A Protocol based on D2D Cooperation for FDD Massive MIMO Communications without Instantaneous CSI Feedback

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***Abstract*—We propose a novel protocol for fast fading massive MIMO systems in Frequency Division Duplex (FDD) mode and, in general, non-reciprocal channels. Our approach relies on Device-to-Device (D2D) cooperation to avoid instantaneous channel state information (CSI) feedback, unaffordable in practical systems. This protocol assumes that clusters of user terminals (UT) cooperate to create virtual MIMO at a target UT via D2D cooperation. The base station (BS) has statistical knowledge of the downlink channel and it is aware of the cooperation but it is oblivious of the statistics of the D2D links and the transmitter is designed based on the downlink channel statistics solely. The performance of the proposed protocol is analyzed and compared to state-of-art schemes based on instantaneous CSI feedback.**

I. Introduction

Very large antenna array or massive MIMO systems introduced in [1], [2] have the characterizing feature that M, the number of antennas at the base station (BS) is much larger than the number of users. This communication paradigm promises a drastic enhancement of both energy efficiency and throughput in ideal conditions. Thus, it is of strategic relevance to transform it in a mature and implementable technology to attain the very challenging performance targeted in the future 5G networks.

In downlink communications, an effective transmission able to make the best use of the potentials of the physical mean relies on an accurate knowledge of the CSI at the transmitter side and the system performance is strongly sensitive to the CSI knowledge. Thus, the CSI acquisition plays a crucial role in the wireless system design. This task implies very specific challenges depending if frequency division duplex (FDD) or time division duplex (TDD) are adopted as duplexing schemes. By appealing to the reciprocity principle, TDD mode enables the acquisition of the CSI for downlink by channel estimation in the uplink and costly feedback can be avoided via open loop feedback. In FDD mode and, more generally, when uplink-downlink channel reciprocity does not hold, the open loop feedback is not an option and a closed loop feedback is required. In a closed loop feedback scheme, each user needs to retransmit an amount of information proportional to the number of antennas at the BS. This task is really costly when the number of antennas is large and becomes even unfeasible in fast fading channel with short coherence time. Thus, [2] limited the applicability of massive MIMO networks to TDD mode. The extension of the massive MIMO technology to FDD mode appeared unfeasible. However, the large majority of currently deployed cellular networks is based on FDD mode thanks to their appealing features in terms of synchronization requirements compared to TDD systems. Then, an effective design of massive MIMO systems in FDD mode is a challenge that the scientific community cannot escape to tackle.

Recently, promising schemes for FDD mode have been proposed in [3]–[6]. In [3], [4], [6] the authors take advantage of the property of reduced rank of the user channel covariance matrices in massive MIMO system pointed out in [3], [7], [8]. In [5] the authors leverage on a sparse model representation of a massive MIMO network and compressive sensing to reduce training and feedback overhead. The Joint Spatial Division and Multiplexing (JSDM) protocol proposed in [3], [4] assumes statistical CSI knowledge at the transmitter and it is based on the key idea of clustering users whose channel covariance matrix span approximately the same subspace called *effective channel subspace* (ECS). This common shared subspace has dimensions substantially lower than M, the dimensions of the full channel space. After clustering users with widely overlapping ECS, the JSDM approach schedules simultaneous transmissions to clusters ideally with orthogonal ECS. The beamforming is performed in two phases. The inter-cluster interference is annihilated by projection of the signals for a specific cluster onto its ECS. The design of this projection is based on statistical CSI knowledge. The intra-cluster interference is mitigated by linear precoders whose design requires knowledge of the instantaneous ECS CSI. Although the instantaneous CSI is substantially reduced in the JSDM protocol, it can be still too costly for practical 5G systems[1]. Then, the objective of this paper is to further reduce feedback using statical CSI at the BS. The transmission protocol differs from the JSDM in [3], [4] in the way we mitigate the intra-cluster interference. In contrast to the JSDM that requires instantaneous CSI feedback, we design the precoder as for a point-to-point MIMO system with only statistical CSI based on the knowledge of the ECS statistics at the transmitter. Additionally, we assume D2D communications among cluster's users such that virtual MIMO systems are created at

[1]In order to keep the feedback limited, in 4G the beamforming design is far from being optimum as each UT selects locally a beamformer from a very limited codebook based on local *statistical* channel knowledge and without accounting for the presence of additional UTs. It is likely that in 5G the standards will mostly support a statistical feedback while instantaneous feedback will be reserved to special and costly services.

978-1-5090-0196-5/15/$31.00

the receiver side and all the transmitted information streams are useful information rather than interference. This concept was initially proposed in [9] where we adopted an elementary suboptimal precoder. In this paper, we refine and improve our initial proposal and we define and analyze a system with a precoder optimally designed for the fictitious point-to-point MIMO system in downlink under the assumption that the BS does not have any kind of CSI, statistical or instantaneous, on the underlying D2D communication systems. The schemes based on D2D communications are compared to the JSDM protocol in [3], [4] adopted as benchmark system.

The following notation has been used throughout the paper: Boldface uppercase and lowercase letters denote matrices and vectors, respectively. Scalars are in italic. $\mathbf{I}_n$ is the identity matrix of size $n \times n$ and $\mathbf{1}_n$ is the n-dimensional vector of ones. The Hermitian operator of a matrix $\mathbf{X}$ is denoted by $\mathbf{X}^H$. $\mathcal{CN}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ denotes a complex Gaussian random vector with mean $\boldsymbol{\mu}$ and covariance $\boldsymbol{\Sigma}$. $\mathbb{E}\{\cdot\}$ is the expectation operator; $\mathrm{tr}(\cdot)$ denotes the trace of the matrix argument. Finally, $\mathrm{diag}(\mathbf{v})$ is the square diagonal matrix having the elements of vector $\mathbf{v}$ as diagonal elements.

II. System Model

As in [9], we consider a single-cell massive MIMO system with the BS equipped with M antennas and serving single antenna UTs. The channel is fast fading and non-reciprocal. Let $\mathbf{R}_k$ denote the covariance matrix of user k channel and let us refer to its image as ECS of user k. As in [3], users with almost overlapping ECSs are clustered together. For a cluster $\mathcal{C}$, we introduce the cluster covariance matrix defined as $\mathbf{R}_c = \sum_{k \in \mathcal{C}} \mathbf{R}_k$ and the image of $\mathbf{R}_c$ is the cluster ECS (ClECS). Simultaneous transmissions are scheduled to clusters with orthogonal (or quasi-orthogonal) ClECSs. Under strict orthogonality of the ClECSs, the projection of the signals intended for a single cluster onto its ClECS by beamforming does not cause interference to the other simultaneously scheduled clusters. Thus, in the following we can focus on a single cluster with n users.

A. Down-link Transmission

The downlink transmission to a single cluster $\mathcal{C}$ is modeled by:

$$\mathbf{y} = \mathbf{H}_c^H \mathbf{B} \mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is the n-dimensional complex column vector of received signals at all the cluster users; $\mathbf{s}$ denotes the vector of i.i.d. Gaussian signals with zero-mean and unit-variance; and $\mathbf{n}$ represents the spatially and temporally white additive Gaussian noise (AWGN) with zero-mean and element-wise variance σ_n^2. Finally, $\mathbf{B}$ is the down-link beamformer such that $\mathrm{tr}\{\mathbf{B}\mathbf{B}^H\} = P_{\max}$, if $P_{\max}$ is the total transmit power constraint. The down-link channel between the BS and the k-th user in the cluster $\mathcal{C}$ is denoted by the M-dimensional complex vector $\mathbf{h}_k$. Therefore,

$$\mathbf{H}_c = \left[\mathbf{h}_1, \mathbf{h}_2, \dots \mathbf{h}_n\right] \in \mathbb{C}^{M \times n} \tag{2}$$

and $\mathbf{R}_k = \mathbb{E}\{\mathbf{h}_k \mathbf{h}_k^H\}$. By leveraging on the low rankness of $\mathbf{R}_c$ and assuming its rank equals b, the cluster covariance matrix can be expressed as

$$\mathbf{R}_c = \widetilde{\mathbf{U}} \widetilde{\boldsymbol{\Lambda}} \widetilde{\mathbf{U}}^H \tag{3}$$

where $\widetilde{\boldsymbol{\Lambda}}$ is the $b \times b$ matrix of the nonzero eigenvalues of $\mathbf{R}_c$ in non increasing order and $\widetilde{\mathbf{U}}$ is the $M \times b$ matrix whose columns are the normalized eigenvectors of $\mathbf{R}_c$. Similarly, $\mathbf{R}_k = \widetilde{\mathbf{U}}_k \widetilde{\boldsymbol{\Lambda}}_k \widetilde{\mathbf{U}}_k^H$, with analogous meaning for b_k, $\widetilde{\boldsymbol{\Lambda}}_k$ and $\widetilde{\mathbf{U}}_k$. Since, by construction, the subspace spanned by the column vectors of $\widetilde{\mathbf{U}}_k$ lies into the subspace spanned by the column vectors of $\widetilde{\mathbf{U}}$, then $\widetilde{\mathbf{U}}_k = \widetilde{\mathbf{U}} \mathbf{T}_k$, where $\mathbf{T}_k$ is a $b \times b$ matrix whose i-th column elements are the coefficients of the i-th column of $\widetilde{\mathbf{U}}_k$ in the basis $\widetilde{\mathbf{U}}$. Additionally, the Gaussian vector $\mathbf{h}_k$ can be expressed as $\mathbf{h}_k = \widetilde{\mathbf{U}}_k \widetilde{\boldsymbol{\Lambda}}_k^{1/2} \widetilde{\mathbf{h}}_k$ being $\widetilde{\mathbf{h}}_k$ a b_k-dimensional vector of zero-mean, unit variance, independent Gaussian elements. Then,

$$\mathbf{H}_c = \widetilde{\mathbf{U}} \left[\mathbf{T}_1 \widetilde{\boldsymbol{\Lambda}}_1^{1/2} \widetilde{\mathbf{h}}_1, \, \cdots \, \mathbf{T}_n \widetilde{\boldsymbol{\Lambda}}_n^{1/2} \widetilde{\mathbf{h}}_n\right] = \widetilde{\mathbf{U}} \mathbf{A}_c, \tag{4}$$

where $\mathbf{A}_c$ is a matrix of Gaussian elements, in general, column-wise correlated. In the following we adopt the notation $\mathbf{a}_{ck} = \mathbf{T}_k \widetilde{\boldsymbol{\Lambda}}_k^{1/2} \widetilde{\mathbf{h}}_k$.

Finally, by projecting the signals to be transmitted onto the ClECS, which implies to structure the matrix $\mathbf{B}$ as $\mathbf{B} = \widetilde{\mathbf{U}} \widetilde{\mathbf{B}}$, being the first operator $\widetilde{\mathbf{U}}$ the projection beamformer, we obtain an equivalent system model in the ClECS with reduced dimensions

$$\mathbf{y} = \mathbf{A}_c^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{n}. \tag{5}$$

The received signal at user k is given by

$$y_k = \mathbf{a}_{ck}^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{n} \tag{6}$$

and the corresponding averaged received power is

$$P_k = \mathrm{tr}\{\mathbf{B}^H \mathbf{R}_k \mathbf{B}\} + \sigma_n^2. \tag{7}$$

B. Intra-cluster D2D Communications

By D2D communications, the users in a cluster retransmit the received signals in orthogonal time intervals. User ℓ amplifies and forwards its received signal y_ℓ such that its transmitted signal is

$$x_\ell = \sqrt{\frac{P_r}{P_\ell}} y_\ell$$

where P_r is the average transmit power constraint as user ℓ acts as relay. To keep the notation easy, we assume that P_r is equal to all the users.

As likely from physical considerations and the analysis in [8], users within a cluster are closely located and far apart from users in other clusters. Then, we can assume that the simultaneous D2D transmissions in other clusters do not interfere with the intra-cluster transmissions. Thus, the signal received by user k from user ℓ is given by

$$\begin{aligned} r_k &= g_{k,\ell} x_\ell + w_k \\ &= \sqrt{\frac{P_r}{P_\ell}} g_{k,\ell} \mathbf{a}_{ck}^H \widetilde{\mathbf{B}}^H \mathbf{s} + \sqrt{\frac{P_r}{P_\ell}} g_{k\ell} n_\ell + w_k \end{aligned} \tag{8}$$

where $g_{k,\ell}$ is the channel coefficient of the fast fading link from user ℓ to user k, realization of a Gaussian random process with variance $\gamma_{k,\ell}$. Finally, w_k is the additive Gaussian noise with variance σ_r^2 at user k when UT k acts as receiver in the D2D communications.

At the end of the relaying phase, user k has n independent received replicas of the original transmitted signal and can act as a virtual MIMO. The corresponding system model is given by

$$\mathbf{r}_k = \mathbf{\Gamma}_k \mathbf{A}_c^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{z}_k \tag{9}$$

where $\mathbf{\Gamma}_k$ is an $n \times n$ diagonal matrix given by

$$\mathbf{\Gamma}_k = \mathrm{diag}\left[\sqrt{\frac{P_r}{P_1}} g_{k,1}, \cdots, \sqrt{\frac{P_r}{P_{k-1}}} g_{k,k-1}, 1, \right. \\ \left. \sqrt{\frac{P_r}{P_{k+1}}} g_{k,k+1} \cdots \sqrt{\frac{P_r}{P_n}} g_{k,n}\right] \tag{10}$$

and $\mathbf{z}$ is the equivalent Gaussian noise with diagonal covariance matrix, at UT k, given by:

$$\mathbf{\Sigma}_k = \mathrm{diag}\left[\frac{P_r}{P_1}\gamma_{k,1}\sigma_n^2 + \sigma_r^2, \cdots, \frac{P_r}{P_{k-1}}\gamma_{k,k-1}\sigma_n^2 + \sigma_r^2, \right. \\ \left. \sigma_n^2, \frac{P_r}{P_{k+1}}\gamma_{k,k+1}\sigma_n^2 + \sigma_r^2 \cdots \frac{P_r}{P_n}\gamma_{k,n}\sigma_n^2 + \sigma_r^2\right]. \tag{11}$$

III. The Proposed System

In this section we present our system for downlink communications in a FDD massive MIMO system. The inter-cluster interference mitigation follows the same line as the JSDM protocol in [3] and it is obtained by a first level beamformer that projects the cluster signals onto the corresponding ClECS. In [3], the intra-cluster interference is mitigated with standard linear precoders based on instantaneous CSI feedback. Instead, the communication systems we propose rely on D2D communications to create virtual MIMO systems at the user terminal side to combat intra-cluster interference. A BS transmits simultaneous information streams to the single user, called target-user, at a time. Then, each of the $n-1$ non-target users forward the received signals to the target user to obtain the virtual MIMO system in (9). The target user role is assigned in a round robin fashion such that all the users receive information streams with the same periodicity[2]. In summary, as for the JSDM protocol, statistical CSI of the down-links is fed back to the BS to combat inter-cluster interference. But, in contrast to the protocol in [3], the instantaneous downlink CSI is not fed back. Similarly, in this work, we assume that the statistics characterizing the D2D links are not fed back and the BS is substantially oblivious of the presence of varying virtual MIMO systems at the receiver side. Then, we design the precoder for optimal transmission on the fictitious point-to-point MIMO system in (5). It is worth noting that the designed precoder is independent of the target user. Since the BS does not know the statistical CSI of the actual virtual MIMO channel (9), each user also need to feedback the actual rate that its virtual MIMO channel can support.

[2]The D2D communication is performed in a different frequency band independently of the communications in the massive MIMO system. It is performed between two subsequent downlink transmissions to the same cluster. In general, transmissions to the same cluster are not consecutive and some cluster scheduling is performed.

Let us observe that here we made a specific design choice but others are equally worth to be explored.

In the following, we deal with the optimal design of the precoder $\widetilde{\mathbf{B}}$ under statistical knowledge of the channel $\mathbf{A}_c$. We focus on BSs equipped with uniform linear array (ULA) and assume that the properties of channels for ULA as $M \to +\infty$ pointed out in [3], [7] are well approximated, i.e. the eigen-bases of all the user channel covariance matrices $\mathbf{R}_k$ coincide with the Fourier matrix. Under this assumption, also the cluster covariance matrix $\mathbf{R}_c$ has the same eigen-basis and each matrix $\mathbf{T}_k = \widetilde{\mathbf{U}}^H \widetilde{\mathbf{U}}_k$ is a "tall" matrix with all the columns having a single unit element and the remaining ones equal to zero and all the rows with at most a single nonzero element. Then, the elements of the matrix $\mathbf{A}_c$ are independent and the variances of its entries can be assembled into the matrix

$$\mathbf{G} = \left(\mathrm{E}\{|a_{c,ij}|^2\}\right)_{\substack{i=1,\dots,b \\ j=1,\dots n}} = \left[\widetilde{\boldsymbol{\lambda}}_1, \widetilde{\boldsymbol{\lambda}}_2, \dots, \widetilde{\boldsymbol{\lambda}}_n\right] \tag{12}$$

where $\widetilde{\boldsymbol{\lambda}}_j$ is the diagonal of the matrix $\widetilde{\mathbf{\Lambda}}_j$, i.e. $\widetilde{\boldsymbol{\lambda}}_j = \mathrm{diag}\widetilde{\mathbf{\Lambda}}_j$.

Then, channel $\mathbf{A}_c^H$ falls into the class of channels studied in [10]. The maximum achievable rate is attained with Gaussian inputs whose covariance matrix $\mathbf{Q}$ is diagonal [10, Theorem 1]. Then, assuming the transmission of a b-dimensional Gaussian vector $\mathbf{s}$ with unit variance independent entries over the virtual MIMO channel, the precoding matrix $\widetilde{\mathbf{B}}$ in (9) is the $b \times b$ diagonal matrix given by

$$\widetilde{\mathbf{B}} = \mathbf{Q}^{1/2}$$

where the entries of the diagonal matrix $\mathbf{Q}$ can be obtained as solution of a converging fixed point equation [11]. Under the above mentioned assumption that the matrices $\mathbf{\Gamma}_k$ and $\mathbf{\Sigma}_k$ are not known by the BS, we optimize the transmission for system model (5). Assume that the total transmit power constraint is such that

$$\mathrm{tr}\mathbf{Q} = P_{\max}.$$

Then, we introduce the normalized matrix $\mathbf{Q}_n$ such that

$$\mathbf{Q} = \frac{P_{\max}}{b}\mathbf{Q}_n.$$

Let us introduce the well known expression of the minimum mean square error (MMSE) at the output of a linear detector for signal s_k (see e.g. [12]) and system model (5)

$$\mathrm{MMSE}_k = \left[1 + Q_{n,k}\frac{P_{\max}}{b\sigma_n^2}\mathfrak{a}_{ck}^H \mathbf{E}_k \mathfrak{a}_{ck}\right]^{-1} \tag{13}$$

where $Q_{n,k}$ is the k-th diagonal element if matrix $\mathbf{Q}_n$, $\mathbf{E}_k = (\mathbf{I}_b + \frac{P_{\max}}{b\sigma_n^2}\mathfrak{A}_{c,k}^H \mathbf{Q}_{n,k}\mathfrak{A}_{c,k})^{-1}$, $\mathfrak{a}_{ck}$ denotes the k-th column of matrix $\mathbf{A}_c^H$ not to be confused with $\mathbf{a}_{ck}$, the k-th column of $\mathbf{A}_c$, $\mathfrak{A}_{c,k}$ is the matrix obtained from $\mathbf{A}_c$ by suppressing the k-th row. Finally, $\mathbf{Q}_{nk}$ is obtained from $\mathbf{Q}_n$ by suppressing the k-th row and column.

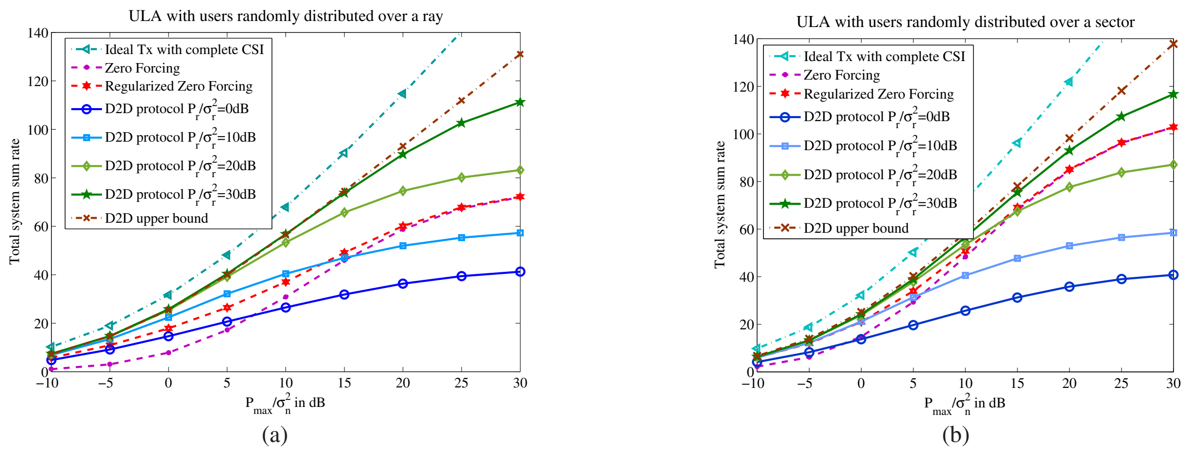

Figure 1: Average total rate vs $P_{\max}/\sigma_n^2$ in downlink for the proposed system (solid lines) for $P_r/\sigma_r^2 = 0$, 10, 20, 30 dB, the benchmark JSDM system (dashed lines) and upper bounds (dot-dashed lines) with a ULA array of $M = 64$ antennas and 4 clusters of 4 users distributed over (a) rays, (b) sectors.

The optimal power allocation $\mathbf{Q}_n^*$ for system (5) requires [10] the solution of the fixed point system of b equations in the normalized power allocation $\mathbf{Q}_n$

$$Q_{n,k} = \frac{1 - \mathbb{E}[\mathrm{MMSE}_k]}{\frac{1}{b}\sum_{\ell=1}^{b}(1 - \mathbb{E}[\mathrm{MMSE}_\ell])} \qquad k = 1, \ldots, b. \tag{14}$$

The algorithm to determine $\mathbf{Q}_n^*$ is iterative and it is initialized assuming equal power distribution. By using the superscript $\cdot^{(m)}$ to denote the values of variables at iteration m, $\mathbf{Q}_n^{(0)} = \mathbf{I}_b$. Using this initial power allocation, the fixed point of the system of equations (14) is determined by iterating on the following system of equations

$$P_{n,k}^{(m+1)} = \frac{1 - \mathbb{E}[\mathrm{MMSE}_k^{(m)}]}{\frac{1}{b}\sum_{\ell=1}^{b}(1 - \mathbb{E}[\mathrm{MMSE}_\ell^{(m)}])} \qquad k = 1, \ldots, b \tag{15}$$

until convergence.

The power allocation $\mathbf{Q}^* = \frac{P_{\max}}{b}\mathbf{Q}_n^*$ optimal for (5) to transmit information to each of the virtual MIMO systems. Then, from (7), the averaged received power at user k is

$$P_{av,k}^* = \frac{P_{\max}}{b}\mathrm{tr}\{\mathbf{Q}_n^*\mathbf{T}_k\widetilde{\mathbf{\Lambda}}_k\mathbf{T}_k^H\} + \sigma_n^2 \tag{16}$$

and the system model (9) reduces to

$$\mathbf{r}_k = \mathbf{\Gamma}_k^*\mathbf{A}_c^H\mathbf{Q}^{*1/2}\mathbf{s} + \mathbf{z}_k$$

being $\mathbf{\Gamma}_k^*$ the matrix defined in (10) with $P_j = P_{av,j}^*$ as in (16) and $\mathbf{z}_k$ is a Gaussian noise with covariance $\mathbf{\Sigma}_k^*$ as in (11) with $P_k = P_{av,k}^*$.

Then, the achievable rate for the target user k is

$$R_k = \frac{1}{n}\mathbb{E}\left[\log\det\left[\mathbf{I}_n + \mathbf{\Gamma}_k^*\mathbf{A}_c^H\mathbf{Q}^*\mathbf{A}_c\mathbf{\Gamma}_k^{*H}\mathbf{\Sigma}_k^{*-1}\right]\right]$$

where the factor n^{-1} is due to the fact that the information streams intended for user k are received each n down-link channel uses. Note that user k feeds back the value nR_k that should be used for encoding at the BS.

The total achievable rate in cluster $\mathcal{C}$ is given by

$$R_c = \sum_{k\in\mathcal{C}} R_k.$$

IV. Simulation Results

This section presents the performance of the proposed communication system obtained by extensive simulations. The proposed system is compared the benchmark JSDM system in [3]. In contrast to the theoretical framework presented in Sections II and III where we focus on a single cluster, in this section we present simulations for a single massive MIMO cell with multiple clusters. This setting allows us to assess the effects on the system performance of the approximations and assumptions made on the massive MIMO system. More specifically, the different ClECS are not strictly orthogonal and and after the projection of the cluster's signals onto its ClECS there is still a leakage of power in the other ClECS which causes intercluster interference. This leakage has different impact on JSDM systems and the proposed system based on D2D cooperation. Thus, it is important to assess the performance and compare the two systems in more complex settings where several clusters are simultaneously transmitting. The expressions of the rate are adapted to account for the effects of the interference as, e.g., in [4], for both systems. Due to space restrictions we do not detail them here.

We adopt the setup utilized in [4]. It consists of a BS endowed of a uniform linear array (ULA) with $M = 64$ antennas and 16 users divided into 4 clusters with the same number of users, i.e. $n = 4$. The downlink channel is fast fading with Gaussian distributed coefficients. The covariance matrices of users' channels are obtained by the one-ring model as in [4]. Because of the finite dimension of the system (M=64), the assumption of pairwise orthogonality of the users' channels is only approximatively satisfied as well as the assumption that the channel covariance matrices have reduced rank and their eigen-bases coincide with the Fourier matrix $\mathbf{F} = M^{-1/2}(\mathbf{f}_0, \mathbf{f}_1, \ldots, \mathbf{f}_{M-1})$ with $\mathbf{f}_m = (1, \mathrm{e}^{-j2\pi m\cdot 1/M}, \ldots \mathrm{e}^{-j2\pi m\cdot(M-1)/M})^T$. We proceed as they were exactly satisfied and our simulations account for these non-ideality of the system. The rank of the cluster covariance matrices for all the clusters is fixed to $b = 11$. This value was determined empirically in [4] and it is the rank of the ClECS that optimizes the performance of the system in [4] in average. In the benchmark system [4], this choice implies that each user in the cluster feeds back $b = 11$ exact coefficients to the base station and the regularized zero forcing (RZF) precoders is designed with perfect CSI of ECSs for transmission over $b = 11$ beams. In our simulations, we do not account for the cost of feedback in terms of reduced available bandwidth. Moreover, the necessary quantization of the instantaneous CSI determines not only a reduction of the available bandwidth for transmission in the JSDM protocol but also a performance degradation that depends on the quantization granularity. Similarly, we assume negligible the cooperation cost for the proposed virtual MIMO scheme based on D2D cooperation. This assumption is motivated by the fact that the cluster's UTs are very close each other and use the D2D bandwidth with a very limited local effect that does not have impact on the global rate of the cell and has only second order effects in the global use of the frequency spectrum. Indeed, the assumption that the D2D communications may have second order effects on the global use of the frequency spectrum requires further investigation. Concerning the D2D communications, the channels between pairs of users are fast fading, independent each other, and follow a complex Gaussian distribution with zero mean and unit variance. All the curves are obtained by averaging over many channels' realizations and cluster's topologies. We consider two specific ways to randomly generate users in the coverage area of the base station. In a first scenario we consider four rays originated at the base station and separated by angles of $\frac{\pi}{4}$ radians: the users' terminals are randomly distributed along the rays. Users on the same ray belong to the same cluster. Under this assumption, the ring model adopted to generate the channel covariance matrix yields to channels of the users in the same cluster with almost identical covariance matrices. We refer to this user configuration as user's distribution on rays. A second way adopted here to generate users configurations consists in randomly generating users on a sector of $\frac{\pi}{4}$ radians. In this case, the users' cluster belonging to the same sector have different covariance matrices.

Figures 1(a)-(b) show the achievable total rate of the system as a function of the total transmit power $P_{\max}$ normalized by the noise variance in the downlink transmitter, i.e. $P_{\max}/\sigma_n^2$. We compare the proposed massive MIMO system with precoder optimized for the MIMO system (5) and D2D cooperation with the non-cooperative JSDM system and with two upper bounds for the total rate. A first upper bound is achieved by an ideal transmitter that has perfect knowledge of the global instantaneous CSI and it is an upper bound for the benchmark systems based on the instantaneous CSI information. The second bound is obtained by assuming perfect transmissions on the D2D links, i.e., the D2D links do not introduce any attenuation and noise. This is a useful upper bound for the performance of the D2D cooperative system. The performance of the JSDM system with ZF and RZF is in dashed lines with circle and squared markers, respectively. The performance of the systems based on D2D cooperation is plotted in solid lines for varying values of the ratio P_r/σ_r^2. The upper bounds are in dot-dashed lines, triangle markers are used for the ideal transmission with full instantaneous CSI while $\times$-markers are used for the upper bound on the D2D protocol. Figure 1 (a) and (b) present the analysis of a massive MIMO system with users randomly distributed over a ray and on a sector, respectively. Systems with users distributed on a sector exploit better user diversity than systems with users randomly distributed over a ray as a straightforward comparison of Figures 1(a) an (b) shows. However, JSDM systems with instantaneous CSI benefit more from it and show a substantially higher total rate above all at high $P_{\max}/\sigma_n^2$ ratios. The proposed system with D2D cooperation is less affected from the detrimental effects of inter-cluster interference compared to the JSDM benchmark system as the curves for high level of P_r/σ_r^2 show but pay a significant price in performance to the attenuation on the D2D link and noise at the D2D link receivers above all at high $P_{\max}/\sigma_n^2$ ratios. This is due to the fact that the noise at the D2D link receiver becomes predominant compared to the noise introduced in the downlink receivers.

The proposed system based on D2D cooperation can outperform the JSDM benchmark system in all the analyzed range of maximum transmit power $P_{\max}$ normalized by the noise variance σ_n^2 for a sufficiently high level of P_r/σ_r^2 as the upper bound for the D2D cooperative system show[3].

Acknowledgments

This work was supported by Huawei France Research Center.

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[3]Note the the upper bound is asymptotically attainable for $P_r/\sigma_r^2 \to +\infty$.