CHANNEL REPRESENTATIVE INTERFERENCE CANCELLATION (CRIC) FOR MIMO MULTI-HOP SYSTEMS IN THE MANHATTAN SCENARIO

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***Abstract* — The particular topology found in metropolitan areas can be exploited by employing relay nodes, which turn one-hop non-line-of-sight connections into multi-hop line-of-sight ones, thereby reducing the shadowing. However, this topology should also be considered to avoid multi-user interference and thus exploit the spatial resources optimally. Nevertheless, in most approaches which deal with this scenario, the interference is either completely neglected or estimated with strong simplifications.**

In this paper, we analyze the interference among users in a 4-way junction on the downlink and show that it should not be ignored. Based on this observation, we propose the *channel representative interference cancelation* (CRIC) scheme. The interference between users in the same street is suppressed by CDMA, whereas the one between users of different streets by the Successive Minimum Mean Square Error (SMMSE) precoder.

Due to the dimensionality restrictions given by SMMSE, we introduce a *channel representative*, which, serving as a virtual user, reflects the spatial features of all users in one street.

***Keywords**: MIMO Systems, Relays, Multi-User Interference, Urban Areas, Downlink*

1. INTRODUCTION

The Manhattan grid as specified in [1] is a common basis for simulations of wireless communications systems in urban environments. Many papers deal with the interference arising in this scenario. Most authors use simplified models due to the large computational complexity required in considering interference explicitly in the simulations. For example, the authors in [2] distinguish between areas with line of sight connection to an interfering base station and thus high interference and areas with minimal or no interference due to large shadowing effects of buildings in the Manhattan scenario. The areas are defined on a purely geometrical basis, taking neither reflections, diffraction nor other spatial effects into account. On the other hand, other schemes assume that the interference is so large that more resources than necessary are spent. For instance, in [3], a two-hop cell with four relay nodes (RNs) is investigated. On the first hop, the base station (BS) transmits the data to four RNs. These are placed as depicted in Fig. 1. The interference between the different RNs on the downlink is not considered further. Instead, the scheme proposed in [3] exclusively allocates time slots for each transmission to a RN. Estimating the interference here offers a high potential of saving resources, because the exclusive allocation of time slots is not necessary. Additionally, the authors in [3] focus on multi-user interference between users that are served from *different* RNs. Losses in capacity through multi-user interference between users in neighboring street canyons that are served by the *same* RN are not investigated. To the best of our knowledge, no complete interference analysis including all the intra-cell multi-user interference exists in the literature. For this analysis, the channels, incorporating shadowing and fading effects, the user grouping and routing, and the used spatial processing schemes have to be taken into account. In this contribution we show that the interference between users in different streets of a 4-way junction cannot be neglected. We develop a new method, the *Channel Representative Interference Cancellation* (CRIC), to spatially suppress multi-user interference.

After a detailed description of the test scenario, the user routing, and the user grouping in Section 2, we describe the CRIC and compare it to a scheme where the interference is neglected in Section 3. Section 4 shows the simulation results while, in Section 5, we draw the conclusions.

The authors gratefully acknowledge the partial support of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under contract no. HA 2239/1-2.

2. TEST SCENARIO, USER ROUTING, USER GROUPING

The scenario under investigation is a Manhattan grid as depicted in Fig. 1. Both BS (depicted through a dark green square) and RNs

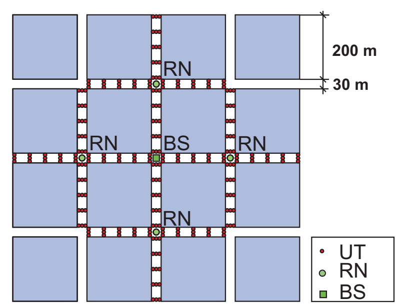

Fig. 1. The investigated Manhattan scenario. The red dots indicate the possible positions of the user terminals (UTs).

(displayed with light green circles) are under the rooftop and are placed in the street crossings. They are equipped with 8 directional antennas, which are arranged in four uniform linear arrays, one for every street. The user terminals (UTs) possess two antennas each. To obtain a realistic insight into the impact of multi-user interference in such a scenario, we consider several realizations of the users' positions. Each realization represents an independent operating condition and is characterized by 16 users located randomly on the grid of red dots shown in Fig. 1.

User Routing: On the downlink, the users are either served by the

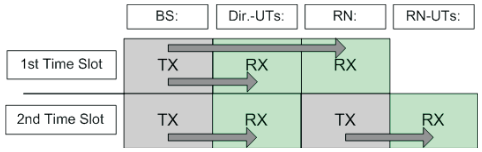

Fig. 2. Timing in the two-hop network. Dir.-UTs are users directly served by the BS where as RN-UTs are served by the RNs.

BS directly (Dir.-UTs) or via the RNs (RN-UTs). The data transmission is organized in two time slots (see Fig. 2). In the first time slot, the BS transmits data to the direct users and serves the RNs with the data for the remaining users. In the second time slot, the direct users are again served by the BS. Additionally, the RNs transmit the data to the indirect users. In this paper, we focus on the second time slot and investigate the interference arising when the UTs are served via RNs. The decision, whether a user is served directly or via one RN, is based on a singular value decomposition (SVD) of the channel matrices from every user to the RNs and the BS, namely $\boldsymbol{H}_{\mathrm{RN,UT}} \in \mathbb{C}^{2\times 8}$ and $\boldsymbol{H}_{\mathrm{BS,UT}} \in \mathbb{C}^{2\times 8}$, respectively

$$\begin{aligned} \boldsymbol{H}_{\mathrm{BS,UT}} &= \boldsymbol{U}_{\mathrm{BS,UT}}\, \boldsymbol{\Sigma}_{\mathrm{BS,UT}}\, \boldsymbol{V}^H_{\mathrm{BS,UT}} \\ \boldsymbol{H}_{\mathrm{RN,UT}} &= \boldsymbol{U}_{\mathrm{RN,UT}}\, \boldsymbol{\Sigma}_{\mathrm{RN,UT}}\, \boldsymbol{V}^H_{\mathrm{RN,UT}}. \end{aligned} \tag{1}$$

Since we focus on *dominant eigenmode transmission* [4], only the strongest eigenmode is considered for routing purposes. A user is routed to a RN instead of being routed directly to the BS, if the strongest singular value of $\boldsymbol{H}_{\mathrm{RN,UT}}$ is greater than the strongest singular value of the $\boldsymbol{H}_{\mathrm{BS,UT}}$. Notice that we do not consider the fact that every multi-hop system experiences throughput losses compared to a single-hop connection, which would require that routing to a RN includes an offset in the channel quality to balance these losses. This is neglected here as we want to assess the improvement due to interference suppression only.

User Grouping: In the CRIC scheme, the users that are served by one RN are divided into groups. The grouping is performed with respect to the urban topology, i.e., one group per street. Corresponding to the four street canyons that are served by one RN, four different groups are possible. The information, how the users are distributed in the four streets is again gained with a SVD of $\boldsymbol{H}_{\mathrm{RN,UT}}$. In this case, the 8 transmit antennas are subdivided into 4 antenna pairs, according to the four streets. The SVD is applied on each of these channel subsets. The users belong to the street for which the channel subset possess the strongest singular value. Within a group, the users are separated via CDMA. The code length is variable, dependent on the number of users per group. Perfect synchronization of the CDMA system is assumed.

3. SPATIAL PROCESSING

In the investigated scenario, transmitters and receivers are equipped with multiple antennas. These are used to separate user groups spatially and suppress multi-user interference. In the following, we introduce the *Channel Representative Interference Cancelation* method. In combination with SMMSE [5], this scheme suppresses the interference between users in different streets of a 4-way junction on the downlink. To demonstrate the necessity of an interference cancelation scheme, we define a technique which completely neglects the interference between streets.

In order to show the gains of the different schemes, based on our simulations, we compute the Interference-to-Signal-Ratio (ISR) for the different user positions. The interference power for all schemes is calculated as follows: let i and j be users in different streets and let further $\mathcal{K}_g$ denote the set of users in the same group of user j. The interference power I_j, experienced by user j, is equal to

$$I_j = \sum_i ||\boldsymbol{d}_j^T \boldsymbol{H}_{j,i} \boldsymbol{m}_i x_i||_2^2, \quad \forall i \neq j, \forall i \notin \mathcal{K}_g. \tag{2}$$

The data symbol x_i is precoded with a specific precoding vector $\boldsymbol{m}_i$ and is decoded with the decoding vector $\boldsymbol{d}_j$. The term $\boldsymbol{H}_{j,i}$ denotes the channel between the RN that serves the interfering user i and the interfered user j. Since we focus on interference between users that are served by the same RN, $\boldsymbol{H}_{j,i}$ is simply the channel from the serving RN to user j. In the general case of multiple data streams per user, the following approximation is often used

$$||\boldsymbol{D}_j^T \boldsymbol{H}_{j,i} \boldsymbol{M}_i \boldsymbol{x}_i||_2 \leq ||\boldsymbol{D}_j^T \boldsymbol{H}_{j,i} \boldsymbol{M}_i||_F ||\boldsymbol{x}_i||_2, \tag{3}$$

where the precoding and decoding vectors are now matrices. This can also be applied to the more specific case of *dominant eigenmode transmission*. In our data model we assume the norm of the data to be upper bounded by one. Hence, the interference power I_j is upper bounded by

$$I_j \leq \sum_{i=1}^{N} ||\boldsymbol{d}_j^T \boldsymbol{H}_{j,i} \boldsymbol{m}_i||_F^2 \quad \forall i \neq j, \forall i \notin \mathcal{K}_g. \tag{4}$$

The signal power S_j of user j is the power of its equivalent channel

$$S_j = ||\boldsymbol{d_j} \boldsymbol{H}_{j,j} \boldsymbol{m}_j||_F^2. \tag{5}$$

Therefore, the resulting ISR_j in percent for the j-th user is then

$$\mathrm{ISR}_j = \frac{I_j}{S_j} \cdot 100\,\%. \tag{6}$$

It is computed based on simulations at different positions in the scenario for the different schemes (see Section 4).

No Interference Suppression: If the interference between neighboring streets of one street crossing is neglected on the downlink, and perfect channel state information (CSI) at the transmitter and the receiver is assumed, the optimum strategy for each user is *dominant eigenmode transmission* [4]. This is referred to as the *no interference cancellation* scheme.

Channel Representative Interference Cancellation: If the interference between neighboring streets of one RN is taken into account, the different user groups have to be separated, e.g., spatially. Here, different spatial processing schemes are possible. We use SMMSE [5] as precoding scheme and minimum mean square error (MMSE) filtering as decoding scheme. SMMSE calculates the precoding matrix to separate users based on their channels. Due to dimensionality restrictions set by the SMMSE algorithm, not all users should be processed jointly. Therefore, we group the users in the same street of a crossing and then, for each group, calculate a channel representative. The latter, as a virtual user, reflects the channels of all users in the street canyon.

Let us now consider one group only, denoted by the index g, where the corresponding users are identified by the index $1 \leq k \leq K_g$, where K_g denotes the number of users in the group. The channels are normalized to unit power: $\bar{\boldsymbol{H}}_k = \frac{\boldsymbol{H}_k}{||\boldsymbol{H}_k||_F}$. The channel representative $\widehat{\boldsymbol{H}}_g$ is obtained from a linear combination of the users' channels. It is defined as

$$\begin{aligned} \widehat{\boldsymbol{H}}_g &= \frac{\max\limits_k\{||\boldsymbol{H}_k||_F\}}{||\widetilde{\boldsymbol{H}}_g||_F} \widetilde{\boldsymbol{H}}_g \\ \widetilde{\boldsymbol{H}}_g &= \sum_{k=1}^{K_g} \boldsymbol{w}_g(k) \cdot \bar{\boldsymbol{H}}_k, \end{aligned} \tag{7}$$

where $\boldsymbol{w}_g(k)$ is the k-th element of the weighting vector $\boldsymbol{w}_g \in \mathbb{R}^{K_g \times 1}$. The latter is chosen depending on the goals that have to be achieved. In our case, we want to balance and, at the same time, maximize the Quality of Service (QoS) for all users. In other words, on one hand, the SIR for all users under a maximum power constraint should be maximized; on the other, due to fairness reasons, the SIR should be almost equal for all users.

To efficiently estimate the individual SIR, we write the k-th user's channel as a sum of two terms, namely $\boldsymbol{H}_{k_{||}}$ and $\boldsymbol{H}_{k_\perp}$. They are obtained by projecting the k-th user's normalized channel $\bar{\boldsymbol{H}}_k$ into the signal and null space of $\widehat{\boldsymbol{H}}_g$, respectively. The signal subspace is the row space of the channel representative, whereas the null space is its orthogonal complement. While $\boldsymbol{H}_{k_\perp}$ carries mostly interference, $\boldsymbol{H}_{k_{||}}$ carries the useful signal. Therefore, we approximate the SIR of user k as $||\boldsymbol{H}_{k_{||}}||_F^2 / ||\boldsymbol{H}_{k_\perp}||_F^2$.

We can now define the following cost function

$$J(\boldsymbol{w}) = \sum_{i=1}^{K_g} \frac{||\bar{\boldsymbol{H}}_{k_\perp}(\boldsymbol{w})||_F^2}{\left|\left|\bar{\boldsymbol{H}}_{k_{||}}(\boldsymbol{w})\right|\right|_F^2} + c\left(\max_i \left\{ \frac{||\bar{\boldsymbol{H}}_{i_\perp}(\boldsymbol{w})||_F^2}{\left|\left|\bar{\boldsymbol{H}}_{i_{||}}(\boldsymbol{w})\right|\right|_F^2} \right\} - \min_i \left\{ \frac{||\bar{\boldsymbol{H}}_{i_\perp}(\boldsymbol{w})||_F^2}{\left|\left|\bar{\boldsymbol{H}}_{i_{||}}(\boldsymbol{w})\right|\right|_F^2} \right\}\right). \quad (8)$$

The first term of $J(\boldsymbol{w})$ accounts for the sum of the SIR's while the second reflects the fairness of the solution, i.e., how the QoS is balanced among users.

By minimizing equation (8) and by setting the scalar c to a constant which normalizes the different ranges of the two terms, we obtain a weighting vector $\boldsymbol{w} = \boldsymbol{w}_{\text{fair}}$

$$\boldsymbol{w}_{\text{fair}} = \arg\min_{\boldsymbol{w}} J(\boldsymbol{w}). \quad (9)$$

This solution represents the trade-off between maximizing and balancing the SIR for all users. We refer to it as *SIR fairness*.

If we neglect any fairness constraint and we want to maximize the sum SIR only, we set $c = 0$ and solve a minimization problem similar to the one given in (9). The resulting weight vector $\boldsymbol{w}_{\max}$ corresponds to the solution which we refer to as *SIR maximizing*.

Unfortunately, there is no closed form solution for the problem in (9). Therefore, a numerical optimization method is required such as using the Hessian or Jacobian of the cost function or the method of steepest descent. Without loss of generality, we can define two additional constraints

$$\boldsymbol{w}_g(k) \geq 0 \quad \forall \ k \in \{1, 2, \ldots K_g\} \ \text{ and } \ \sum_{k=1}^{K_g} \boldsymbol{w}_g(k) = 1. \quad (10)$$

As a comparison for our approach we choose a channel averaging method based on [6]. This method, which we refer to as *correlation based interference cancelation*, consists of building the channel representative $\widehat{\boldsymbol{H}}_g$, for the g-th group, from the correlation matrix $\boldsymbol{R}_g$ via the following eigenvalue decomposition

$$\begin{aligned} \boldsymbol{R}_g &= \sum_{k=1}^{K_g} \boldsymbol{H}_k^H \boldsymbol{H}_k = \boldsymbol{V}_g \boldsymbol{\Lambda}_g \boldsymbol{V}_g^H \\ \widetilde{\boldsymbol{H}}_g &= \boldsymbol{V}_g^H; \ \widehat{\boldsymbol{H}}_g = \frac{\max_k\{||\boldsymbol{H}_k||_F\}}{||\widetilde{\boldsymbol{H}}_g||_F} \widetilde{\boldsymbol{H}}_g, \end{aligned} \quad (11)$$

Notice that the channel representatives obtained via the three methods differ only in the signal subspace, as their power is normalized to the one of the strongest user's channel.

As already mentioned, SMMSE is used to separate the different user groups so that the precoding matrix for the RNs in the second time slot is calculated based on the channel representatives. Notice that the users in the same street canyon are served with the same precoding vector, and that at most, four different precoding vectors exist, one for every street of the 4-way junction. The MMSE filtering at the receiving UT is not calculated based on the channel representative but on the actual channel between the RN and the UTs, thus assuming perfect CSI at the receiver. Moreover, we apply *dominant eigenmode transmission*. The interference that each UT experiences is calculated according to (4).

4. SIMULATION RESULTS

In this section, we assess the interference-to-signal-ratio (ISR) as defined in (6) at the user positions depicted in Fig. 1, averaged over 20 channel realizations per user position. The BS and the four RNs are equipped with 8 antennas each, whereas the UTs possess two antennas. We use the B1 WINNER channel model for the metropolitan area, as described in [7]. As transmit antennas, we use directional antennas with a front-to-back ratio of 12 dB. The interference is calculated according to (4). The following four schemes are compared: the CRIC *SIR maximizing* scheme, where the channel representative is calculated based on (8) with $c = 0$, the CRIC *SIR fairness* scheme, where c is used to normalize the different ranges of the two terms of (8), the non iterative *correlation based interference cancellation*, with the channel representative computed with the help of (11), and the *no interference cancellation*, where interference is neglected. The latter two schemes serve as a comparison to show the improvements brought by the proposed method. For the two CRIC cost functions, we choose an iterative optimization based on the Hessian of the cost function and as a starting point, an equal weighting of the channel matrices. Fig. 3 shows the cumulative distribution function (CDF) of the average interference percentages for the different user positions. In order to characterize the performance of the algorithms in a compact way, in addition to the curves, we introduce two measures: the median interference m and the minimum QoS interference $I_{90\%}$. The first is the largest average interference experienced by the best 50 % of the users. The median is a better indicator than the mean in case of non-symmetric distributions. For the second measure, $I_{90\%}$, we focus our attention on a minimum QoS that can be achieved. We define a *minimum satisfied user criterion* when 90 % of the users achieve the desired QoS. We then take the largest value of the average interference experienced by the best 90 % of the users. These measures are listed in Table 1 for the different schemes. In the case of the *no interference cancellation scheme*, represented by the chain dotted green line in Fig. 3, it can be seen that most of the users experience interference. This is also represented by a m of 1.39 % and a high $I_{90\%}$ of 4.74 %. The values for the median interference are reduced for all schemes which take the interference into account and suppress it with the help of a channel representative. In the case of the non iterative *correlation based interference*

	NoIntCan	CorrBased	SIRmax	SIRfair
m [%]	1.39	0.62	0.33	0.29
$I_{90\%}$ [%]	4.74	6.85	3.04	2.66

Table 1. Average interference-to-signal-ratio for 50 % of the users (m) and 90 % of the users ($I_{90\%}$).

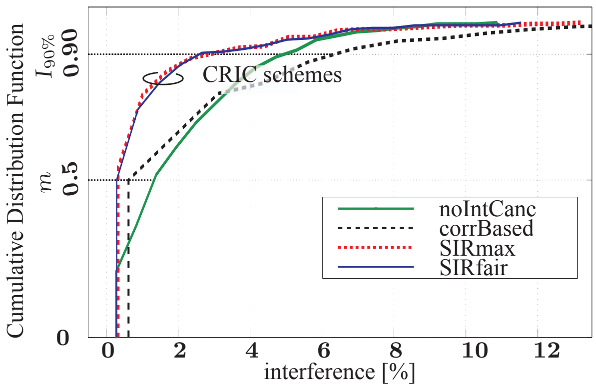

Fig. 3. CDF of the average interference percentage considering the different user positions for different spatial processing schemes; the interference cancellation schemes (SIRmax, SIRfair) achieve a better Interference-to-signal-ratio then the non iterative scheme (corrBased) and the scheme without cancellation at all (noIntCanc).

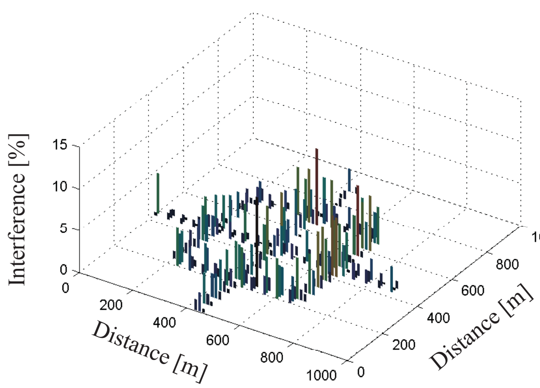

Fig. 4. Average interference-to-signal-ratios in % for different user positions in the Manhattan grid without interference cancellation.

cancellation (dashed black line), m lies at 0.62 %, so that normally the users experience negligible average interference, however $I_{90\%}$ with at most 6.85 % is extremely high and the difference to m is very large which indicates that this scheme is quite unfair with respect to the *minimum satisfied user criterion*. For the two iterative CRIC schemes, besides very low values for the median (0.33 % and 0.29 %), $I_{90\%}$ achieves remarkable improvements compared to the *no interference cancellation scheme*. In the case of the *SIR fairness* method (blue solid line), the value for the maximum average interference which 90 % of the users suffer from is, with 2.66 %, slightly better than in the case of pure *SIR maximization* (red dotted curve) with 3.04 %. To show the influence that the CRIC approach has, the average interference percentage is plotted for the different user positions without (Fig. 4) and with CRIC (Fig. 5).

5. CONCLUSIONS

In this paper, we investigate the multi-user interference between users in different streets of a 4-way junction in a Manhattan grid. It is shown that the interference, although often assumed to be negligible, indeed plays a role and should be considered when managing the spatial resources available. Based on this observation, the users in one street of a 4-way junction are grouped to take advantage of the specific topology of the Manhattan grid. In order to spatially separate these user groups via SMMSE, a new iterative approach, the *channel representative interference cancellation* (CRIC) is presented. It calculates a channel representative which maps all users in a group onto one virtual user. This is performed iteratively with and without taking fairness criteria into account. Simulations based on synthetic MIMO channels for different user positions show that the new approach significantly reduces the multi-user interference between the different user groups while taking advantage of the specific structure offered by the urban scenario. This is contrary to known approaches which either estimate the interference with strong simplifications or do not take the specific conditions in the urban environment into account.

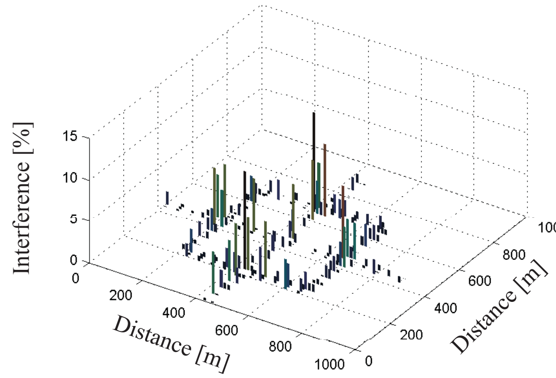

Fig. 5. Average interference-to-signal-ratios in % for different user positions in the Manhattan grid with *SIR fairness* CRIC.

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