LOCATION AIDED WIRELESS COMMUNICATIONS

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ABSTRACT

The availability of location information of mobile terminals, relays, femto cells and primary units provides opportunities to greatly enhance the operation of wireless communication systems. We provide an overview of some of the possibilities, starting with physical layer considerations for a single link. However, most of the opportunities concern resource allocation aspects. Especially for multi-user systems, for which recent information theory progress has shown that an optimized handling may lead to significant system capacity increase. But the optimization of multi-user systems requires very precise Channel State Information at the Transmitter (CSIT). The problem is compounded when taking furthermore user selection into account. CSIT is typically obtained by feedback (FB), which leads to transmission overhead. Channel reciprocity based TDD systems only represent a limited alternative in multi-cell settings, or for user selection. For single-cell multi-user communications, we argue for a revival of SDMA (Spatial Division Multiple Access). We then consider the multi-cell problem, and cognitive radio. Some (but not all) of the location aided techniques require substantial databases, which have come into vogue in the context of flexible spectrum access. 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. Of course, proposals for location aided techniques need to be weighted against classical approaches (CSIT learning) in order to assess their definitive value.

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

1. INTRODUCTION

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. However, Nokia-Siemens in [1] work with a database of channel impulse responses directly (which are claimed to be stable over $40'$ in some measurements), to overcome the problem of delay in channel FB. They consider a combination of FB + location aided approaches as realistic.

2. SINGLE-USER ASPECTS

On the *receiver* (Rx) side: position information can lead to information about the channel statistics via a database, which can be used to improve channel estimation. This could be compared to learning of the channel statistics from previous channel estimates (which is hardly possible though in short packet mode!) or with sparse techniques. On the *transmitter* (Tx) side: adapt AMC and resource allocation (see further).

Location and Database aided Channel Estimation/Prediction

These days, optimized LMMSE channel estimation and tracking is often considered [2], which requires 2D covariance information in the form of the Power Delay Doppler Profile (PDDP). In multi-antenna systems the space dimension could also be added to that profile. For fast fading channel estimation and short-term prediction, the channel PDDP an be
(1) learned from consecutive channel estimates, but knowledge will often come a bit late in this way and may require long data and stationarity for extensive PDDPs, or
(2) determined from position information + (extensive) database, leading to instantaneous knowledge & extended (short-term) channel prediction range. A Kalman filter performing integrated position tracking and channel tracking is one solution here. Approach (2) allows furthermore longer-term prediction, but of channel statistics only. If the database content is limited, a combination of both approaches could be considered.

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Position based Adaptive Modulation and Coding (AMC) and (OFDMA) Resource Allocation

(Position information leads to) Environment information which in turn leads to information on the channel diversity structure, on the channel frequency selectivity and would allow to adapt frequency allocation/interleaving. One could consider adapting the (OFDM) Cyclic Prefix (CP) and pilot structure on the basis of environment parameters. This would lead to minimized overhead and would avoid to design for the worst case. Information on the MIMO channel richness (e.g. rank) allows to adapt the spatial multiplexing and the (linear) space-time coding. Information on the mobility provides temporal diversity information, which can be used to adapt interleaving in time. All these adaptations can take into account channel non-Rayleigh aspects (e.g. LOS/NLOS, LOS leads to reduced or no fading).

3. SINGLE-CELL MULTI-USER COMMUNICATIONS

3.1. Location aided Multi-User Resource Allocation

Some possibilities are:

- *Multi-user 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), ...
- *Multicell aspects* (interference coordination) or for *Cognitive Radio* (interference from secondary to primary systems): the interference level can be predicted from position information.

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.

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.

3.2. 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 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 (see below) users and extract essential CSIT from position information (or from DoA estimates - in both cases the knowledge of the antenna araay manifold is (eventually) required).

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 [4]. This is a small generalization of the LOS case. In the NADA case, the MIMO channel $\mathbf{H}$ (assumed frequency-flat here or we assume a narrowband case (e.g. an OFDM subcarrier)) is of the form

$$\mathbf{H} = \sum_i \mathbf{h}_r(\theta_i)\mathbf{h}_t^T(\phi_i) = \mathbf{B}\,\mathbf{A}^T\ ,\quad \mathbf{A} = \left[\mathbf{h}_t(\phi)\ \dot{\mathbf{h}}_t(\phi)\right] \tag{1}$$

where $\mathbf{h}_r(.)$ is the receive side antenna array response, $\mathbf{h}_t(.)$ is the transmit side antenna array response, θ_i is the Angle of Arrival (AoA) of path i and ϕ_i is the Angle of Departure (AoD) of path i. In the case of narrow AoD spread, we have

$$\phi_i = \phi + \Delta\phi_i \tag{2}$$

where ϕ is the nominal (LOS) AoD and $\Delta\phi_i$ is small. Hence

$$\mathbf{h}_t(\phi_i) \approx \mathbf{h}_t(\phi) + \Delta\phi_i\ \dot{\mathbf{h}}_t(\phi)\ . \tag{3}$$

This leads to the second equality in (1). 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 $\dot{\mathbf{h}}_t(\phi)$ 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 $\mathbf{B}$ remains random.

In what follows, we shall focus on the LOS limit for considerations of location based processing. We propose that location based MU MIMO transmission involves position based user selection (attenuation, nominal AoD, AoD spread) and associated beamforming (BF) and power control (PC).

3.3. Location Based SDMA

3.3.1. Sum Rate Lower Bound

In [5] one can find a discussion of the importance of CSIT in MU MISO and of the state of the art on this. The analysis in [5] concerns optimization of the CSIT FB. We shall work here with the same lower bound of the sum rate attained by ZF BF based on approximate channel knowledge. The frequency-flat system we consider consists of a BS having n_t transmit antennas and K ($K \leq n_t$) single-antenna user terminals. In the DL, the signal received by k-th user can be expressed as

$$y_k = \mathbf{h}_k^H \mathbf{x} + n_k \,,\ k = 1, 2, \ldots, K \tag{4}$$

where $\mathbf{h}_k$ is the (complex conjugated) channel vector of user k, $\mathbf{x}$ denotes the n_t-dimensional signal transmitted by the BS and n_k is independent complex Gausian noise with zero mean and unit variance. We omit the time index for simplicity. The concatenation of the K user channels is $\mathbf{H}^H = [\mathbf{h}_1 \mathbf{h}_2 \cdots \mathbf{h}_K]$. The channel input from the BS must satisfy an (average) transmit power constraint of P, i.e. $\mathbb{E}[||\mathbf{x}||^2] \leq P$. In this setting, the transmit power P equals the (transmit) SNR at each user due to the normalized noise variances. We will assume the BF to be based on an approximate (knowledge) $\widehat{\mathbf{h}}_j$ of the channel vectors. In ZF precoding, the unit-norm BF vector for the k-th user (denoted as $\bar{\mathbf{v}}_k$) is chosen to be orthogonal to the channel vectors of all other selected users, i.e., $\widehat{\mathbf{h}}_j^H \bar{\mathbf{v}}_k = 0 \,,\ j \neq k$. If $\mathbf{W}$ is the pseudo-inverse of $\widehat{\mathbf{H}}$, i.e.

$$\mathbf{W} = \widehat{\mathbf{H}}^H \left(\widehat{\mathbf{H}} \widehat{\mathbf{H}}^H \right)^{-1} , \tag{5}$$

then the precoding matrix $\bar{\mathbf{V}} = [\bar{\mathbf{v}}_1 \bar{\mathbf{v}}_2 \cdots \bar{\mathbf{v}}_K]$ can be obtained from $\mathbf{W}$ by normalizing all of its columns. The channel for user k can be decomposed as $\mathbf{h}_k = \widehat{\mathbf{h}}_k + \widetilde{\mathbf{h}}_k$ where the entries of the error term $\widetilde{\mathbf{h}}_k$ are modeled as i.i.d. Gaussian with zero mean and variance $\sigma_{\widetilde{h}}^2$. If $\mathbf{u}$ represents the vector of Gaussian information symbols (u_k intended for user k), the transmitted signal $\mathbf{x}$ becomes $\mathbf{x} = \bar{\mathbf{V}}\mathbf{u}$ and the signal received by the k-th selected user (4) can be expressed as follows:

$$\begin{aligned} y_k &= \mathbf{h}_k^H \bar{\mathbf{V}} \mathbf{u} + n_k \\ &= \mathbf{h}_k^H \bar{\mathbf{v}}_k u_k + \textstyle\sum_{j \neq k} \mathbf{h}_k^H \bar{\mathbf{v}}_j u_j + n_k \\ &= \widehat{\mathbf{h}}_k^H \bar{\mathbf{v}}_k u_k + \widetilde{\mathbf{h}}_k^H \bar{\mathbf{v}}_k u_k + \textstyle\sum_{j \neq k} \widetilde{\mathbf{h}}_k^H \bar{\mathbf{v}}_j u_j + n_k \\ &= \widehat{\mathbf{h}}_k^H \bar{\mathbf{v}}_k u_k + \textstyle\sum_{j=1}^{K} \widetilde{\mathbf{h}}_k^H \bar{\mathbf{v}}_j u_j + n_k . \end{aligned} \tag{6}$$

The rate lower bound comes from relegating the signal part $\widetilde{\mathbf{h}}_k^H \bar{\mathbf{v}}_k u_k$ into the interference and by treating all the interference terms as additional independent Gaussian noise.The SINR of the k-th user can be written as

$$\mathrm{SINR}_k = \frac{p |\widehat{\mathbf{h}}_\mathbf{k}^\mathbf{H} \bar{\mathbf{v}}_\mathbf{k}|^2}{1 + p \sum_{j \in \mathcal{S}} \mathbb{E}_{\widetilde{\mathbf{h}}_\mathbf{k}} |\widetilde{\mathbf{h}}_\mathbf{k}^\mathbf{H} \bar{\mathbf{v}}_\mathbf{j}|^2} = \frac{p |\widehat{\mathbf{h}}_\mathbf{k}^\mathbf{H} \bar{\mathbf{v}}_\mathbf{k}|^2}{1 + pK\sigma_{\widetilde{h}}^2} \tag{7}$$

where $p = \frac{P}{K}$ in the case of uniform power control. This leads to the sum rate lower bound

$$\mathrm{SR}_{LB} = \sum_{k=1}^{K} \mathbb{E}_{\widehat{\mathbf{H}}} \log \left(1 + \frac{\frac{P}{K} |\widehat{\mathbf{h}}_\mathbf{k}^\mathbf{H} \bar{\mathbf{v}}_\mathbf{k}|^2}{1 + P\sigma_{\widetilde{h}}^2} \right) = R_{\mathrm{ZF}}(K, n_t, \frac{P}{1 + P\sigma_{\widetilde{h}}^2}) \,. \tag{8}$$

3.4. Location based SDMA: ZF BF sum rate

Although some extension to the more general NADA case could probably be considered, we shall focus here on the LOS case. So a first restriction in the SDMA user selection process is that for MU-MISO purposes, users to be considered need to be in LOS mode. So in this case we get for the downlink channel to user k:

$$\mathbf{h}_k^H \ = \ \gamma_k \, e^{j\psi_k} \, \mathbf{h}_t^T(\phi_k) \tag{9}$$

where $\mathbf{h}_t(.)$ is the (unit norm) BS antenna array response, ϕ_k is the AoD for user k, which in the LOS case can be computed from the user's position, $\gamma_k > 0$ is a complex attenuation factor, and ψ_k is a phase that is unimportant for transmitter considerations. There are a variety of ways in which the information of γ_k can be obtained:

- User feedback of just the scalar γ_k.
- Infer γ_k from the uplink. Not only in TDD but even in FDD, in the case of a LOS channel, the channel gain should be reciprocal (because there is no frequency-dependent superposition of multipath contributions).
- Determine the attenuation from the position and simple (e.g. free space (LOS!)) propagation laws.

3.4.1. Effect of LOS deviation on ZF BF sum rate

In this case we can model the user's channels as

$$\mathbf{h}_k^H \ = \ \gamma_k \, e^{j\psi_k} \, \mathbf{h}_t^T(\phi_k) + \widetilde{\mathbf{h}}_k^H \tag{10}$$

where $\widetilde{\mathbf{h}}_k$ could in a first instance be modeled as random with i.i.d. zero mean components with variance $\sigma_{\widetilde{h}}^2$. The ratio $\frac{\gamma_k^2}{n_t \, \sigma_{\widetilde{h}}^2}$ could be considered as a Ricean factor. The reasoning leading to the sum rate LB (8) can be adapted to yield the following sum rate LB for location based ZF BF (for uniform transmit power over the set $\mathcal{S}$ of $|\mathcal{S}|$ selected users)

$$\mathrm{LB}^{Rice} = \sum_{k \in \mathcal{S}} \mathbb{E} \log \left(1 + \frac{1}{1 + P\sigma_{\widetilde{h}}^2} \frac{P}{|\mathcal{S}|} \gamma_k^2 \, |\mathbf{h}_t^T(\phi_k) \bar{\mathbf{v}}_k|^2 \right) \tag{11}$$

where the expectation is over the distribution of the ϕ_k and the γ_k. Hence

$$\mathrm{LB}^{Rice} = R_{\mathrm{ZF}}^{los}(|\mathcal{S}|, n_t, \frac{1}{1 + P\sigma_{\widetilde{h}}^2} \, P) \tag{12}$$

where the perfect LOS case would be obtained by putting $\sigma_{\widetilde{h}}^2 = 0$. In contrast to the training based approach, here the performance increases with the number K of users to choose from as then they can be better chosen to have close to orthogonal antenna array responses (note that K should grow with SNR if sum rate saturation at high SNR is to be avoided). Another contrast to the training based approach in which $\sigma_{\widetilde{h}}^2$ is due to channel estimation error, in which case $\sigma_{\widetilde{h}}^2$ in (7) decreases with the UL SNR, here $\sigma_{\widetilde{h}}^2$, which is now due to LOS approximation error, is independent of SNR. The result of this is that at high SNR the sum rate will saturate and the spatial multiplexing factor will be lost. This only happens though at SNR above which the interference resulting from channel approximation error dominates the noise, i.e. when $P > \frac{1}{\sigma_{\widetilde{h}}^2}$.

One remark is in order here about antenna spacing. For the purpose of DoA estimation, and considering a uniform linear array (ULA) of antennas, it is generally considered that an antenna spacing of $\lambda/2$ is good. However, for the purpose of SDMA, in which we would like the antenna array responses between different angles to be easily orthogonal, it is preferable that the antenna spacing is larger. Indeed, the larger the antenna spacing, the larger the number of angles within a sector for which the array response is orthogonal to the array response at a given angle in the same sector. This multiplicity of "orthogonal" angles on the other hand leads to ambiguities in the DoA estimation problem. In the case where the DoA is not estimated from received signal data but is computed on the basis of the position, these ambiguity problems are irrelevant and then antenna spacing should indeed be as large as possible (although not too large to invalidate the far field and narrowband assumptions).

3.4.2. *Effect of position error on ZF BF sum rate*

Assume a (2D) position error Δp_k for user k, with mean square value $\sigma_p^2 = \mathbb{E}\,\|\Delta p_k\|^2$ (assuming also the position error to be isotropic). The position error will lead to a AoD error

$$\Delta\phi_k = \frac{\Delta p_k}{d_k\sqrt{2}} \tag{13}$$

where d_k is the distance of user k from the BS, and $\sqrt{2}$ is not an exact representation but leads to the correct AoD error variance, accounting for the fact that AoD error only depends on the component of Δp_k orthogonal to the LOS direction. The AoD error will lead to an error in the steering vector, which for small AoD error we can approximate by a first order Taylor series expansion (similar to the NADA case)

$$\mathbf{h}_t(\phi_k + \Delta\phi_k) \approx \mathbf{h}_t(\phi_k) + \Delta\phi_k\; \dot{\mathbf{h}}_t(\phi_k)\;. \tag{14}$$

Paralleling the reasoning in the previous cases, we can obtain a ZF BF sum rate LB

$$\mathrm{LB}^{loc} = \sum_{k\in\mathcal{S}} \mathbb{E}\log\left(1 + \frac{\frac{P}{|\mathcal{S}|}\gamma_k\,|\mathbf{h}_t^T(\phi_k)\,\bar{\mathbf{v}}_k|^2}{1+\frac{P}{|\mathcal{S}|}\,\gamma_k\,\frac{\sigma_p^2}{2\,d_k^2}\,\sum_{j\in\mathcal{S}}|\dot{\mathbf{h}}_t^T(\phi_k)\,\bar{\mathbf{v}}_j|^2}\right)\,. \tag{15}$$

The effect of the position error is hence to reduce the SNR for user k by a factor

$$1+\frac{P}{|\mathcal{S}|}\,\gamma_k\,\frac{\sigma_p^2}{2\,d_k^2}\,\sum_{j\in\mathcal{S}}|\dot{\mathbf{h}}_t^T(\phi_k)\,\bar{\mathbf{v}}_j|^2 \;\;. \tag{16}$$

3.4.3. *From MU MISO to MU MIMO Downlink*

In MU MISO, all ZF has to be done by the Tx. In MU MIMO however, the ZF can be shared between Tx and Rx. All possible distributions of the ZF task between Tx and Rxs lead to many possible local optima of the sum rate at high SNR, hence providing potential for improved performance while complicating the task of TX/RX design. For a location-aided approach, with limited CSIT, consider restricting MU-MIMO to NADA users, and base the Tx design on the LOS components only. The interference due to angular spread around the LOS can then be handled by the multiple Rx antennas at the MT. In the NADA model, the MIMO channel is of rank two, hence the received signal lives in a two-dimensional subspace, which is independent of the BF design. Two Rx antennas are sufficient to allow the Rx to suppress all interference, regardless of the number of users.

A further evolution would be to consider *mixed CSIT* [6], in which NADA users with location based CSIT get mixed with other users which have FB based CSIT. Another interesting recent development appears in [7] where blind ZF is proposed, interweaving PDP (or PDDP) polyphase components.

3.4.4. *Comparative Simulations of Location based SDMA vs LTE Quantization-FB based SDMA*

In [8, Section6.5] one can find some comparative evaluations of sum rate for ZF BF, based on the one hand on a Ricean channel model with BF done with knowledge (from location information) of the LOS components only, and on the other hand on quantized CSIT according to codebooks used in LTE. It can be concluded that the location based precoders are capable to achieve higher system capacity in most scenarios than a LTE system due to the limited codebook size (FB rate) in the LTE system. The capacity enhancement is significant already for a 2-user MISO system.

4. MULTI-CELL COMMUNICATIONS

Whereas single cell designs are applicable even in a multi-cell context, for users in the interior of the cell, intercell interference needs to be considered for the cell edge users. In the *single antenna* case: the multi-cell aspect requires Tx power coordination, which can fairly easily be done location-aided (locations translate into distances and attenuations; databases could be used for further statistical characteristics (e.g. slow fading)).

Multi-antenna techniques: require downlink channel knowledge, in principle of all channels at all transmitters (cells). Several approaches are possible, in increasing complexity:

- *single-cell Tx, multi-cell Rx*: the BS perform single-cell Tx; inter-cell interference gets handled by the MT Rx antennas. The CSIT requirements remain local, per cell. In the LOS case, the MT needs to have a number of antennas at least equal to the number of cells (BS signals) to be handled (ZF). In the NADA case, the required number of antennas gets doubled.
- *multi-cell coordinated beamforming*: also called the MISO or MIMO Interference Channel (IFC) in the case of one MT per cell. In the MISO case, the BSs need to ZF towards the users in other cells. In the MIMO case, this ZF can be shared between Txs and Rxs (interference alignment (IA)). The case of multiple MTs per cell, with interfering cells, is called the Interfering Broadcast Channel (IBC), or sometimes also simply the multi-cell problem. The IFC/IBC models are applicable also when the interfering cells correspond to heterogeneous systems (e.g. macro-femto coexistence).
- *network MIMO*: also called Coordinated Multi-Point Tx (CoMP): requires not only global CSIT at all Txs (BSs) but furthermore distribution of all Tx signals over the BSs.

Whenever we mention ZF BF above, this refers to the high SNR case, and could be replaced by optimized BF at finite SNR. Also BF could be replaced by DPC or other more optimal Tx techniques.

4.1. MIMO Interference Channel (IFC)

The joint Tx/Rx design is plagued by numerous local optima. In [9], we proposed a deterministic annealing approach for guaranteeing the global optimum of the weighted sum rate (WSR). At high SNR, the optimum WSR design becomes ZF (IA), with typically many possible solutions due to the nonlinearity of the ZF conditions. Nevertheless, we may remark, as in [9], [10], that the ZF problem simplifies enormously in the LOS case. Indeed, let $\mathbf{f}_{i,n}$ be the Rx spatial filter for stream n of user i and $\mathbf{g}_{k,m}$ the Tx filter for stream m of BS k, and $\mathbf{H}_{i,k}$ the MIMO channel from BS k to MT i, then the ZF (IA) requirement for this particular cross link is $\mathbf{f}_{i,n}\mathbf{H}_{i,k}\mathbf{g}_{k,m} = 0$. These ZF condistions need to be considered jointly for all cross links and hence they are coupled through the Tx and Rx filters. Stating the solutions for the filters analytically is impossible in general. However, consider the case in which all MIMO channels would be in LOS and hence of rank one: $\mathbf{H}_{i,k} = \mathbf{u}_{i,k}\mathbf{v}_{i,k}^H$. Then the ZF condition just considers becomes

$$\mathbf{f}_{i,n}\mathbf{u}_{i,k}\;\mathbf{v}_{i,k}^H\mathbf{g}_{k,m} = 0 \;\;\text{iff}\;\; \mathbf{f}_{i,n}\mathbf{u}_{i,k} = 0 \;\;\text{or}\;\; \mathbf{v}_{i,k}^H\mathbf{g}_{k,m} = 0\;. \tag{17}$$

Hence, apart from the distribution of the ZF roles over Txs and Rxs, the design of the Tx and Rx filters becomes decoupled, and their design only requires knowledge of the channels connected to them (in general the design of a Tx or Rx filter in the MIMO IFC problem requires the knowledge of all channels appearing in the IFC). Furthermore, the factors $\mathbf{u}_{i,k}$ depend only on the antenna array of BS k and the location of MT i. Hence the design of the Tx filters can be carried out on the basis of the location information of the various MTs. To go beyond LOS, the NADA and mixed CSIT cases could be considered. Another issue is the strength of the interfering links. In a ZF/IA approach, all link strengths are considered of equal order of magnitude, but in reality not all interfering links equally important. In [11], the concept of *generalized degrees of freedom* (gdof) is introduced. The dof are the prelog of user rates at high SNR. In a MIMO IFC, the dof of a link correspond to the number of streams for which ZF/IA is feasible. Those dof become gdof when one models the Interference to Noise Ratios (INRs) as evolving with the SNR to a certain power, e.g. smaller than one for the case of weak interference. Whereas such analysis may lead to qualitative insights into the relative effect of certain interference terms, the gdof results are quantitatively of limited use since in practice one needs to work at a finite SNR, at which one cannot unambiguously define α and β in a relation of the form $\text{INR} = \beta\,\text{SNR}^{\alpha}$. The problem is due to only considering exponents in asymptotic analysis. Analysis needs to evolve from gdof or tier 1 interferers only (a model introduced in [12] in which interferers beyond tier one are ignored for dof analysis) to location (distance & propagation) dependent interference strengths.

4.2. Femto Cells

Femto cells are clearly a potentially important application for positioning: an operator needs to know (e.g. 911) the position of its BSs, including femto cells. Intercell Interference Coordination (ICIC) is part of LTE and has been shown to be greatly improved when exploiting location information, see [13, section 4]. ICIC is of crucial importance in the macro-femto coexistence. However, femtos are static, so all the time is available to perform communications based measurements of the attenuations of various links, so the relative advantage brought by location information is less clear.

4.3. Relays

Relays are affected by resource allocation aspects in the form of relay and cell handover, cell-center to cell-edge transitions, association of (which and how many) relays etc. Position information can play a crucial role here to reduce handover dead times and significantly reduce handover hysteresis. The use of relays allows to overcome near-far effects to a large extent and minimize slow fading variations. Relays may hence constitute an essential ingredient in the recent and necessary tendency towards green wireless. However, since relays serve mainly users at the cell edge, intercell interference is going to be strong and needs to be dealt with. In any case, location information may be usefully exploited to shortcut heavy communication overhead required in the coordination of relay resource allocation. See [13, section 2] for examples of work in this direction.

5. COGNITIVE RADIO

5.1. Single Receive Antenna Case

5.1.1. Location Aided Underlay Cognitive Radio

Underlay Cognitive Radio (CR) is a popular CR design problem, in which a secondary network is allowed to operate in the presence of a primary system with interference limits at the primary Rxs, and this without any collaboration or even awareness of the primary system. To make underlay feasible, the exploitation of position information to determine attenuations constitutes probably the only realistic approach. In the MISO case, the location information could also be translated to Direction of Departure (DoD) based ZF BF. The cases of LOS and NADA need to be explored.

5.1.2. Weighted Sum Rate (WSR) Maximization in the Underlay Cognitive MISO IFC

In [14] we study a CR MISO IFC with K secondary MISO BS-MT pairs and an additional set of L single-antenna Primary Users (PUs). This setting is relevant in the case of a network of two or more cognitive femto cells, that represent the secondary system, where each femtocell BS is serving a single user in the time-frequency unit of interest. The femto cells are deployed in the same area of a macro cell (primary system) and they want to coexist with L mobile users that belong to one or more macro cells. The picture is as in Fig. 1 except that the Rxs have only a single antenna and hence no receive filters. In [14] the objective is to find the set of BF vectors $\{\mathbf{g}_i\}$ that maximize the WSR of the secondary IFC network, under Tx power constraints for the secondary BS, and interference level constraints at the primary Rxs. Unfortunately, this problem is non-convex. The proposed solution, which is an iterative algorithm based on augmenting the set of variables and performing alternating optimization, converges to a local optimum. Deterministic Annealing (DA) could be added as in [9] to find the global optimum. In [15] the alternative problem formulation of SINR balancing is considered.

5.2. Multi-Antenna Case

5.2.1. Multi-Antenna Cognitive Radio Paradigms

The extension of a number of standard cognitive radio paradigms to the multi-antenna case is not as straightforward and unambiguous as it may seem at first. Here we propose some possible multi-antenna extensions for these paradigms.

Spatial Overlay: MISO/MIMO Interference Channel

In the overlay paradigm, primary and secondary collaborate. This collaboration could be interpreted at multiple levels, at the level of an exchange of Tx signals (as in network MIMO), or just at the level of CSIT, which in the single antenna case translates to coordinated power control. In the case of multiple antennas, if we limit cooperation to CSIT, this would lead to the exploitation of the multiple antennas for coordinated BF to achieve parallel interference-free channels. Coordinated BF applies to multiple antennas at the Tx side (MISO IFC). In the case of multiple antennas at the Rxs, we can have coordinated Rxss. The case of the coordination of the multiple antennas on both sides corresponds to the (noisy) MIMO IFC which was discussed earlier in the multi-cell setting. The recent Authorized Shared Access (ASA) proposal by Qualcomm and Nokia-Siemens Networks fits in the realm of overlay cognitive radio.

Spatial Underlay:

In the underlay paradigm, interference caused by a secondary Tx to a primary Rx is acceptable as long as the interference remains under a maximum tolerance level. One possible definition of spatial underlay then would be that the primary Rx equipped with multiple antennas allows primary interference as long as it has enough antennas to handle it. Hence the primary Rx needs to be active. So, the primary Rx allows an interference subspace of maximum dimension equal to the excess of its number of antennas over the number of primary streams it needs to receive. The primary system is secondary-aware.

Of course, the secondary Txs need to align the interference caused to primaries in subspaces of limited dimension.

Spatial Interweave:
In the interweave paradigm, the primary system should not be disturbed at all, and is not required to exhibit any cooperation with the secondary systems. So in a spatial interweave version, with multiple primary Rx antennas also, the secondary systems need to zero-force to all primary Rx antennas individually. In this case there is still room for secondary Tx if the secondary Txs have more antennas than the combined primary Rxs. The spatial interweave paradigm requires significant CSIT and can be reciprocity based in TDD, or location based in the case of LOS secondary-primary cross channels. In the LOS case, the number of primary Rx antennas becomes irrelevant (assuming they are in the far field from the secondary). In the case of NLOS, the secondary Tx needs to have more antennas than the number of propagation paths to all primary Rxs.

5.2.2. Spatial Interweave for a MIMO Secondary IFC with Multiple Primary Users

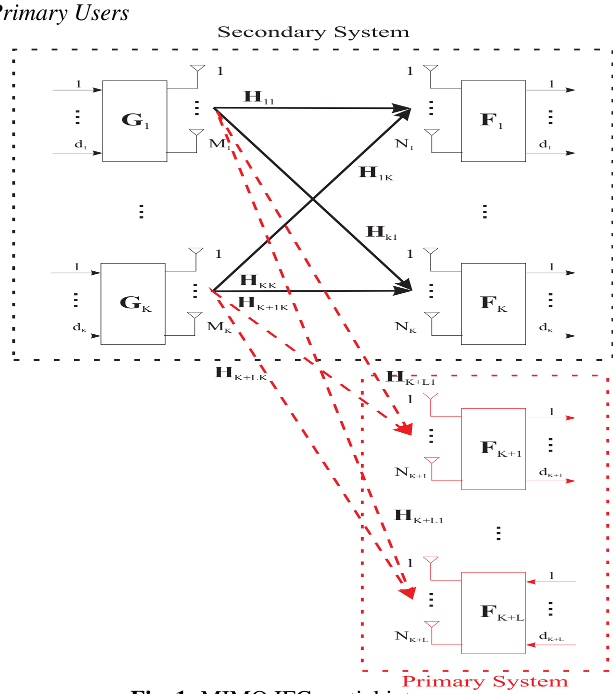

Fig. 1. MIMO IFC spatial interweave.

This CR setting is depicted in Fig. 1. It can be used to model the coexistence of a set of K femto cells (MIMO IFC) in the presence of L primary macro-users (PRs). The objective considered in [16] is to design IA BF matrices at the secondary Txs such that the interference received at the primary Rxs is confined in a subspace of proper dimension. To solve this optimization problem we propose an iterative algorithm that is based on the reciprocity of IA. The proposed algorithm iterates between the downlink (DL) and its dual uplink (UL) problem, determining the Tx and Rx filters such that the leakage interference is minimized. In addition we propose a set of feasibility conditions for the combined primary and secondary IA.

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