Interference-based Clustering for MIMO D2D Underlay Communications

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***Abstract*—Clustering of Device-to-Device (D2D) pairs with cellular transmissions is particularly challenging to manage interference in future fifth generation networks. D2D pairs should coexist with cellular users in underlay scenario, taking advantage of frequency and spatial dimensions. We consider a Multiple Input Multiple Output (MIMO) channel where all users (whether cellular or devices) are equipped with $N > 1$ antennas, and the Base Station (BS) has $M \geq N$ antennas. Interference between D2D pairs, between D2D transmitters and the BS and between cellular users and D2D receivers is then managed by determining clusters of D2D pairs and cellular users with very low relative interference levels. Clusters are obtained after graph-coloring on a pairwise interference-leakage based matrix. Then, several Resource Blocks (RB) allocation algorithms are proposed, with various fairness levels. A final orthogonalization step using Minimum Mean Square Error (MMSE) may be added at the BS in order to further reduce interference. Simulation results show very large D2D data rates improvements, while cellular data rates degradation due to interference can be controlled.**

I. INTRODUCTION

Device-to-Device (D2D) communications can offload the cellular traffic in dense urban areas by allowing direct communications between nearby users [1], [2]. Several D2D pairs may be multiplexed on the same frequency resources, referred to as Resource Blocks (RB), if they are far enough to generate low interference levels. They may also be multiplexed with one cellular transmission per RB in the uplink in underlay communications, provided that they generate low cumulative interference at the Base Station (BS). This paper deals with clustering of D2D pairs and cellular users on RB when interference can be mitigated thanks to distant locations or thanks to Multiple Input Multiple Output (MIMO) semi-orthogonality between cellular and D2D streams.

Taking MIMO into account in D2D underlay communications adds the spatial dimension for clusters' setting, on top of the distance. The spatial dimension for D2D underlay communications has been investigated in [3]–[5] but for ideal massive MIMO at the BS and with some very specific assumptions, such as different number of antennas between transmitters and receivers of D2D pairs, or with the strong constraint that only one D2D pair may be multiplexed with a cellular user. In this paper, a very generic scenario is considered, where the precoding and postcoding matrices are selfishly optimized for each link using the Singular Value Decomposition (SVD) followed by waterfilling on the streams, thus leading to the optimal solution in terms of sum data rate in the absence of interference. Then interference is handled by clustering in a second step.

Clustering of D2D pairs and cellular users using graph-coloring techniques has been studied in recent papers [6]–[8], but for single antenna and without taking fairness into consideration. In this paper, on the contrary, we determine several graph-coloring based clustering algorithms with various fairness levels. For that purpose, we first define an interference indicator based on pairwise interference leakage. An interference graph per cellular user and per RB is then defined. RB allocation finally assigns clusters composed of one cellular user and several D2D pairs according to a metric that quantifies the amount of interference per cluster. In a last step, Minimum Mean Square (MMSE) may be added at the BS in order to further decrease interference.

The paper is organized as follows: the MIMO D2D system model is detailed in Section II. Then, the proposed clustering algorithms are presented in Section III. Their performance results are evaluated in Section IV, and conclusions are given in Section V.

II. SYSTEM MODEL

A. MIMO D2D system model

We consider K_c cellular users and K_d D2D pairs active in the same cellular area covered by one BS. They transmit on L orthogonal RB of bandwidth B_c each. All transmit and receive devices, except the BS, are equipped with N antennas. The BS is equipped with $M \geq N$ antennas. To simplify notations, we refer to k_d for both transmitter and receiver of D2D pair k_d.

In the following, notations without a tilde are used for D2D data transmissions, whereas notations with a tilde are used for cellular data transmissions. $\mathbf{s}_{k_d}^l \in \mathbf{C}^{N\times 1}$ is the isotropic zero-mean Gaussian stream vector of D2D transmitter k_d, such that $\mathbb{E}\left[(\mathbf{s}_{k_d}^l)^H \mathbf{s}_{k_d}^l\right] = 1$, where $\mathbb{E}\left[.\right]$ is the expectation operator. Similarly, $\widetilde{\mathbf{s}}_{k_c}^l$ is the stream vector of cellular user k_c.

The MIMO channel responses for transmission in RB l including only flat fading are denoted as $\mathbf{H}_{j_d k_d}^l \in \mathbf{C}^{N\times N}$ from D2D transmitter of pair k_d to D2D receiver of pair j_d, $\mathbf{H}_{0k_d}^l \in \mathbf{C}^{M\times N}$ from D2D transmitter k_d to the BS, $\widetilde{\mathbf{H}}_{0k_c}^l \in \mathbf{C}^{M\times N}$ from cellular transmitter k_c to the BS, and $\widetilde{\mathbf{H}}_{k_d k_c}^l \in \mathbf{C}^{N\times N}$ from cellular transmitter k_c to the D2D receiver of pair k_d.

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$\mathbf{V}^l_{k_d} \in \mathbf{C}^{N\times N}$ is the precoding matrix at D2D transmitter k_d. The covariance of the transmitted signal of D2D transmitter k_d is:

$$\mathbf{\Phi}^l_{k_d} = \mathbf{V}^l_{k_d}(\mathbb{E}\left[\mathbf{s}^l_{k_d}(\mathbf{s}^l_{k_d})^H\right])(\mathbf{V}^l_{k_d})^H \tag{1}$$

The postcoding matrix $\mathbf{W}^l_{j_d} \in \mathbf{C}^{N\times N}$ is applied on the received signal $\mathbf{y}^l_{j_d} \in \mathbf{C}^{N\times 1}$ as follows: $\widehat{\mathbf{s}_{j_d}}^l = (\mathbf{W}^l_{j_d})^H\mathbf{y}^l_{j_d}$. Similarly, $\widetilde{\mathbf{V}}^l_{k_c}$ is the precoding matrix at cellular user k_c, and the covariance of the transmitted signal is $\widetilde{\mathbf{\Phi}}^l_{k_c}$.

The inverse of path loss and shadowing is denoted with $g_{j_dk_d}$ from D2D transmitter k_d to D2D receiver j_d, g_{0k_d} from D2D transmitter k_d to the BS, $\widetilde{g}_{j_dk_c}$ from cellular transmitter k_c to D2D receiver j_d and $\widetilde{g}_{0k_c}$ from cellular transmitter k_c to the BS.

The transmit power values are set using an open-loop power control, with the aim to reach a target Signal-to-Noise Ratio (SNR) per RB, denoted as SNR_d for D2D transmission. Consequently, for D2D transmitter k_d, it is equal to:

$$P_{k_d} = \min\left\{\frac{P_{\max}}{L}, \frac{\text{SNR}_d \times N_0B_c}{g_{k_dk_d}}\right\} \tag{2}$$

The transmit power values are the same on all active RB, but are optimized per MIMO stream as will be detailed in section II-B. A similar definition is used for cellular transmissions, where the transmit power of user k_c, denoted $\widetilde{P}_{k_c}$, aims at achieving the target SNR denoted as SNR_c.

Then, the data rate at D2D receiver k_d in RB l is:

$$R^l_{k_d} = B_c\log_2(\det(\mathbf{I}_N + g_{k_dk_d}P_{k_d}\times (\mathbf{Q}^l_{k_d})^{-1}(\mathbf{W}^l_{k_d})^H\mathbf{H}^l_{k_dk_d}\mathbf{\Phi}^l_{k_d}(\mathbf{H}^l_{k_dk_d})^H\mathbf{W}^l_{k_d})) \tag{3}$$

where $\mathbf{I}_N$ is the identity matrix of size N. $\mathbf{Q}^l_{k_d}$ is the covariance matrix of noise plus interference at receiver k_d in RB l after postcoding, defined as:

$$\mathbf{Q}^l_{k_d} = (\mathbf{W}^l_{k_d})^H\left(\mathbf{Q}_n + \sum_{\substack{j_d\in\mathcal{S}^l\\ j_d\neq k_d}} g_{k_dj_d}P_{j_d}\mathbf{H}^l_{k_dj_d}\mathbf{\Phi}^l_{j_d}(\mathbf{H}^l_{k_dj_d})^H + \sum_{j_c\in\widetilde{\mathcal{S}}^l}\widetilde{g}_{k_dj_d}\widetilde{P}_{j_c}\widetilde{\mathbf{H}}^l_{k_dj_c}\widetilde{\mathbf{\Phi}}^l_{j_c}(\widetilde{\mathbf{H}}^l_{k_dj_c})^H\right)\mathbf{W}^l_{k_d} \tag{4}$$

with $\mathbf{Q}_n = N_0B_c\mathbf{I}_N$ the noise covariance matrix, assuming white noise. $\mathcal{S}^l$ is the set of D2D pairs that are active in RB l and $\widetilde{\mathcal{S}}^l$ is the set of cellular users that are active in RB l. $\widetilde{\mathcal{S}}^l$ only contains one element because of the orthogonality constraint on cellular allocation.

The data rate at the BS if cellular user k_c is active in RB l is:

$$\widetilde{R}^l_{k_c} = B_c\log_2\left(\det\left(\mathbf{I}_N + \widetilde{g}_{0k_c}\widetilde{P}_{k_c}\times +(\widetilde{\mathbf{Q}}^l_{0[k_c]})^{-1}(\widetilde{\mathbf{W}}^l_{0[k_c]})^H\widetilde{\mathbf{H}}^l_{0k_c}\widetilde{\mathbf{\Phi}}^l_{k_c}(\widetilde{\mathbf{H}}^l_{0k_c})^H\widetilde{\mathbf{W}}^l_{0[k_c]}\right)\right) \tag{5}$$

where $\widetilde{\mathbf{W}}^l_{0[k_c]}$ is the postcoding matrix at the BS if cellular user k_c is allocated in RB l. $\widetilde{\mathbf{Q}}^l_{0[k_c]}$ is the covariance matrix of noise plus interference at the BS if cellular user k_c is allocated in RB l and is defined as:

$$\widetilde{\mathbf{Q}}^l_{0[k_c]} = (\widetilde{\mathbf{W}}^l_{0[k_c]})^H\Big(N_0B_c\mathbf{I}_M + \sum_{j_d\in\mathcal{S}^l} g_{0j_d}P_{j_d}\mathbf{H}^l_{0j_d}\mathbf{\Phi}^l_{j_d}(\mathbf{H}^l_{0j_d})^H\Big)\widetilde{\mathbf{W}}^l_{0[k_c]} \tag{6}$$

B. Selfish precoder and postcoder derivation

The precoding and postcoding matrices are computed with the objective to maximize the sum of interference-free data rates. The SVD of the MIMO channel matrix of D2D pair k_d in RB l is:

$$\mathbf{H}^l_{k_dk_d} = \mathbf{\Upsilon}^l_{k_d}\mathbf{\Delta}^l_{k_d}(\mathbf{\Gamma}^l_{k_d})^H \tag{7}$$

where $\mathbf{\Upsilon}^l_{k_d} \in \mathbf{C}^{N\times N}$ and $\mathbf{\Gamma}^l_{k_d} \in \mathbf{C}^{N\times N}$ are unitary matrices and $\mathbf{\Delta}^l_{k_d} = \text{diag}\left\{\lambda^l_{k_d,1}, \lambda^l_{k_d,2}, ...\right\} \in \mathbf{C}^{N\times N}$ is a diagonal matrix with real non-negative elements. Consequently, the selfish precoder and postcoder are $\mathbf{V}^l_{k_d} = \mathbf{\Gamma}^l_{k_d}$ and $\mathbf{W}^l_{k_d} = \mathbf{\Upsilon}^l_{k_d}$. With this setting, the interference-less data rate of D2D pair k_d in RB l becomes a sum of per-stream data rates :

$$R^l_{k_d} = B_c\sum_{j=1}^{N}\log_2\left(1 + \rho_{k_d}\gamma^l_{k_d,j}\left(\lambda^l_{k_d,j}\right)^2\right) \tag{8}$$

where $\rho_{k_d} = \frac{g_{k_d,k_d}P_{k_d}}{N_0B_c}$ is the average SNR and $\gamma^l_{k_d,j}$ is the normalized power per RB l and per stream j. The interference-less data rate of user k_d in RB l is maximized when distributing power on the streams according to water-filling:

$$\gamma^l_{k_d,j} = \max\left\{0, \mu - \frac{1}{\rho_{k_d}\left(\lambda^l_{k_d,j}\right)^2}\right\} \tag{9}$$

with μ a constant set so that $\sum_{j=1}^{N}\gamma^l_{k_d,j} = 1$. The corresponding precoder's covariance matrix is:

$$\mathbf{\Phi}^l_{k_d} = \mathbf{V}^l_{k_d}\text{diag}\left\{\gamma^l_{k_d,1}, \gamma^l_{k_d,2}, ...\right\}(\mathbf{V}^l_{k_d})^H \tag{10}$$

SVD is also used for transmission from cellular users to the BS. Since it is computed before RB allocation, the precoders and postcoders per RB are evaluated for all cellular users, even though only one cellular user will eventually be allocated per RB. The main difference with D2D is that for cellular user k_c, since the MIMO channel response matrix is not square, the receive matrix at the BS is:

$$\widetilde{\mathbf{W}}^l_{0[k_c]} = \widetilde{\mathbf{\Upsilon}}^l_{0[k_c]} \times \left[\mathbf{I}_N; \mathbf{0}_{\{(M-N)\times N\}}\right] \tag{11}$$

where $\mathbf{0}_{\{(M-N)\times N\}}$ is the all-zeros matrix of size $(M-N)\times N$ and $\widetilde{\mathbf{\Upsilon}}^l_{0[k_c]}$ is obtained by applying SVD on $\widetilde{\mathbf{H}}^l_{0k_c}$.

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III. D2D AND CELLULAR CLUSTERING

Two heuristic algorithms are proposed to perform clustering and RB allocation for D2D and cellular communications. They are centrally performed at the BS, assuming that it knows all the relative interference indicators that are defined next[1].

A. Relative interference

The pairwise relative interference measures the interference leakage at each receiver compared to its useful signal gain. The relative interference from D2D transmitter k_d to D2D receiver j_d in RB l is defined as follows, where 'Tr' is the trace:

$$I^l_{j_d k_d} = \frac{P_{k_d} g_{j_d k_d}}{P_{j_d} g_{j_d j_d}} \times \frac{\mathrm{Tr}\left((\mathbf{W}^l_{j_d})^H \mathbf{H}^l_{j_d k_d} \mathbf{\Phi}^l_{k_d} (\mathbf{H}^l_{j_d k_d})^H \mathbf{W}^l_{j_d}\right)}{\mathrm{Tr}\left((\mathbf{W}^l_{j_d})^H \mathbf{H}^l_{j_d j_d} \mathbf{\Phi}^l_{j_d} (\mathbf{H}^l_{j_d j_d})^H \mathbf{W}^l_{j_d}\right)} \quad (12)$$

The relative interference from D2D transmitter k_d to the BS, if cellular user k_c is active in RB l, is:

$$I^l_{k_c k_d} = \frac{P_{k_d} g_{0 k_d}}{\widetilde{P}_{k_c} \widetilde{g}_{0 k_c}} \frac{\mathrm{Tr}\left((\widetilde{\mathbf{W}}^l_{0[k_c]})^H \mathbf{H}^l_{0 k_d} \mathbf{\Phi}^l_{k_d} (\mathbf{H}^l_{0 k_d})^H \widetilde{\mathbf{W}}^l_{0[k_c]}\right)}{\mathrm{Tr}\left((\widetilde{\mathbf{W}}^l_{0[k_c]})^H \widetilde{\mathbf{H}}^l_{0 k_c} \widetilde{\mathbf{\Phi}}^l_{k_c} (\widetilde{\mathbf{H}}^l_{0 k_c})^H \widetilde{\mathbf{W}}^l_{0[k_c]}\right)} \quad (13)$$

Finally, the relative interference from cellular user k_c to D2D receiver j_d is:

$$\widetilde{I}^l_{j_d k_c} = \frac{\widetilde{P}_{k_c} \widetilde{g}_{j_d k_c}}{P_{j_d} g_{j_d j_d}} \times \frac{\mathrm{Tr}\left((\widetilde{\mathbf{W}}^l_{k_c})^H \widetilde{\mathbf{H}}^l_{j_d k_c} \widetilde{\mathbf{\Phi}}^l_{k_c} (\widetilde{\mathbf{H}}^l_{j_d k_c})^H \widetilde{\mathbf{W}}^l_{k_c}\right)}{\mathrm{Tr}\left((\mathbf{W}^l_{j_d})^H \mathbf{H}^l_{j_d j_d} \mathbf{\Phi}^l_{j_d} (\mathbf{H}^l_{j_d j_d})^H \mathbf{W}^l_{j_d}\right)} \quad (14)$$

The relative interference level between any two couples of D2D k_d and cellular k_c is the defined as:

$$\Omega^l_{k_d,k_c} = \max\left\{I^l_{k_c k_d}, \widetilde{I}^l_{k_d k_c}\right\} \quad (15)$$

B. Interference graphs for graph-coloring

Clustering is performed with the objective to select, in each RB, one cellular user and several D2D pairs, so that the relative interference among all involved users in the cluster is below a given threshold that depends on the type of interference (D2D to D2D, D2D to BS or cellular to D2D).

Let $\mathbf{F}^l_{k_c}$ be the $(K_d+1)\times(K_d+1)$ boolean matrix indicating which D2D pairs cannot be in the same cluster as cellular user k_c. It can consequently be seen as a global interference indicator matrix. In the first $K_d \times K_d$ rows and columns, matrix $\mathbf{F}^l_{k_c}$ contains a symmetric submatrix representing the interference among all K_d D2D pairs in RB l. $\mathbf{F}^l_{k_c}(k_d, j_d) = 1$ if $I^l_{j_d k_d} \geq T_{\text{D2D}}$ or if $I^l_{k_d j_d} \geq T_{\text{D2D}}$, where T_{D2D} is a given interference threshold.

Then row K_d+1 of matrix $\mathbf{F}^l_{k_c}$ contains the indicator of the relative interference at the BS coming from each D2D transmitter in RB l, taking into account the fact that the potential cellular user in RB l is k_c. We set $\mathbf{F}^l_{k_c}(K_d+1, j_d) = 1$ if $I^l_{k_c k_d} \geq T_{\text{BS, D2D}}$, where $T_{\text{BS, D2D}}$ is the D2D to BS interference threshold per D2D pair.

Finally, column K_d+1 of matrix $\mathbf{F}^l_{k_c}$ contains the indicator of the relative interference at each D2D transmitter in RB l, coming from cellular user k_c. $\mathbf{F}^l_{k_c}(k_d, K_d+1)$ is equal to 1 if $\widetilde{I}^l_{j_d k_c} \geq T_{\text{D2D, cell}}$, with $T_{\text{D2D, cell}}$ the cellular to D2D interference threshold. The thresholds are set so as to keep a very low cumulative interference level at the BS and favor D2D multiplexing.

Once the interference matrix has been defined, graph-coloring is performed, using a modified version of DSATUR algorithm. DSATUR algorithm [9] is a low-complexity sequential algorithm in which nodes are chosen based on the degree of saturation, defined as the the number of different colors used for its neighbors in the current solution. In our modified algorithm, once the node with highest degree of saturation has been chosen, its assigned color is not the lowest possible, but the one with lowest cardinality so far.

Then, the potential cluster of cellular user k_c in RB l, noted $\mathcal{C}^l_{k_c}$, is defined as the set of D2D pairs that share the same color as cellular user k_c after graph coloring based on matrix $\mathbf{F}^l_{k_c}$.

In order to perform RB allocation, a unique metric per cellular user and RB is defined. It measures the amount of interference in the cluster of user k_c and RB l, noted $M^l_{k_c}$. It is equal to the sum of the relative interference levels $\Omega^l_{k_d,k_c}$ between k_c and all the D2D pairs $k_d \in \mathcal{C}^l_{k_c}$. If $\mathcal{C}^l_{k_c}$ is empty (when no D2D pair is allowed to transmit in RB l with cellular user k_c), $M^l_{k_c}$ is set to infinity.

$$M^l_{k_c} = \begin{cases} \sum_{k_d \in \mathcal{C}^l_{k_c}} \Omega^l_{k_d,k_c} & \text{if } \left|\mathcal{C}^l_{k_c}\right| > 1 \\ \infty & \text{otherwise} \end{cases} \quad (16)$$

C. Proposed RB allocation algorithms with multiplexing

1) Unfair RB allocation: The first proposed heuristic algorithm aims at minimizing the relative interference. It is called 'unfair' since there is no constraint on the number of RB allocated per cellular user. In each RB l, the allocated cellular user is the one with the lowest summed relative interference level. Then the D2D pairs belonging to the cluster of this cellular user are also allocated in RB l.

$$\widetilde{\mathcal{S}}^l = \left\{\arg\min_{k_c, M^l_{k_c} \neq \infty} M^l_{k_c}\right\}$$
$$\mathcal{S}^l = \mathcal{C}^l_{\widetilde{\mathcal{S}}^l} \ \forall l \in \{1, ..., L\} \quad (17)$$

If $M^l_{k_c} \neq \infty$ for all k_c, this metric is not relevant in RB l. The cellular user selected in RB l is then the one with the largest interference-free data rate, and no D2D pair is allowed to transmit in RB l.

2) Fair RB allocation : The second heuristic algorithm is fair with respect to cellular users. It forces all cellular users to obtain the same number of RB, noted $N_{RB} = \lfloor L/K_d \rfloor$. Let $\mathcal{T}$ be the set of cellular users' candidate for RB allocation, and $\mathcal{L}$ be set of RB that can be allocated. Initially, they include all users and RB: $\mathcal{T} \times \mathcal{L} = \{k_1, ..., K_D\} \times \{1, ..., L\}$. The RB

[1]This assumption is of course quite optimistic. Consequently, the achieved performances can be seen as upper bounds to what could be achieved with more realistic assumptions on channel knowledge.

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allocation algorithm iteratively chooses the RB and the cellular user that minimize the sum of relative interference level:

$$\left\{\widetilde{\mathcal{S}}^{l^*}, l^*\right\} = \left\{\arg \min_{(k_c,l)\in\mathcal{T}\times\mathcal{L}, M^l_{k_c}\neq\infty} M^l_{k_c}\right\}$$
$$\mathcal{S}^{l^*} = \mathcal{C}^{l^*}_{\widetilde{\mathcal{S}}^{l^*}} \quad (18)$$

As with the unfair algorithm, if at some point of the algorithm, $M^l_{k_c} \neq \infty$ for all k_c and $l \in \mathcal{T}\times\mathcal{L}$, the optimization criterion changes and the pair (k_c, l) that maximizes the interference-free data rate is chosen, while no D2D pair is allocated. Once RB l and cellular user k_c have been selected, RB l is removed from set $\mathcal{L}$. If the number of RB allocated to this cellular user k_c reaches N_{RB}, then user k_c is also removed from set $\mathcal{T}$.

D. Single-D2D pair clustering techniques

In order to evaluate the influence of D2D multiplexing on the D2D and cellular performances, we compare the proposed algorithms with two variants where only one D2D pair is allowed to transmit per RB. The unfair single-D2D pair clustering technique proceeds as follows: in each RB l, the allocated cellular user and D2D pair are the ones that minimize the relative interference level:

$$\left\{\widetilde{\mathcal{S}}^l, \mathcal{S}^l\right\} = \left\{\arg \min_{k_d,k_c} \Omega^l_{k_d,k_c}\right\} \ \forall l \in \{1, ..., L\} \quad (19)$$

Fair single-D2D pair clustering uses the same criterion, but prevents cellular users to obtain more than $N_{RB} = \lfloor L/K_d \rfloor$ RB. This is performed by removing any cellular user from the list of allowed users $\mathcal{T}$ as soon as its number of allocated RB reaches N_{RB}.

E. MMSE post-processing at the BS

If $M > N$, cellular data rates can be further improved by applying linear MMSE at the BS in order to mitigate D2D interference. The MMSE postcoder at the BS in RB l, when cellular user k_c has been allocated, is equal to:

$$\widetilde{\mathbf{W}}^l_{0[k_c]} = \frac{(\widetilde{\mathbf{q}}^l_{0[k_c]})^{-1}\widetilde{P}_{k_c}\widetilde{g}_{0k_c}\widetilde{\mathbf{H}}^l_{0k_c}\widetilde{\mathbf{V}}^l_{k_c}}{\left\|(\widetilde{\mathbf{q}}^l_{0[k_c]})^{-1}\widetilde{P}_{k_c}\widetilde{g}_{0k_c}\widetilde{\mathbf{H}}^l_{0k_c}\widetilde{\mathbf{V}}^l_{k_c}\right\|_F} \quad (20)$$

where $\|.\|_F$ is the Frobenius norm and precoder $\widetilde{\mathbf{V}}^l_{k_c}$ is computed using SVD and waterfilling on the streams. $\widetilde{\mathbf{q}}^l_{0[k_c]}$ is the interference plus noise covariance matrix before postcoding:

$$\widetilde{\mathbf{q}}^l_{0[k_c]} = N_0 B_c \mathbf{I}_M + \sum_{j_d\in\mathcal{S}^l} g_{0j_d} P_{j_d} \mathbf{H}^l_{0j_d} \mathbf{\Phi}^l_{j_d} (\mathbf{H}^l_{0j_d})^H \quad (21)$$

IV. Performance Evaluation

A. Simulation assumptions

We consider $K_c = 6$ cellular users and $K_d = 24$ D2D pairs, with $N = 2$ and $M = 4$ antennas. They transmit in $L = 6$ RB of bandwidth $B_c = 180$ kHz each. Cellular users are uniformly distributed in the cell, whereas D2D transmitters are uniformly located at cell's border, at a distance in $[R/\sqrt{2}, R]$ from the BS. Each D2D receiver is uniformly located around its transmitter from 5 to 50 m. The target SNR per RB is equal to 20 dB for both cellular and D2D transmissions. Other simulation parameters are given in Table I, where d is in km and PL stands for Path Loss.

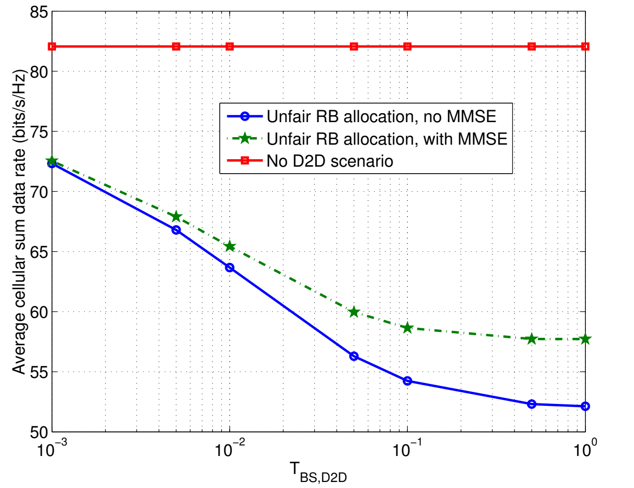

Fig. 1. Influence of $T_{\text{BS, D2D}}$ when $T_{\text{D2D}} = 0.5$ and $T_{\text{D2D, cell}} = 1$ on cellular sum data rate

TABLE I
SIMULATION PARAMETERS

Cell radius R	500 m
P_{max}	21 dBm
Noise power spectral density	-174 dBm/Hz
PL model to BS (LTE urban at 2.6 GHz)	$128.1 + 37.6\log_{10}(d)$
PL model to devices (small cells)	$140 + 36.8\log_{10}(d)$
Shadowing standard deviation, BS	9 dB
Shadowing standard deviation, devices	4 dB
MIMO channel response fading	i.i.d. Rayleigh fading

B. Impact of MMSE at the BS

We first evaluate the influence of MMSE at the BS. The sum cellular data rate achieved with the unfair RB allocation algorithm is compared with the cellular data rate that would be achieved without any D2D pair in the cell. In this reference case, cellular users are allocated with the objective to maximize their sum rate. Only parameter $T_{\text{BS, D2D}}$ has a real influence on cellular rates. Consequently, the two other parameters are fixed to quite high values, that allow large multiplexing of D2D pairs, $T_{\text{D2D}} = 0.5$ and $T_{\text{D2D, cell}} = 1$.

Fig. 1 shows that adding MMSE is particularly useful when $T_{\text{BS, D2D}}$ increases, which means that the D2D interference at the BS increases. When $T_{\text{BS, D2D}}$ is lower than 0.001, the proposed clustering is sufficient to avoid large interference and MMSE is no longer needed. We can notice that the cellular sum rate degradation due to D2D interference is lower than 11% when $T_{\text{BS, D2D}}$ is lower than 0.001.

As shown in Table II, the number of multiplexed D2D pairs is quite large, since more than one third of the D2D pairs are active on the same RB. A good trade-off between cellular and

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D2D data rates is achieved when setting $T_{\text{BS, D2D}}$ to 0.01: the sum cellular rate then only decreases of 20% compared to a scenario without any D2D pair, while the D2D sum rate is multiplied by 6 compared to the reference scenario with only one D2D pair per RB, in which case the D2D sum data rate is only equal to 70.9 bits/s/Hz.

TABLE II
INFLUENCE OF $T_{\text{BS, D2D}}$ WHEN $T_{\text{D2D}} = 0.5$ AND $T_{\text{D2D, CELL}} = 1$ ON D2D

$T_{\text{BS, D2D}}$	D2D sum rate (bits/s/Hz)	Number of active D2D pairs
0.001	380.1	7.0
0.005	421.2	8.1
0.01	**429.5**	**8.3**
0.05	443.3	8.8
0.1	446.0	8.9
0.5	448.5	9.0
1	448.8	9.0

C. Data rate results

Fig. 2 and Fig. 3 represent the Cumulative Distribution Function (CDF) of the sum data rates, for D2D pairs and cellular users, respectively, without MMSE and with $T_{\text{BS, D2D}} = 0.01$. The D2D data rate is very large thanks to efficient multiplexing, whereas the cellular rate is almost equivalent to that achieved when only one D2D pair is allocated per RB. Imposing that all cellular users obtain the same number of RB has little influence on the sum cellular data rate, because the first proposed algorithm is not really unfair, since its objective is to minimize the relative interference level. The sum D2D data rate only slightly decreases with fair allocation, of 8.6% in average, because some clusters of D2D pairs subject to larger interference from cellular users are then chosen.

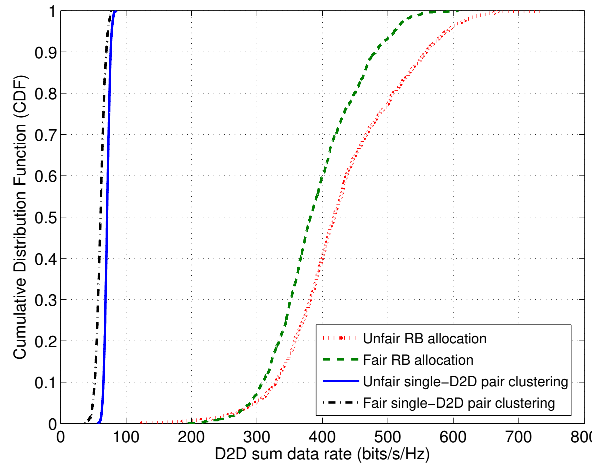

Fig. 2. Comparison of D2D sum data rates

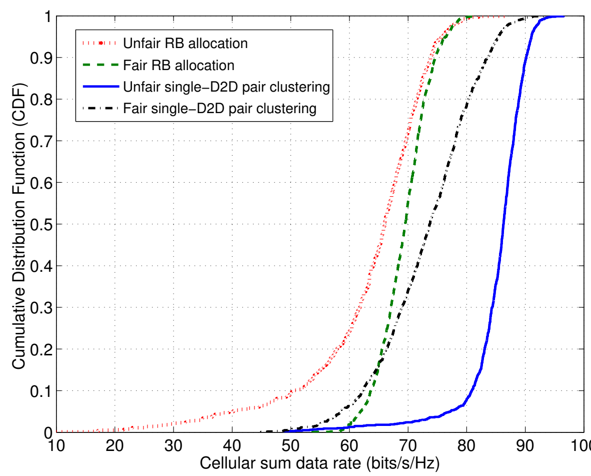

Fig. 3. Comparison of cellular sum data rates

V. CONCLUSIONS

This paper has proposed two clustering and RB allocation algorithms for D2D and cellular MIMO communications. D2D and cellular users in the same cluster generate low relative interference levels to each others. Then, the clusters are allocated to RB to decrease the overall interference leakage, with an optional fairness constraint on the cellular RB allocation and with additional MMSE post-processing at the BS. The proposed algorithms lead to very large data rates for D2D pairs, while maintaining the cellular sum rate within 20% of its interference-free value.

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