Interference Nulling for Offloaded Heterogeneous Users Using Macro Generalized Inverse Precoder

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***Abstract*—Heterogeneous networks are a crucial paradigm that will allow future mobile networks to meet growing wireless traffic demands. An important issue in heterogeneous networks is the crosstier interference between femtocells and macrocells. In this paper, we show that a generalized inverse precoder at the macro base station can null interference to offloaded femtocell users. Under ideal conditions, the precoder can achieve perfect interference nulling, and achieve interference suppression using practical suboptimal methods under non-ideal conditions. Simulations show that even with realistic imperfect channel state information, our precoder achieves significant interference suppression while maintaining zero macro inter-user interference.**

***Index Terms*—Heterogeneous networks, interference management, interference nulling, precoder, nullspace.**

I. Introduction

Interference management has become an important consideration in the future fifth generation (5G) wireless cellular systems [1]. In 5G systems, a dense heterogeneous network (HetNet) deployment of low power small cells such femtocells (also known as femtocell access points, or FAPs) within the coverage area of a macrocell base station (MBS) is deemed inevitable [2]. One advantage of FAPs is that they can provide load balancing in the network by serving offloaded user equipments (UEs) from the MBS. However, this can create significant downlink interference for those UEs who are served by FAP but still continue to receive a strong signal from the MBS [3], thus degrading overall UE experience and quality of service. Such an interference scenario, e.g., if UE is a cell edge user, may be particularly common during cell range expansion (CRE) offloading [4]. This scenario is one of several important femtocell interference scenarios outlined in industry white papers such as [5].

The conventional approaches to interference management in cellular networks rely on interference avoidance through resource allocation, including variants of frequency, time, space and/or power [6]–[8]. In the current fourth generation (4G) systems, techniques such as Intercell Interference Coordination (eICIC), Almost Blank Subframes (ABS) and Coordinated Multipoint (CoMP) communications have been introduced for co-channel interference management [1], [9]. However, many of these techniques require reliable backhaul between individual nodes and the availability of highly accurate channel state information (CSI).

In downlink 4G systems, interference management is mostly a network-side operation. UE-side interference *cancellation* by advanced receivers with interference detection/decoding is considered in [1], [4], but such methods require additional complexity and processing at UEs which may degrade battery life. Currently, interference *nulling* using signal processing at the base station is not as commonly considered as resource management methods, even though the former may bring considerable benefits to multi-user systems. Some research has been conducted into nullspace learning and updates at clustered base station groups, but these require extensive CoMP and cooperation [10], [11].

Conventional precoding methods such as zero-forcing (ZF) and channel psuedoinverses [12] are well known techniques for managing interference in wireless communications, but generally do not consider effects on offloaded users. We showed in [14] that a generalized inverse precoder structure allows interference suppression to offloaded users under a macro base station power constraint, while maintaining transmission to the other MBS users with no additional inter-user interference but at the expense of a slight decrease in macro user rates. Generalized inverses for precoding are also used in [12], [13], but in this paper the structure is designed for the purpose of interference nulling and suppression, while in [12], [13] the focus is throughput and energy efficiency respectively.

In this paper, we show how a generalized inverse procoder can completely null interference to a particular offloaded user while maintaining interference-free transmission to macro users. In contrast to our work in [14], where the degree of interference suppression was controlled through a regularization parameter which also decreased the macro user rates due to a power constraint, here we show how interference can be nulled without compromising macro user rates at the expense of additional base station transmission power. Further, we show the interference suppression performance when suboptimal but more practical methods are used to calculate the precoder.

The rest of the paper is organized as follows. Section II describes the MBS and FAP system models. The problem statement and precoder conditions are also outlined. Section III describes the generalized inverse precoder structure as well as three suboptimal practical alternatives for interference suppression. Simulation results in Section IV compare the relative performance and benefits of the proposed methods. Finally, conclusions are presented in Section V.

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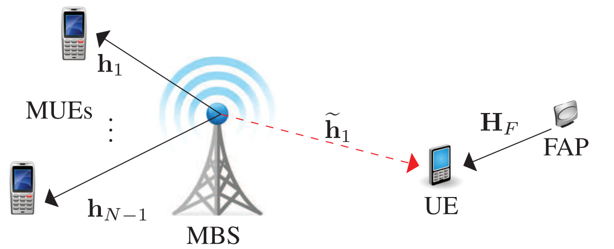

Fig. 1: System model comprising of MBS, MUEs, UE and FAP. Interference from MBS to one UE is illustrated.

II. System Models and Problem Statement

In this section we describe the downlink system models for both MBS and FAP transmissions to particular UEs. Conventional mathematical notations are used for matrix operations, including $(\cdot)^T$ and $(\cdot)^H$ for matrix transpose and conjugate transpose respectively, $(\cdot)^{-1}$ for matrix inverse, $(\cdot)^+$ for matrix psuedoinverse, $\|\cdot\|$ for Frobenius norm, $\mathbf{I}_N$ for identity matrix of dimension N, and $\mathbf{0}_{M,N}$ for an $M \times N$ zero matrix.

A. Macro Transmission

Consider an MBS with N antennas serving $N-k$ users, with k offloaded users (collectively denoted as UEs) being served by an FAP with N_f antennas. The UEs are still within the MBS cell radius and thus are receiving interference from the MBS. All users employ single antennas. The system with $k=1$ as an example is illustrated in Fig. 1. For simplicity, pathloss and transmit powers are normalized and hence omitted in our formulation as they do not affect the interpretation of our system model. Note that in our simulation results in Section IV, path loss and transmit powers are considered in accordance with 3GPP standards.

The channels of the $N-k$ macro users are assumed to be known by the MBS and can be denoted as

$$\mathbf{H} = \begin{pmatrix}\mathbf{h}_1 & \dots & \mathbf{h}_{N-k}\end{pmatrix}, \tag{1}$$

where each column $\mathbf{h}_i$ is the channel vector for the ith user whose elements are independent and identically distributed Rayleigh channels following a complex normal distribution $\sim \mathcal{CN}(0,1)$.

The k offloaded users' channels from the MBS are similarly defined as

$$\widetilde{\mathbf{H}} = \begin{pmatrix}\widetilde{\mathbf{h}}_1 & \dots & \widetilde{\mathbf{h}}_k\end{pmatrix}, \tag{2}$$

whose entries follow the same distribution as (1).

If conventional ZF precoding is used [12], let the $N \times (N-k)$ precoder matrix $\mathbf{W}$ for the $N-k$ users be the psuedoinverse of the channel matrix $\mathbf{H}^H$, that is

$$\mathbf{W} = (\mathbf{H}^H)^+ = \mathbf{H}(\mathbf{H}^H\mathbf{H})^{-1} = \begin{pmatrix}\mathbf{w}_1 & \dots & \mathbf{w}_{N-k}\end{pmatrix}. \tag{3}$$

The received signals by all users due to MBS transmission form the vector

$$\mathbf{y} = \begin{pmatrix}\mathbf{H}^H \\ \widetilde{\mathbf{H}}^H\end{pmatrix}\mathbf{W}\mathbf{x} + \mathbf{n} = \begin{pmatrix}\mathbf{I}_{N-k} \\ \widetilde{\mathbf{H}}^H\mathbf{W}\end{pmatrix}\begin{pmatrix}x_1 \\ \vdots \\ x_{N-k}\end{pmatrix} + \mathbf{n},$$

where $\mathbf{x}$ is the vector of $N-k$ independent data streams, one for each macro-served user, and $\mathbf{n} \sim \mathcal{CN}(0,1)$ is the additive white Gaussian noise (AWGN) vector of dimension $N \times 1$ whose independent elements have zero mean and unit power.

B. Femto Transmission

We assume that FAP has channel knowledge of all its UEs, and uses any suitable transmit scheme to serve them (ZF or scheduling) during its downlink transmission. Thus, the received signals at the UEs are denoted as

$$\mathbf{y}_F = \underbrace{\mathbf{H}_F^H\mathbf{x}_F}_{\text{desired}} + \underbrace{\widetilde{\mathbf{H}}^H\mathbf{W}\mathbf{x}}_{\text{interference}} + \mathbf{n}_F, \tag{4}$$

where $\mathbf{H}_F$ is the $k \times k$ equivalent diagonal Rayleigh fading channel matrix from FAP to UEs, $\mathbf{x}_F$ is the data $k \times 1$ vector transmitted from the FAP and $\mathbf{n}_F$ is the $k \times 1$ AWGN vector whose independent elements follow $\sim \mathcal{CN}(0,1)$. We assume the FAP has no initial users, but our system can be extended without loss of generality to include any initial users.

Assuming the transmit signals $\mathbf{x}_F$ and $\mathbf{x}$ have unit power, the signal-to-noise-plus-interference ratio (SINR) at the kth UE is

$$SINR = \frac{\left\|\mathbf{H}_F^H(k,k)\right\|^2}{\left\|\widetilde{\mathbf{H}}^H\mathbf{W}\right\|^2 + 1}. \tag{5}$$

We assume that there is limited feedback between the FAP and MBS rather than full coordination or cooperation. That is, feedback of system features such as SINR is possible, but perfect CSI or transmit data are not exchanged.

C. Problem Statement

Ideally, we desire interference nulling such that SINR = SNR = $\left\|\widetilde{\mathbf{H}}_F^H\right\|$. Any interference nulling technique should not introduce additional inter-user interference for the other $N-k$ MBS users. Thus, we desire a precoding matrix $\mathbf{W}$ which will satisfy the following two conditions:

1) $\mathbf{H}^H\mathbf{W} = \mathbf{I}_{N-k}$. This ensures that the other $N-k$ MBS users still only receive their intended data stream from the MBS, i.e., no additional inter-user interference.
2) Minimize $\left\|\widetilde{\mathbf{H}}^H\mathbf{W}\right\|$. If this can be made to zero, interference from MBS to UEs is nulled. Otherwise, interference is suppressed.

III. Interference Nulling and Suppression

In this section we present a generalized inverse precoder structure which, under perfect CSI conditions, will completely null the MBS interference to the femto-served UE. We also describe three suboptimal but more practical alternative methods of achieving interference suppression if CSI is not perfectly known by the MBS. In all cases, no MBS inter-user interference is introduced.

A. Generalized Inverse Precoder with Perfect CSI

We design a new precoding matrix for the $N-k$ MBS users using the generalized inverse structure

$$\mathbf{W} = (\mathbf{H}^H)^+ + \mathbf{U}\mathbf{B}, \tag{6}$$

where $\mathbf{U}$ is the $(N-k) \times k$ nullspace of $\mathbf{H}^H$, i.e., $\mathbf{H}^H\mathbf{U} = \mathbf{0}_{N-k,k}$, and $\mathbf{B}$ is a $k \times (N-k)$ matrix of coefficients. The precoder in (6) does not introduce additional inter-user interference since

$$\mathbf{H}^H\mathbf{W} = \mathbf{H}^H(\mathbf{H}^H)^+ + \mathbf{H}^H\mathbf{U}\mathbf{B} = \mathbf{I}_{N-k}. \tag{7}$$

The elements in $\mathbf{B}$ represent the weighting factors for the nullspace vectors of $\mathbf{H}^H$ which can be tuned so as to achieve the desired interference nulling or suppression.

To null interference from MBS to UEs and satisfy condition 2), we desire

$$\widetilde{\mathbf{H}}^H\left((\mathbf{H}^H)^+ + \mathbf{U}\mathbf{B}\right) = \mathbf{0}_{k,N-k}, \tag{8}$$

which will be only satisfied with an optimal set of coefficients in $\mathbf{B}$ that must be calculated using perfect CSI of the channel $\widetilde{\mathbf{H}}$. If perfect CSI is available at the MBS, the MBS can calculate an optimal $\mathbf{B}$ by expanding brackets in (8) and rearranging to obtain

$$\mathbf{B} = -(\widetilde{\mathbf{H}}^H\mathbf{U})^{-1}\widetilde{\mathbf{H}}^H(\mathbf{H}^H)^+. \tag{9}$$

For k FAP users, $\widetilde{\mathbf{H}}^H\mathbf{U}$ will be a $k \times k$ square matrix. Thus, $\mathbf{B}$ should always exist as long as $\widetilde{\mathbf{H}}^H\mathbf{U}$ is invertible, which is equivalent to having all channels independent of each other.

B. Imperfect CSI

Often, only imperfect CSI may be available at the MBS. We define the imperfect CSI as an erroneous MBS estimate of a particular true MBS-UE channel $\widetilde{\mathbf{h}}$, and is denoted as

$$\widetilde{\mathbf{h}}_{\text{est}} = \widetilde{\mathbf{h}} + \rho\mathbf{e}, \tag{10}$$

where $\mathbf{e}$ is random and independent normally distributed error with zero mean and unit variance, and $0 \leq \rho \leq 1$ is a scalar factor representing the degree of imperfection. Substituting $\widetilde{\mathbf{H}}_{\text{est}}$ in place of $\widetilde{\mathbf{H}}$ to calculate (9) and (6) will give a suboptimal solution and lead to interference suppression.

C. Codebook

In scenarios where the MBS has no access to any CSI, suppose that both UE and MBS have access to a predetermined orthonormal codebook, such as the Fourier codebook of discrete Fourier transform vectors, e.g.,

$$\text{codebook} = \begin{pmatrix}\mathbf{f}_1 & \mathbf{f}_2 & \dots & \mathbf{f}_N\end{pmatrix}. \tag{11}$$

The MBS may use each column as an estimate of $\widetilde{\mathbf{h}}$ to calculate the precoder, and use the vector which yields minimum interference, or the first one which is below an SINR threshold. This method does not require any complex training or adaptive process, and can be used if the MBS has no CSI.

TABLE I: Values of Simulation Parameters

Parameter	Value
MBS antennas	$N = 8$
FAP antennas	$N_f = 2$
Number of offloaded users	$k = 1$
UE antennas	1
Carrier frequency	2 GHz
Bandwidth	20 MHz
MBS transmit power	43 dBm
FAP transmit power	0 dBm
MBS distance to UE	100 m $\leq d_M \leq$ 500 m
FAP distance to UE	d_F = 10 m
MBS to UE path loss	15.3 + 37.6$\log_{10}(d_M)$ (dB)
FAP to UE path loss	38.5 + 20$\log_{10}(d_F)$ (dB)
Noise spectral density	-174 dBm/Hz
Imperfect CSI variance	$0.1 \leq \rho \leq 0.5$

D. Fourier Estimate

In scenarios where reliable channel feedback is not possible between UE and MBS, but CSI is known at the UE due to its detection of MBS pilot signals, UE can exploit the basic feedback capabilities between the FAP and MBS, or simply feedback from UE to MBS if a reliable backhaul doesn't exist. Suppose that $\widetilde{\mathbf{h}}$ is broken down into a linear combination of the codebook basis vectors. That is, $\widetilde{\mathbf{h}}$ can be written as

$$\widetilde{\mathbf{h}} = a_1\mathbf{f}_1 + a_2\mathbf{f}_2 + \ldots + a_N\mathbf{f}_N \tag{12}$$

for scalars a_i, $i = 1, \ldots, N$. If the largest two contributors with index values i and j are to be used as channel estimates, the MBS can receive feedback of i, j, a_i, a_j and use

$$\widetilde{\mathbf{h}}_{\text{est}} = a_i\mathbf{f}_i + a_j\mathbf{f}_j. \tag{13}$$

In general, the closer the channel estimate to the true channel, i.e., higher order estimate with more codebook components, the greater the interference suppression.

IV. Simulation Results

We compare the bit error rate (BER) performance with respect to downlink FAP transmission to one offloaded UE of our generalized inverse precoder under interference nulling and suppression scenarios. The conventional ZF precoder ($\mathbf{W} = (\mathbf{H}^H)^+$, i.e., MBS does nothing to reduce its interference to UE) serves as the lower bound for all possible interference suppression methods. For the Fourier estimate, the two largest contributions described by (13) are used as estimates, while the codebook method uses all codebook vectors and chooses the one that gives the lowest interference. All simulations use 16-QAM transmission at both the MBS and FAP, with perfect FAP-UE CSI known at the FAP. Precoders are calculated with normalized channel estimates, and interference calculated with normalized precoders.

Simulation parameters are presented in Table 1 [15]. The parameters were chosen so as to reflect worst case values and situations where significant interference is present. The axes of

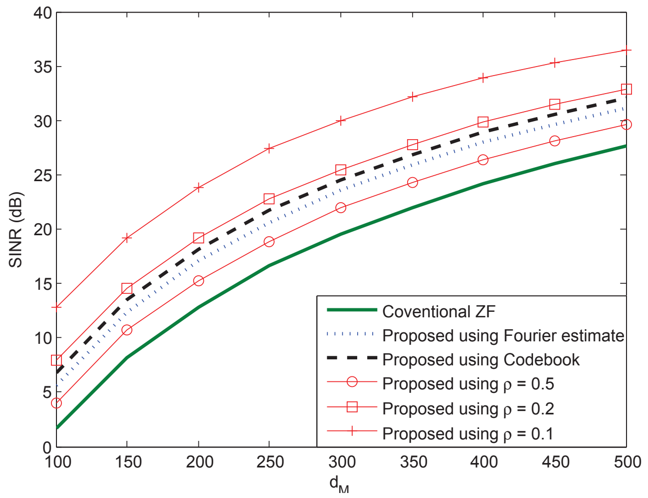

Fig. 2: MBS to UE distance (d_M) vs SINR at UE for various interference suppression methods.

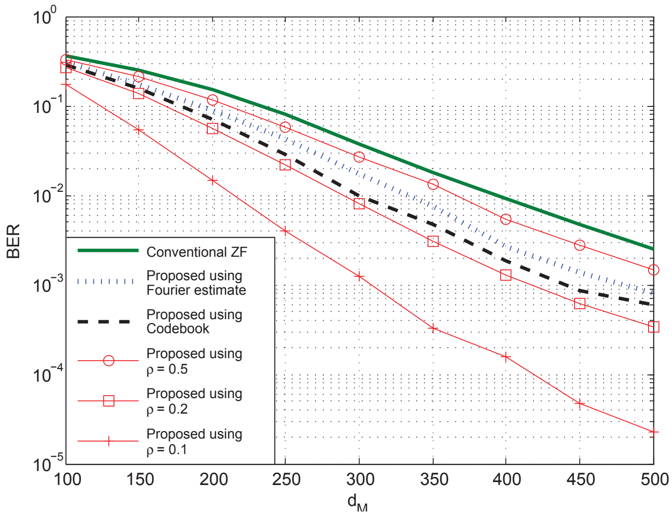

Fig. 3: MBS to UE distance (d_M) vs BER at UE for various interference suppression methods.

the figures were chosen so as to provide network planning and design insights, such as FAP positioning and hotspot locations.

Fig. 2 shows the SINR with varying MBS-UE distance. Even with imperfect CSI of $\rho = 0.5$, an almost 3 dB gain compared to conventional ZF can be made using the generalized inverse precoder, while a 10 dB gain is achieved if $\rho = 0.1$.

Fig. 3 plots the BER of the offloaded UE. The FAP transmit power is kept constant while the distance d_M, and hence interference, from the MBS is varied. Interference nulling using perfect CSI results in almost zero BER using the generalized inverse precoder, and thus for figure scaling the plot is not displayed. Comparing the proposed suboptimal methods for interference suppression, using an imperfect CSI estimate for precoder design outperforms the codebook based methods for $\rho = 0.2$, and is far better for even smaller ρ. For instance, for $\rho = 0.1$, an FAP may be placed twice as close to an interfering MBS and still achieve the same BER. Given that such imperfect CSI is often available at the MBS, using these estimates is therefore a practical precoding method. With no CSI knowledge, using a Fourier estimate may be a suitable low complexity alternative. Testing all codebook vectors does outperform the Fourier estimates but would likely be too computationally extensive for fast fading channels.

V. Conclusions

We presented in this paper an MBS precoder structure which, under perfect CSI, can completely null MBS interference to an FAP served user. Three practical methods are also proven to be beneficial, and in all scenarios no additional inter-user interference is introduced. Our generalized inverse precoder can achieve significant interference suppression under realistic imperfect CSI values or when using practical suboptimal methods, and will always benefit the offloaded user compared to conventional ZF precoding.

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