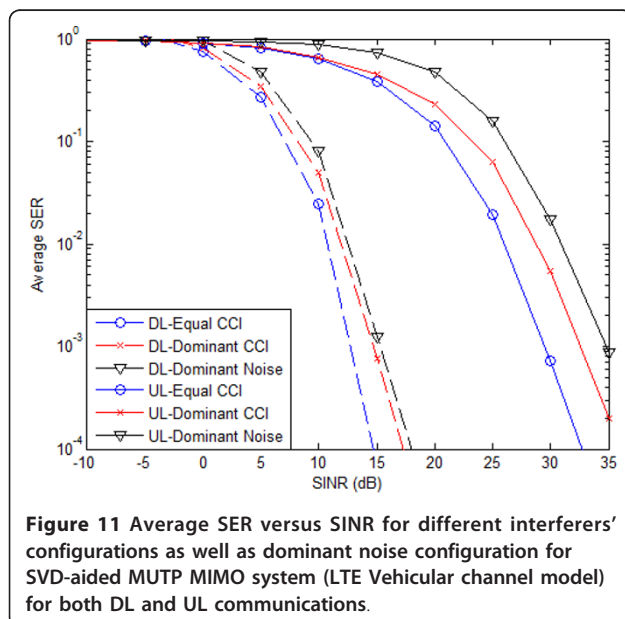
In Figure 12, in contrast to our initial assumption of perfect CSI (PCSI), we demonstrate the impact of imperfect CSI (ICSI) on the performance of MUP-aided MIMO systems. The channel estimation employed in this study is based on the MIMO pilot-assisted symbol modulation [22]. It follows then the channel matrix  $\mathcal{H}$  can be expressed as  $\mathcal{H} = \hat{\mathcal{H}} + \mathcal{E}$ , where  $\hat{\mathcal{H}}$  is the predicted channel matrix with zero mean and variance  $(1 - \psi)$  and  $\mathcal{E}$  is the CSI error matrix with zero mean and mean square error  $\psi$ . As it can be seen from the plot that to achieve a target error rate of  $10^{-4}$ , PCSI results in SINR gains of 6 and 7 dB for DL and UL transmissions, respectively, compared to ICSI. This is due to the fact that ICSI results in



perturbation in the eigenvalues contributing to imperfect removal of CCI and MSI in the context of both DL and UL transmissions. Figure 13 shows the impact of power control (PC) on the MUP-aided MIMO system for both the DL and UL transmissions. We can see from the figure that SINR gains of approximately 3 and 5 dB are achieved for a target SER of  $10^{-3}$  for DL and UL, respectively, when power control is invoked.

#### 4. Conclusion

In this article, we have investigated the performance of multi-cell MIMO system with joint VBLAST/STBC



processing for DL transmission and STBC processing for UL transmission aided by transmitter preprocessing. We have drawn comparisons between systems with and without TP and, also with other widely known precoding techniques. It is discerned from the analysis that the system with TP can significantly enhance the achievable SER performance thus allowing support for more users, and resulting in higher capacity than conventional system employing a linear ZF detector. Also, this study has confirmed that the presence of dominant interferers can degrade the system performance. Nevertheless, the performance gain in interference-limited environments is better than in the noise-limited scenario due to the presence of dominant noise in the latter case. Moreover, it is inferred that ICSI can considerably degrade the system performance due to eigenvalue perturbation. In the context of multi-cell MIMO systems, it is further observed that SVD-aided MUP outperforms other precoding techniques by mitigating MSI and CCI. Throughout this article, we have made an idealistic assumption of perfect synchronization among the BSs. Our future study will focus on the assessment of the system performance under imperfect synchronization between BSs and network latency.

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#### Competing interests

The authors declare that they have no competing interests.

Received: 6 April 2011 Accepted: 11 June 2012 Published: 11 June 2012

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doi:10.1186/1687-1499-2012-194

**Cite this article as:** Nagaradjane et al.: Performance of MUP-aided MIMO systems over correlated frequency-selective wireless communication channels: a multi-cell perspective. *EURASIP Journal on Wireless Communications and Networking* 2012 **2012**:194.

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