DEGREES OF FREEDOM OF DOWNLINK SINGLE- AND MULTI-CELL MULTI-USER MIMO SYSTEMS WITH LOCATION BASED CSIT

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ABSTRACT

Multiple antennas facilitate the coexistence of multiple users in wireless communications, leading to spatial multiplexing and spatial division and to significant system capacity increase. However, this comes at the cost of very precise channel state information at the transmitters (CSIT). We advocate the use of channel propagation models to transform location information into (possibly incomplete) CSIT. We investigate the resulting multi-user sum rate from a DoF (Degree of Freedom, high SNR rate prelog, spatial multiplexing factor) point of view. For single-cell multi-user communications, we argue for a revival of SDMA (Spatial Division Multiple Access). In the MIMO case, the receive antennas can suppress the Non Line of Sight (NLoS) channel components to transform the MIMO channel into a MISO LoS channel, allowing the CSIT to be limited to LoS information. For the multi-cell problem, we consider the feasibility of interference aligment in the case of reduced rank MIMO channels. We then focus on the LoS components. Whereas in general MIMO multi-cell coordinated beamforming, the transmitters require global CSIT due to the coupling between transmit and receive filters, in the LoS case decoupling arises, permitting location based transmit beamforming. Location aided techniques may furthermore exploit location prediction through mobility trajectory information. This would allow slow fading (and even connectivity) predictibility, something that is difficult to achieve without location information.

Index Terms— Wireless communications, location, SDMA, MIMO, multi-user, multi-cell.

I. INTRODUCTION

In TDD single-cell systems, channel reciprocity can turn CSIR (Receiver) into CSIT. In multi-cell systems however, TDD reciprocity is of limited interest as it only leads to only local CSIT. In FDD systems, CSIT needs to be acquired by feedback, which increases with the MIMO, multi-cell and Doppler dimensions. The problem is compounded when taking furthermore user selection into account.

Wireless network based localization offers an alternative and/or complement to GNSS based localization. Satellite connectivity may pose problems in urban canyons and indoor, and not all mobile terminals (MTs) are GNSS equipped. Wireless network based localization is now part of LTE-A, based on the following techniques: Enhanced Cell Id = Cell Id + RSS (Received Signal Strength), O-TDoA (Observed Time Difference of Arrival), and AoA (Angle of Arrival at the base station (BS)).

The availability of location information offers in turn opportunities to enhance the wireless communications. The position based information that can be exploited comprises slow fading channel characteristics of various links:

- LOS/NLOS ((Non) Line of Sight)
- attenuation
- delay spread, frequency selectivity
- angular spreads, MIMO channel characteristics (rank)
- speed, direction of movement, acceleration (predictibility of movement), trajectory

Some of these aspects may require the use of databases (containing these characteristics as a function of position), compatible with a cognitive radio setting. Compared to feedback (FB) based approaches: some of these characteristics can not easily be determined from isolated channel estimates, or not predicted at all (e.g. slow fading prediction). What can not be inferred on the basis of position (as generally believed) is the fast fading state, the instantaneous complex channel impulse response. In what follows, we consider a number of problem formulations in which fast fading state information can essentially be avoided. In this paper, Tx may denote transmit/transmitter/transmission and Rx may denote receive/receiver/reception.

II. PROPAGATION CHANNEL MODEL

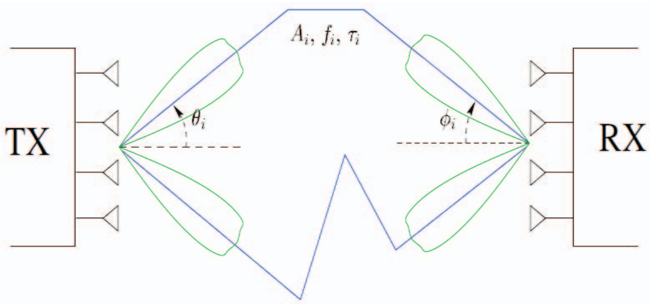

Fig. 1. MIMO transmission with M transmit and N receive antennas.

II-A. Specular Wireless MIMO Channel Model

Consider a MIMO transmission configuration as depicted in Fig. 1. We get for the matrix impulse response of the time-varying

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channel $\mathbf{h}(t,\tau)$ [1]

$$\mathbf{h}(t,\tau) = \sum_{i=1}^{N_p} A_i(t)\, e^{j2\pi\, f_i\, t}\, \mathbf{h}_r(\phi_i)\, \mathbf{h}_t^T(\theta_i)\, p(\tau-\tau_i) \ . \qquad (1)$$

The channel impulse response $\mathbf{h}$ has per path a rank 1 contribution in 4 dimensions (Tx and Rx spatial multi-antenna dimensions, delay spread and Doppler spread); there are N_p pathwise contributions where

- A_i: complex attenuation
- f_i: Doppler shift
- θ_i: direction of departure (AoD)
- ϕ_i: direction of arrival (AoA)
- τ_i: path delay (ToA)
- $\mathbf{h}_t(.)$, $\mathbf{h}_r(.)$: $M/N \times 1$ Tx/Rx antenna array response
- $p(.)$: pulse shape (Tx filter)

The fast variation of the phase in $e^{j2\pi\, f_i\, t}$ and possibly the variation of the A_i (when the nominal path represents in fact a superposition of paths with similar parameters) correspond to the fast fading. All the other parameters (including the Doppler frequency) vary on a slower time scale and correspond to slow fading. We shall assume here OFDM transmission, as is typical for 4G systems, with the Doppler variation over the OFDM symbol duration being negligible. We then get for the channel transfer matrix at any particular subcarrier of a given OFDM symbol

$$\mathbf{H} = \sum_{i=1}^{N_p} A_i\, \mathbf{h}_r(\phi_i)\, \mathbf{h}_t^T(\theta_i) \qquad (2)$$

where with some abuse of notation we use the same complex amplitude A_i in which we ignored the dependence on time (particular OFDM symbol), through at least the Doppler shift, and on frequency (subcarrier), through the Tx (and Rx) filter(s).

II-B. Narrow AoD Aperture (NADA) case

The idea here is to focus on the category of mobiles for which the angular spread seen from the BS is limited [2]. This is a small generalization of the LoS case. In the NADA case, the MIMO channel $\mathbf{H}$ is of the form

$$\mathbf{H} = \sum_i A_i\, \mathbf{h}_r(\phi_i)\mathbf{h}_t^T(\theta_i) \approx \mathbf{B}\ \mathbf{A}\ , \quad \mathbf{A} = \Big[\mathbf{h}_t(\theta)\ \dot{\mathbf{h}}_t(\theta)\Big]^T \ . \qquad (3)$$

In the case of narrow AoD spread, we have

$$\theta_i = \theta + \Delta\theta_i \qquad (4)$$

where θ is the nominal (LoS) AoD and $\Delta\theta_i$ is small. Hence

$$\mathbf{h}_t(\theta_i) \approx \mathbf{h}_t(\theta) + \Delta\theta_i\, \dot{\mathbf{h}}_t(\theta)\ . \qquad (5)$$

This leads to the second equality in (3). Hence $\mathbf{H}$ is of rank 2 (regardless of the AoA spread). The LOS case is a limiting case in which the power of the $\dot{\mathbf{h}}_t(\theta)$ term becomes negligible and the channel rank becomes 1. The factor $\mathbf{A}$ in $\mathbf{H}$ depends straightforwardly on position (which translates into LOS AoD), only $\mathbf{B}$ (which depends on the $A_i\, \mathbf{h}_r(\phi_i)$ and the $\Delta\theta_i$) remains random.

III. LOCATION AIDED MULTI-USER RESOURCE ALLOCATION

Some possibilities are:

- *Multi-user MIMO* (MU MIMO): Use environment information to preselect users, to limit channel feedback to a reduced set of preselected users. The user preselection can e.g. involve: users with similar attenuation, users with rank 1 MIMO channels (close to LOS), ... MU-MIMO is in the context of a single cell, and the DL problem is referred to in information theory as the Broadcast Channel (BC).
- *Multicell aspects* (interference coordination) or for *Cognitive Radio* (interference from secondary to primary systems): the interference level can be predicted from position information. The multi-cell DL problem is referred to in Information Theory as the Interference Channel (IC). In the IC, each Tx has a signal at the intention of one corresponding Rx, in contrast to the Network MIMO (NW MIMO) or Coordinated Multi-Point (CoMP) in which all Txs possess the signals at the intention of all the Rxs. Hence NW MIMO is a form of MU MIMO with distributed Txs. The use of linear Txs in MIMO/MISO IC is also referred to as Coordinated Beamforming (BF).

A transversal aspect is also that location tracking can lead to location prediction. This leads in turn to slow fading predictibility (and not just fast fading prediction, which can in principle be done also from past channel response estimates). Another aspect is that user selection (multi-user diversity) potentially leads to an explosion of CSIT requirements and associated overhead. Location based covariance CSIT might offer a (partial) solution.

IV. SINGLE-CELL MULTI-USER COMMUNICATIONS

In this section, we shall focus on the Spatial Division Multiple Access (SDMA) problem, which in Information Theory is called the Broadcast Channel (BC). The SDMA terminology dates from the early nineties. These days it is referred to as the multi-user MISO (or MIMO) communications problem, and we shall particularly focus on the more difficult downlink.

IV-A. SDMA considerations

Whereas single user (SU) MIMO communications represented a big breakthrough and are now integrated in a number of wireless communication standards, the next improvement is indeed multi-user MIMO (MU MIMO). This topic is nontrivial as e.g. illustrated by the fact that 3gpp had a lot of difficulty to get it included in the LTE standard. MU MIMO is a further evolution of SDMA, which was THE hot wireless topic in the early nineties. The MU MIMO area has now sufficiently evolved to allow us to understand the following key elements:

- SDMA is a suboptimal approach to MU MIMO, with transmitter precoding limited to linear beamforming, whereas optimal MU MIMO requires Dirty Paper Coding (DPC).
- Channel feedback (FB) has gained much more acceptance, leading to good CSIT, a crucial enabler for MU MIMO, whereas SDMA was either limited to TDD systems (channel CSIT through reciprocity) or Covariance CSIT. In the early nineties, the only feedback that existed was for slow power control.
- Since SDMA, the concepts of multiuser diversity and user selection have emerged and their impact on the MU MIMO

sum rate is now well understood. Furthermore, it is now known that user scheduling allows much simpler precoding schemes (such as Zero-Forcing (ZF) beamforming (BF)) to be close to optimal.
- Whereas SU MIMO allows to multiply transmission rate by the spatial multiplexing factor, when mobile terminals have multiple antennas, MU MIMO allows to reach this same gain with single antenna terminals.
- Whereas in SU MIMO, various degrees of CSIT only lead to a variation in coding gain (the constant term in the sum rate), in MU MIMO however CSIT affects the spatial multiplexing factor (multiplying the log(SNR) term in the sum rate).

In the process attempting to integrate MU-MIMO into the LTE-A standard, a number of LTE-A contributors had at some point become quite sceptical about the usefulness of the available MU-MIMO proposals. The issue is that they consider MU-MIMO in the same spirit as SU-MIMO, i.e. with FB of CSI limited to just a few bits! However, MU-MIMO requires very good CSIT! Some possible solutions are:

- Increase CSI FB enormously (possibly using analog transmission); LTE-A went recently a bit in this direction.
- Exploit channel reciprocity in TDD (there may be an electronics calibration issue though [3]).
- Limit MU-MIMO (SDMA) to NADA users and extract essential CSIT from position information (or from DoA estimates - in both cases the knowledge of the antenna array manifold is (eventually) required).

IV-B. Location Based SDMA

The MISO case was treated in [4], where we proposed that location based MU MIMO transmission involve position based user selection (attenuation, nominal AoD, AoD spread) and associated beamforming (BF) and power control (PC). For the location aided MISO case, we need to essentially consider users with LoS channels. The effect of location error or of weak multipath on the resulting sum rate was also investigated.

In the MIMO BC case, the multiple Rx antennas at the MTs cannot help to augment the totale number of streams, which are limited by the number of BS antennas. They allow to vary the number of streams per user though and thus to combine SU MIMO with MU MIMO. In the case of partial CSIT (as in LTE-A), it may seem beneficial to augment the number of streams per user. This is because in comparison the CSIR can be considered as as good as perfect (semi-blind channel estimation can be performed at the Rx). This means that at least the interference due to CSIT imperfections coming from other streams of the same user can be handled by the Rx, in effect reducing the number of undecoded interfering streams. Ignoring CSIT imperfections, on the basis of diversity considerations it may be beneficial to have some MIMO aspect per user (to distribute the ZF/MMSE task between Tx and Rx) in case of a rich channel model [5], whereas in the perhaps more realistic case of poorer multipath a single stream per user is to be preferred [6]. The effect of user selection may play a role also. In the context of location aided, we shall consider good but incomplete CSIT. As a result, it may be beneficial to focus on the case of a single stream per user.

IV-C. MIMO BC with Incomplete CSIT

The concept of incomplete CSIT was considered in [7] for the MIMO IC with a single stream per link. What is shown in [7] is that in the MIMO IC case, ZF may be possible with less than global CSIT. However, this only occurs for cases of very non-uniform antenna numbers over the Txs and Rxs. Incomplete CSIT differs from partial CSIT, which usually means that the Tx has a noisy (possibly quantized) version of the channel. In incomplete CSIT, the knowledge is (close to) perfect, but only of part of the channel (with the rest being unknown).

Consider MIMO BC with a single stream per user. We shall show that it is sufficient for ZF BF (and hence for DoF) that the BS knows for each user a vector in the row span of its MIMO channel. Let $\mathbf{H}_k$ be the $N \times M$ MIMO channel of user k and let $\mathbf{c}_k\mathbf{H}_k$ be the equivalent MISO channel that the BS is aware of for user k, where $\mathbf{c}_k$ is a $1 \times N$ vector (the number of receive antennas can vary with user but we shall keep the notation as N). For ZF BF, the BS shall use for user k a spatial filter $\mathbf{g}_k$ such that

$$\mathbf{g}_k^H = \mathbf{c}_k\mathbf{H}_k P^{\perp}_{(\mathbf{cH})_{\overline{k}}} / ||\mathbf{c}_k\mathbf{H}_k P^{\perp}_{(\mathbf{cH})_{\overline{k}}}|| \tag{6}$$

where $P^{\perp}_{\mathbf{X}} = I - P_{\mathbf{X}}$ and $P_{\mathbf{X}} = \mathbf{X}^H(\mathbf{X}\mathbf{X}^H)^{-1}\mathbf{X}$ are projection matrices and $(\mathbf{cH})_{\overline{k}}$ denotes the stacking of $\mathbf{c}_i\mathbf{H}_i$ for users $i = 1, \ldots, M$, $i \neq k$. The $N \times 1$ received signal at user k is

$$\mathbf{y}_k = \mathbf{H}_k\,\mathbf{g}_k\,x_k + \sum_{i=1,\neq k}^{M} \mathbf{H}_k\,\mathbf{g}_i\,x_i + \mathbf{v}_k \tag{7}$$

where x_i is the signal intended for user i, and $\mathbf{v}_k$ is additive noise. For the reception, user k shall use a linear filter $\mathbf{f}_k$ with corresponding Signal-to-Interference Ratio (SIR) (for ZF and DoF considerations)

$$\mathrm{SIR}_k = \frac{|\mathbf{f}_k\mathbf{H}_k\mathbf{g}_k|^2\sigma_k^2}{\sum_{i=1,\neq k}^{M}|\mathbf{f}_k\mathbf{H}_k\mathbf{g}_i|^2\sigma_i^2} \tag{8}$$

where σ_i^2 is the power of x_i. Maximizing SIR_k w.r.t. $\mathbf{f}_k$ leads to $\mathbf{f}_k \sim \mathbf{c}_k$ if $\mathbf{H}_k$ is full row rank (and to $\mathbf{f}_k\mathbf{H}_k \sim \mathbf{c}_k\mathbf{H}_k$ otherwise) with maximum SIR

$$\max_{\mathbf{f}_k} \mathrm{SIR}_k = \mathrm{SIR}_k(\mathbf{f}_k = \mathbf{c}_k) = \infty \tag{9}$$

since the interference power becomes zero. This leads to:

Theorem 1: **Sufficiency of Incomplete CSIT for Full DoF in MIMO BC** In the MIMO BC with perfect CSIR, it is sufficient that the BS knows for each of the K users any vector in the row space of its MIMO channel (as long as the resulting vectors are linearly independent) in order for ZF BF to produce $\min(M, K)$ DoF.

IV-D. Location Based MU-MIMO

Consider now a propagation channel model as in (2), combined with the NADA model, in which a cluster of paths contributes the equivalent of two paths. Counting paths in this way, assume that the total number $N_p{}'$ of equivalent paths satisfies $N_p{}' \leq N$ (again, the number of Rx antennas could be variable with user but we shall omit this notation).

Assume one of the paths is the LoS path which is known by the BS (location aided). The situation that arises now is similar to chip equalization in the 3G downlink: due to the synchronicity of the downlink, 3G systems use CDMA with orthogonal codes such that a simple correlator at the Rx would suffice to suppress all intracell interference. This ideal scenario is perturbed by the multipath propagation channel whose frequency-selectivity perturbs the orthogonality of the spreading codes. However, since in the downlink from the BS to a particular user all intracell signals pass through the same channel of that user, it suffices for the user to equalize that channel to restore the code orthogonality and to allow a correlator to suppress the interference. In SDMA, the temporal spreading of CDMA is replaced by spatial filtering at the BS. This spatial filtering $\mathbf{g}_k$ is based on the hypothesis of a LoS channel. Hence, for the reception at the user through the LoS path, all interference will be supressed. But the interference arrives at the user through the multipath components. However, regardless of the beamforming employed at the BS, all interference received by user k passes through the same multipath components of the channel of that user. Now, if ${N_p}' \leq N$, the user can employ Rx spatial filtering $\mathbf{f}_k$ to suppress all paths, except for the LoS path, so that $\mathbf{f}_k\mathbf{H}_k$ only contains the LoS path. Combined with the LoS based BF $\mathbf{g}_k$ design, this allows to suppress all interference and hence to produce full DoF.

For the previous reasoning to work, it would have been sufficient (in terms of DoF) that the Bs knows any vector in the row space of $\mathbf{H}_k$, but clearly the LoS path is typically much stronger than the other paths. Hence the knowledge of the LoS path leads to better performance at finite SNR. When there is no LoS path, it suffices to use another path, preferably the strongest path. Whereas the LoS path can be computed on the basis of only the user position (and a calibrated antenna array), in case another (and hence single- or multi-bounce) path needs to be used, this will typically require a database containing the information of the AoD of the strongest path, as a function of the position of the user.

When ${N_p}' > N$, there is no guarantee that the LOS Tx antenna array response lies in the row space of the MIMO channel matrix.

Related work appears in [8], [9] where a not so rich propagation environment leads to subspaces (slow CSIT) for the channel vectors so that the fast CSIT can be reduced to the smaller dimension of the subspace.

A further evolution would be to consider *mixed CSIT* [10], in which NADA users with location based CSIT get mixed with other users which have FB based CSIT.

V. MIMO INTERFERENCE CHANNEL (IC)

V-A. IA feasibility singular MIMO IC

This subject was treated by [11] for the general $K = 2$ user case and for certain symmetric cases with $K = 3$. Related work also appears in [12] where for the case of no relay (as considered here) only some bounds were provided.

Interference Alignment (IA) is joint Tx/Rx ZF BF and allows to attain the correct DoF in an IC. For d_k streams of user k, a $M_k \times d_k$ Tx filter $\mathbf{G}_k$ and a $d_k \times N_k$ Rx filter $\mathbf{F}_k$ is used. In the rank deficient case, if $0 \leq r_{ik} \leq \min(N_i, M_k)$ denotes the rank of MIMO channel $\mathbf{H}_{ik}$ then we can factor $\mathbf{H}_{ik} = \mathbf{B}_{ik}\mathbf{A}_{ik}$ for some full rank $N_i \times r_{ik}$ $\mathbf{B}_{ik}$ and $r_{ik} \times M_k$ $\mathbf{A}_{ik}$. The ZF from BS k to MT i requires

$$\mathbf{F}_i\mathbf{H}_{ik}\mathbf{G}_k = \mathbf{F}_i\mathbf{B}_{ik}\mathbf{A}_{ik}\mathbf{G}_k = 0 \tag{10}$$

which involves $\min(d_id_k, d_ir_{ik}, r_{ik}d_k)$ constraints to be satisfied by the $(N_i - d_i)d_i/(M_k - d_k)d_k$ variables parameterizing the row/column subspaces of $\mathbf{F}_i/\mathbf{G}_k$. The overall IA feasibility gets determined by verifying whether the system is proper [7]: for each subset of MTs and subset of BSs, the total number of Tx/Rx variables involved needs to be at least equal to the total number of constraints in the corresponding conditions (10). When the rank constraints are active (number of constraints involves r_{ik}), counting the # of variables vs. the # of ZF constraints gives the complete answer since we have traditional (one-sided) Tx or Rx ZF ($\mathbf{F}_i\mathbf{B}_{ik} = 0$ or $\mathbf{A}_{ik}\mathbf{G}_k = 0$). When the rank constraints are not active (min attained for d_id_k) then counting arguments may not be sufficient in very rectangular (non-square) MIMO channel cases [13], [14]. Note also that the full rank requirement on $\mathbf{F}_k\mathbf{H}_{kk}\mathbf{G}_k$ leads to $1 \leq d_k \leq r_{kk} \leq \min(N_k, M_k)$ (the first inequality reflects that we consider only active links).

Consider now some examples that were also considered in [11]. In the full rank case with K links of $N \times M$, we have that $d_k = \frac{M+N}{K+1}$ is feasible in the not too rectangular case. In the uniform singular $K = 2$ case with $(M, N, r)^2$, $d = \min(r, \dfrac{M+N-r}{2})$ is possible (with $d_1 = d_2 = d$). For the uniform square $K = 3$ case $(M, M, r)^3$, $d = \min(r, M/2)$ is feasible. Still in the $K = 3$, $M \times M$ case with

$$r_{ik} = \begin{cases} r_0 & , i = k \\ r_1 & , i > k \\ r_2 & , i < k \end{cases} \tag{11}$$

we get $d = \min(r_0, M - \dfrac{\min(M, r_1 + r_2)}{2})$.

V-B. IA feasibility singular MIMO IC with Tx/Rx decoupling

In this case we shall insist that (10) be satisfied by

$$\mathbf{F}_i\mathbf{B}_{ik} = 0 \text{ or } \mathbf{A}_{ik}\mathbf{G}_k = 0\ . \tag{12}$$

This leads to a possibly increased number of ZF constraints $r_{ik}\min(d_i, d_k)$ and hence to possibly reduced IA feasibility. Of course, the task of ZF of every cross link now needs to be partitioned between all Txs and Rxs, taking into account the limited number of variables each Tx or Rx has. The main goal of this approach however is that it leads to Tx/Rx decoupling. Whereas in the general case (10) the design of the Txs depends on the Rxs and vice versa, in (12) the ZF constraints are linear and involve Tx or Rx but not both. The ZF constraints for a Tx (or a Rx) only require local channel knowledge (of the channel connected to it). Of course, the gobal ZF task partitioning needs to be known. This leads to a category of IA feasibility with incomplete CSIT, different from the one appearing in [7] as described earlier.

In the uniform case $(M, N, r)^K$ with $d \leq r$ per user, (12) leads to

$$d \leq \frac{1}{2}(M + N - (K-1)r) \tag{13}$$

whereas the general coupled case (10) would have led to $d \leq \frac{1}{2}(M + N - (K-1)d)$. There is no loss if $d = r$, in which case $d = r \leq \frac{M+N}{K+1}$.

In the case of general rank distribution but with a single stream per user ($d_k \equiv 1$), we get

$$\sum_{i=1}^{K}(M_k + N_k) \geq 2K + \sum_{i \neq k} r_{ik}\ . \tag{14}$$

The non-decoupled case would correspond to replacing all the r_{ik} in (14) by 1.

V-C. LoS Case

In what follows, we shall focus on the LoS limit for considerations of location based processing. This is a special case of (13) with $d = r = 1$ and leads to the requirement

$$M + N \geq K + 1 \qquad (15)$$

for IA feasibility with a single stream per user. In the MISO or SIMO cases this becomes $M \geq K$ or $N \geq K$. The meaning of (15) is: $(M-1)+(N-1) \geq K-1$: that each BS performs ZF towards $M-1$ MTs. As a result, each MT still receives interference from $(K-1)-(M-1)$ cross links but with its N antennas it can ZF $N-1$ streams.

In the decoupled approach, the design of any Tx G_k only depends on the factors A_{ik} of the channels connected to it and in general even only on a subset of this local CSIT (e.g. in the LoS case, only $M-1$ cross link A_{ik} are required to be known for any given BS). In the LoS case, the A_{ik} are clearly only a function of the positions of the BS and MTs (and the BS antenna array response).

One can go somewhat beyond the LoS case by considering (LoS) NADA and other multipath components. The number of components (and hence the r_{ik}) to be considered could vary with the cross links. An issue that arises here is that different cross links may have multipath components with the same AoD from a certain BS, because the paths may bounce on the same scatterer. In this case the multiple paths get ZF'd simultaneously, leading to a reduction in required Tx antennas.

VI. FURTHER DIRECTIONS

See [15] for location aided Tx/Rx design with partial CSIT. The location aided BF can be extended to 2D antenna arrays for BF in 3D. The antenna array calibration can also be made location aided. In the time domain, another interesting recent development appears in [16] where blind ZF is proposed, interweaving Power Delay (Doppler) Profile (PDP/PDDP) polyphase components. The exploitation of different user Doppler spectrum supports (different Doppler shifts/spreads) has already been exploited in certain forms of blind IA (BIA), see e.g. [17].

Location based LoS array responses which determine the LoS channel up to a scalar are sufficient for BC or IC, but the construction of beamformers for Network MIMO or CoMP would still require the feedback of these scalars. Finally, whereas LoS/NADA models may be appropriate for macrocells in many environments, the development of small cells may pose a problem for the ideas presented here.

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