Downlink Interference Alignment

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***Abstract*—We develop an interference alignment (IA) technique for a downlink cellular system. In the uplink, IA schemes need channel-state-information exchange *across base-stations of different cells*, but our downlink IA technique requires feedback *only within a cell*. As a result, the proposed scheme can be implemented with a few changes to an existing cellular system where the feedback mechanism (within a cell) is already being considered for supporting multi-user MIMO. Not only is our proposed scheme implementable with little effort, it can in fact provide substantial gain especially when interference from a dominant interferer is significantly stronger than the remaining interference: it is shown that in the two-isolated cell layout, our scheme provides four-fold gain in throughput performance over a standard multi-user MIMO technique. We also show through simulations that our technique provides respectable gain under a more realistic scenario: it gives approximately 28% gain for a 19 hexagonal wrap-around-cell layout. Furthermore, we show that our scheme has the potential to provide substantial gain for *macro-pico* cellular networks where pico-users can be significantly interfered with by the nearby macro-BS.**

***Index Terms*—Downlink, interference alignment, macro-pico cellular networks, multi-user MIMO.**

I. Introduction

ONE of the key performance metrics in the design of cellular systems is that of cell-edge spectral efficiency. As a result, fourth-generation (4G) cellular systems, such as 3GPP-LTE [1] and WiMAX [2], require at least a doubling in cell-edge throughput over previous 3G systems [1]. Given the disparity between average and cell-edge spectral efficiencies (ratios of about 4:1) [2], the desire to improve cell-edge throughput performance is likely to continue.

Since the throughput of cell-edge users is greatly limited by the presence of co-channel interference from other cells, developing an intelligent interference management scheme is the key to improving cell-edge throughput. One interesting recent development, called *interference alignment* (IA) [3], [4], manages interference by aligning multiple interference signals in a signal subspace with dimension smaller than the number of interferers. While most of the work on IA [4]–[6] has focused on K point-to-point interfering links, it has also been shown in [7]–[9] that IA can be used to improve the cell-edge user throughput in a cellular network. In particular, it was shown in [7] that *near interference-free throughput* performance can be achieved in the cellular network.

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While IA promises substantial theoretical gain in cellular networks, it comes with challenges in implementation. First, the uplink IA scheme in [7] requires extensive channel-state-information (CSI) to be exchanged over the backhaul *between base-stations (BSs) of different cells*. A second challenge comes from realistic cellular environments that involve multiple unaligned out-of-cell interferers. Lastly, the integration of IA with other system issues, such as scheduling, needs to be addressed.

We propose a new IA technique for downlink cellular systems that addresses many of these practical concerns. Unlike the uplink IA scenario, our downlink IA scheme requires feedback only within a cell. As a consequence, our technique can be implemented with small changes to existing 4G standards where the within-a-cell feedback mechanism is already being considered for supporting multi-user MIMO.

Our proposed technique improves on the idea of the IA technique in [7] that aims to cancel interference only from one neighboring BS, which does well in a two-cell layout. In particular, the IA technique in [7] gives up the opportunity of providing matched-filtered gain (also called beam-forming gain in the case of multiple antennas) in the presence of a large number of interferers. Our new technique balances the two advantages of interference cancellation and matched-filtering gain, inspired by the idea of the standard MMSE receiver that unifies a zero-forcing receiver (optimal in the high SNR regime) and a matched filter (optimal in the low SNR regime). Through simulations, we show that our scheme provides approximately 60% and 28% gain in cell-edge throughput performance for a linear cell layout and 19 hexagonal wrap-around-cell layout, respectively, as compared to a standard multi-user MIMO technique.

We also find that our scheme has the potential to provide significant performance for heterogeneous networks [10], e.g., macro-pico cellular networks where dominant interference can be much stronger than the residual interference. For instance, pico-users can be significantly interfered with by the nearby macro-BS, as compared to the aggregated remaining BSs. We show that for these networks our scheme can give around 40% to 200% gain over the standard technique. Furthermore, our scheme is easily combined with a widely-employed opportunistic scheduler [11] for significant multi-user-diversity gain.

II. Review of Uplink Interference Alignment

System Model: We begin by reviewing uplink IA in [7]. Fig. 1 illustrates an example for the case of two isolated cells α and β. Suppose that there are K users in each cell and each user (e.g., user k in cell α) sends one symbol (or

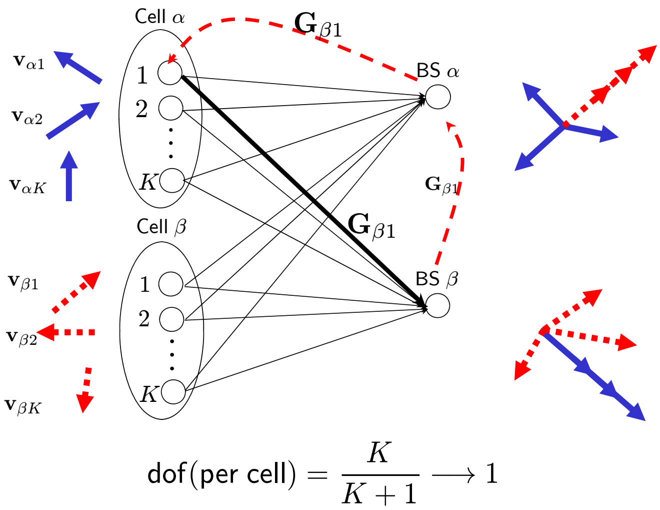


Fig. 1. Uplink interference alignment. Interference-free degrees-of-freedom can be asymptotically achieved with an increase in K. While this scheme provides promising theoretical gain, it comes with implementation challenge. The scheme requires each user to know its *cross*-channel information to the other BS and this may require exchange of cross-channel information over the backhaul between BSs of different cells.

stream) $x_{\alpha k} \in \mathbb{C}$ along a transmitted vector $\mathbf{v}_{\alpha k} \in \mathbb{C}^M$. We can generate multiple dimensions by using subcarriers (in an OFDM system), antennas, or both:

$$M = (\text{\# of subcarriers}) \times (\text{\# of transmit antennas}). \quad (1)$$

We avoid employing multiple time slots for creating dimensions. This is because the interference alignment technique (to be described shortly) requires knowledge of the CSI, but the future CSI is not available beforehand due to causality. Let S be the total number of streams. In this case, $S = K$, as all of the users are sending their own symbols.

The received signal of BS α is given by

$$\mathbf{y}_\alpha = \sum_{k=1}^{K} (\mathbf{H}_{\alpha k}\mathbf{v}_{\alpha k}) x_{\alpha k} + \sum_{k=1}^{K} (\mathbf{G}_{\alpha k}\mathbf{v}_{\beta k}) x_{\beta k} + \mathbf{z}_\alpha, \quad (2)$$

where $\mathbf{H}_{\alpha k} \in \mathbb{C}^{N\times M}$ indicates direct-channel from user k of cell α to BS α, and $\mathbf{G}_{\alpha k} \in \mathbb{C}^{N\times M}$ denotes cross-channel from user k of cell β to BS α. We assume that the channels are constant over a few time slots with respect to channel estimation and CSI feedback procedures. Here N is the number of dimensions at the receiver: $N =$ (# of subcarriers) $\times$ (# of receive antennas). We focus on the symmetric configuration, i.e., $M = N$. In fact, the extension to the asymmetric case is not straightforward, although we will provide a natural, but potentially suboptimal, variant of the IA scheme (to be described) in Section VII-A. We will discuss more details in Section VII-A. Note that the combined use of antennas and subcarriers induces a block-diagonal structure for the channel matrices. We assume that noise is additive white Gaussian and without loss of generality assume that it has unit power, i.e., $\mathbf{z}_\alpha \sim \mathcal{CN}(0, \mathbf{I})$.

Description: The idea of interference alignment is to design the transmitted vectors so that they are aligned onto a one-dimensional linear subspace at the other BS. Specifically, user k in cell β sets its transmitted vector as $\mathbf{v}_{\beta k} = \mathbf{G}_{\alpha k}^{-1}\mathbf{v}_{\text{ref}}$, where $\mathbf{v}_{\text{ref}} \in \mathbb{C}^M$ is an arbitrary non-zero vector that can be fixed, independent of channel state information, e.g., $\mathbf{v}_{\text{ref}} = [1, \cdots, 1]^t$, where $[\cdot]^t$ indicates a transpose. Similarly user k in cell α sets its transmitted vector as $\mathbf{v}_{\alpha k} = \mathbf{G}_{\beta k}^{-1}\mathbf{v}_{\text{ref}}$. We use the same $\mathbf{v}_{\text{ref}}$ across the cells, although it can be different. The received signal of BS α is then

$$\mathbf{y}_\alpha = \sum_{k=1}^{K} (\mathbf{H}_{\alpha k}\mathbf{G}_{\beta k}^{-1}\mathbf{v}_{\text{ref}}) x_{\alpha k} + \mathbf{v}_{\text{ref}} \left(\sum_{k=1}^{K} x_{\beta k} \right) + \mathbf{z}_\alpha. \quad (3)$$

Notice that the interference space collapses to a one-dimensional linear subspace spanned by the $\mathbf{v}_{\text{ref}}$. On the other hand, due to the randomness in wireless channels, the transmitted vectors associated with the desired symbols $x_{\alpha k}$'s are likely to be linearly independent. Note that for $M = K + 1$, $\text{rank} \left[\mathbf{H}_{\alpha 1}\mathbf{G}_{\beta 1}^{-1}\mathbf{v}_{\text{ref}}, \cdots, \mathbf{H}_{\alpha K}\mathbf{G}_{\beta K}^{-1}\mathbf{v}_{\text{ref}} \right] = K$, while the interference signals only occupy a one-dimensional subspace. Hence, the BS can recover K desired symbols using $K + 1$ dimensions. Notice that this full rank condition holds with high probability under typical wireless channels and for the block-diagonal structure of the channel matrices. The performance in the interference-limited regime can be captured by a notion of degrees-of-freedom (dof). Here, the dof per cell $= \frac{K}{K+1}$. We use the notion normalized by the total number $M = K+1$ of dimensions. Notice that as K gets large, we can asymptotically achieve interference-free dof $= 1$.

While this IA technique provides promising theoretical gain, it comes with some implementation challenge. The IA scheme requires each user to know its *cross*-channel information to the other BS. While in a time-division-multiplexing system, channels can be estimated using reciprocity, in a frequency-division-multiplexing system, an implementation issue arises. One way to obtain the cross-channel is that the other-cell BS directly feeds back the cross-channel information to the users. However, this requires additional communication sessions between different cells, thus increasing the control channel overhead. Another way (possibly more plausible) is to exchange such channel knowledge over the backhaul between BSs of different cells. Fig. 1 shows a route to obtain the CSI of $\mathbf{G}_{\beta 1}$: *BS* $\beta \rightarrow$ *backhaul* $\rightarrow$ *BS* $\alpha \rightarrow$ *feedback* $\rightarrow$ *user* 1 *of cell* α. However, this requires the use of additional links (backhaul). On the contrary, in the downlink, we show that IA can be applied without inter-cell communication sessions or backhaul cooperation, thereby resolving this implementation issue.

III. Downlink Interference Alignment

A. Description

Fig. 2 illustrates an example of downlink IA where there are two users $(K = 2)$ in each cell. The uplink-downlink duality theorem [7], [12], [13] states that the dof of the uplink is the same as that of the downlink. Hence, in this example, the dof per cell $= \frac{K}{K+1} = \frac{2}{3}$. To achieve this, each BS needs to send two streams $S = 2$ over three dimensions $M = 3$. The idea is similar to that of the uplink IA in a sense that two dimensions are used for transmitting desired signals and the remaining one dimension is reserved for interference signals. However, the method of interference alignment is different.

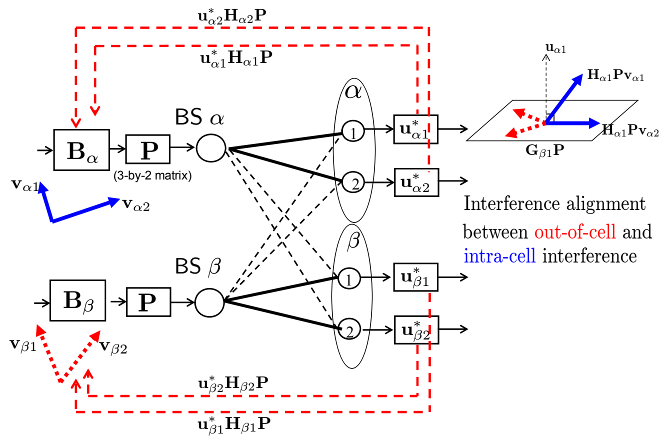


Fig. 2. Downlink interference alignment. Interference alignment is achieved between out-of-cell and intra-cell interference vectors at multiple users at the same time. Unlike the uplink IA, our downlink IA scheme does not require backhaul cooperation or inter-cell communication sessions.

While in the uplink, we set the reference vector $\mathbf{v}_{\text{ref}}$ at receivers, in the downlink, we fix a M-by-S precoder matrix $\mathbf{P}$ at transmitters. Remember that $M = 3$ and $S = 2$ in this example. Notice that this fixed precoder is independent of channel gains. For simplicity we use the same precoder, although it can be different across cells. Each BS (e.g., BS α) has a second precoder $\mathbf{B}_\alpha = [\mathbf{v}_{\alpha 1}, \mathbf{v}_{\alpha 2}] \in \mathbb{C}^{2\times 2}$, which precedes the fixed precoder. Using these two cascaded precoders, it sends two symbols ($x_{\alpha 1}$, $x_{\alpha 2}$), each of which is intended for each user in the cell. The received signal of user k in cell α is then given by

$$\mathbf{y}_{\alpha k} = \mathbf{H}_{\alpha k}\mathbf{P}(\mathbf{v}_{\alpha 1}x_{\alpha 1} + \mathbf{v}_{\alpha 2}x_{\alpha 2}) + \underbrace{\mathbf{G}_{\beta k}\mathbf{P}\sum_{k=1}^{2}\mathbf{v}_{\beta k}x_{\beta k}}_{\text{out-of-cell interference}} + \mathbf{z}_{\alpha k},$$

where $\mathbf{H}_{\alpha k} \in \mathbb{C}^{3\times 3}$ indicates the direct-channel from BS α to user k of cell α, and $\mathbf{G}_{\beta k} \in \mathbb{C}^{3\times 3}$ denotes the cross-channel from BS β. With a minor abuse of notation, we use the same notation as we did in the uplink. We assume that $\mathbf{z}_{\alpha k} \sim \mathcal{CN}(0, \mathbf{I})$.

Next, user k in cell α estimates the interference $\mathbf{G}_{\beta k}\mathbf{P}$ using pilots or a preamble. It then generates a null vector $\mathbf{u}_{\alpha k}$ such that $\mathbf{u}_{\alpha k}^*\mathbf{G}_{\beta k}\mathbf{P} = 0$ (and $||\mathbf{u}_{\alpha k}|| = 1$). Since the $\mathbf{G}_{\beta k}\mathbf{P}$ is of dimension 3-by-2, such a vector $\mathbf{u}_{\alpha k}$ always exists, and when applied to the received signal, it will null out the out-of-cell interference: $\tilde{y}_{\alpha k} := \mathbf{u}_{\alpha k}^*\mathbf{y}_{\alpha k} = \mathbf{u}_{\alpha k}^*\mathbf{H}_{\alpha k}\mathbf{P}(\mathbf{v}_{\alpha 1}x_{\alpha 1} + \mathbf{v}_{\alpha 2}x_{\alpha 2}) + \tilde{z}_{\alpha k}$, where $\tilde{z}_{\alpha k} := \mathbf{u}_{\alpha k}^*\mathbf{z}_{\alpha k} \sim \mathcal{CN}(0, 1)$. Note that the receive vector $\mathbf{u}_{\alpha k}$ does not guarantee the cancellation of intra-cell interference intended for the other user in the same cell α. This is accomplished as follows. User k feeds back its equivalent channel $\mathbf{u}_{\alpha k}^*\mathbf{H}_{\alpha k}\mathbf{P}$ (obtained after applying the receive vector) to its own BS α. BS α then applies the following zero-forcing precoder $\mathbf{B}_\alpha$ (which precedes the fixed precoder $\mathbf{P}$):

$$\mathbf{B}_\alpha := [\mathbf{v}_{\alpha 1}, \mathbf{v}_{\alpha 2}] = \begin{bmatrix} \mathbf{u}_{\alpha 1}^*\mathbf{H}_{\alpha 1}\mathbf{P} \\ \mathbf{u}_{\alpha 2}^*\mathbf{H}_{\alpha 2}\mathbf{P} \end{bmatrix}^{-1} \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix} \in \mathbb{C}^{2\times 2},$$

where γ_k is a normalization factor for meeting the transmit power constraint. Considering user 1's received signal, this zero-forcing precoder guarantees that user 2's transmitted signal $\mathbf{H}_{\alpha 1}\mathbf{P}\mathbf{v}_{\alpha 2}$ lies in the interference space $\mathbf{G}_{\beta 1}\mathbf{P}$. Note that $\mathbf{u}_{\alpha 1}^*(\mathbf{H}_{\alpha 1}\mathbf{P}\mathbf{v}_{\alpha 2}) = 0$. This enables user 1 to recover its own signal. Similarly, user 2 can recover its signal and therefore BS α can send 2 symbols using 3 dimensions, thus achieving dof per cell $= \frac{2}{3}$. In fact, a series of these operations enables interference alignment, as will be explained in Remark 1. Also this scheme makes use of zero-forcing receive vector. Hence, we call this scheme *zero-forcing IA*.

*Remark 1 (**Interference Alignment Interpretation**):* Observing the interference plane of user 1 in cell α, we can see this scheme achieves interference alignment. Note that three interference vectors - two *out-of-cell* interference vectors and one *intra-cell* interference vector - are aligned onto a two-dimensional linear subspace. Interference alignment is achieved between out-of-cell and intra-cell interference signals. Without carefully designing the transmit-and-receive vector pairs, three interfering vectors span three dimensions in general. However, our IA technique enables us to constrain the interference within only two dimensions (not three), thus enabling us to transmit in one dimension interference-free. ■

*Remark 2 (**Feedback Mechanism**):* Note two key system aspects of the technique. First, unlike the uplink IA, the exchange of cross-channel information between BSs or between users in different cells is not needed. Each BS can fix precoder $\mathbf{P}$, *independent of channel gains*. Each user can then specify the null space orthogonal to the out-of-cell interference signal space. This enables the user to design a zero-forcing receive vector *without knowing the interfering vectors that were actually transmitted*. For example, user 1 in cell α can compute $\mathbf{u}_{\alpha 1}$ without knowing $\mathbf{B}_\beta\mathbf{P}$ (the interfering vectors actually transmitted). Each user then feeds back its equivalent channel $\mathbf{u}_{\alpha k}\mathbf{H}_{\alpha k}\mathbf{P}$ and the BS forms the zero-forcing transmit vectors *only with the feedback of the equivalent channels*. Hence, the scheme requires only within-a-cell feedback mechanism. This is in contrast to the uplink IA which requires inter-cell communication sessions or backhaul cooperation between different BSs.

Secondly, while feedback is required from the user to the BS, this feedback is the same as the feedback used for standard multi-user MIMO techniques. The only difference is that in downlink IA, two cascaded precoders (e.g., $\mathbf{B}_\alpha$ and $\mathbf{P}$) are used and the receive vector of each user is chosen as a null vector of out-of-cell interference signal space. Therefore, the scheme can be implemented with little change to an existing cellular system supporting multi-user MIMO. ■

B. Performance and Limitations

Fig. 3 shows the sum-rate performance of zero-forcing IA in a two-isolated cell layout where $M = 4$ (e.g., a 4-by-4 antenna configuration), the number S of streams is $M - 1 = 3$ and the total number K of users in each cell is 3. As a baseline scheme, we use a *matched filter receiver*: one of the standard multi-user MIMO techniques [14], [15]. This baseline uses the dominant left-singular vector of the direct-channel as a receive vector:

$$\mathbf{u}_{\alpha k}^{\text{MF}} = \text{a maximum left-singular vector of } \mathbf{H}_{\alpha k}. \quad (4)$$

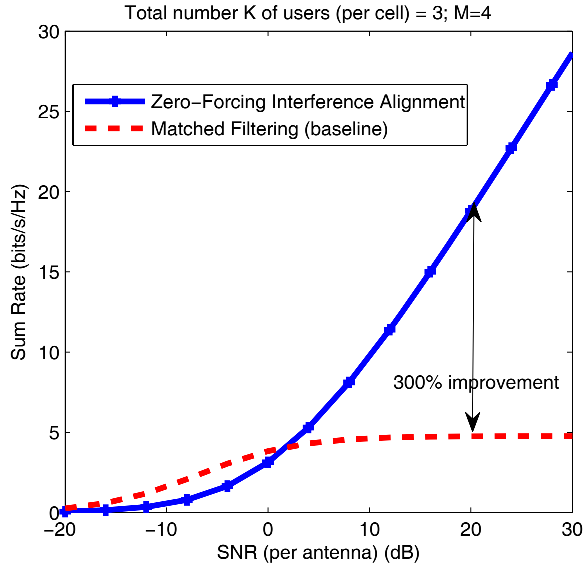


Fig. 3. Performance of zero-forcing interference alignment for a two-isolated cell layout where $M = 4$ (e.g., a 4-by-4 antenna configuration), the number S of streams is $M - 1 = 3$ and the total number K of users in each cell is 3.

Note that the matched filter receiver maximizes beam-forming gain while ignoring the interference signal space. We assume a zero-forcing vector at the transmitter to null out intra-cell interference. Nulling intra-cell interference is important as its power has the same order as the desired signal power. The zero-forcing transmit vectors are designed as:

$$[\mathbf{v}_{\alpha 1}^{\mathsf{ZF}}, \cdots, \mathbf{v}_{\alpha S}^{\mathsf{ZF}}] = \mathbf{H}^*(\mathbf{H}\mathbf{H}^*)^{-1}\mathsf{diag}\{\gamma_1, \cdots, \gamma_S\} \in \mathbb{C}^{M \times S}, \tag{5}$$

where γ_k is a normalization factor and $\mathbf{H} := [\mathbf{u}_{\alpha 1}^{\mathsf{MF}*}\mathbf{H}_{\alpha k}; \cdots ; \mathbf{u}_{\alpha S}^{\mathsf{MF}*}\mathbf{H}_{\alpha k}] \in \mathbb{C}^{S \times M}$ denotes the composite matrix.

Note that in (4), receiver vectors are initially chosen as dominant left-singular vectors of the channels, as transmit vectors are not decided yet. However, once transmit vectors are designed as above, we can now update the receiver vectors so as to maximize beam-forming gain by aligning them into the determined direction of the transmitted signals. Given the updated received vectors, we can also update the transmit vectors accordingly. This iterative algorithm was introduced in [14], [15] and we call this scheme *iterative matched filtering*.

While in matched filtering, this iterative procedure updates the receive-and-transmit vector pairs to potentially improve the performance, in the zero-forcing IA, it does not change the vector pairs. Recall that the receive vector in the IA scheme depends only on the interference space, so it is irrelevant to the transmit vectors. Hence, for fair comparison of CSI overhead, we assume no iteration for the matched filtering in Fig 3: the receive-and-transmit vectors are designed successively according to (4) and (5) without any iterations.

In Fig. 3, one can clearly see that the zero-forcing IA provides significant performance gain over the matched filtering. In fact, for large SNR, the scheme provides the asymptotically optimal performance, since it achieves the optimal dof [7]. The gain comes from the fact that in the two-isolated-cell case, there exists only a single interferer (no residual interferers) and our IA scheme completely removes the interference from the single interferer.

However, for realistic multi-cellular environments, the performance may not be very good due to the remaining interferers. In order to take multi-cellular environments into account, we introduce a parameter γ that captures the relative strength of the interference power from a dominant interferer to the remaining interference power (summed from the other BSs):

$$\gamma := \frac{\mathsf{INR}_{\mathsf{rem}}}{\mathsf{INR}_{\mathsf{dom}}}, \tag{6}$$

where $\mathsf{INR}_{\mathsf{dom}}$ and $\mathsf{INR}_{\mathsf{rem}}$ denote the ratios of the dominant and aggregate interference power over the noise power, respectively. Note that by adapting γ, one can cover arbitrary mobile location and cellular layouts.

While, at one extreme ($\gamma = 0$), the zero-forcing IA provides significant performance, at the other extreme ($\gamma \gg 1$), the scheme may not be good as it completely loses receive beam-forming gain. Remember that the zero-forcing IA receiver depends only on the interference space and therefore it is independent of the direct-channel, thus losing beam-forming gain. In this case, one can expect that matched filtering will perform much better than the IA scheme. This motivates the need for developing a new IA technique that can balance the degrees-of-freedom gain with the matched-filtered power gain depending on the value of γ.

IV. Proposed New IA Scheme

The zero-forcing IA and matched filtering schemes are analogous to a conventional zero-forcing receiver and a matched-filter receiver in a point-to-point channel with colored noise. So it is natural to think of a unified technique like the standard MMSE receiver. However, in our cellular context, a straightforward design of an MMSE receiver requires the knowledge of transmitted vectors from the other cell. Moreover, a chicken-and-egg problem arises between different cells, due to the interconnection of the transmit-and-receive vector pairs. In order to *decouple* the vector design between cells, we consider uncoordinated systems, i.e., transmit vector information is not exchanged between different cells. Under this assumption, a goal is to mimic an MMSE receiver.

A. Idea

The idea for accomplishing this goal consists of three parts: (1) *coloring* an interference signal space, independent of the actually transmitted vectors; (2) designing a coloring parameter κ (to be defined shortly) to unify the two extreme cases: $\gamma \ll 1$ and $\gamma \gg 1$; (3) designing an MMSE-like receiver based on the coloring parameter.

Coloring the interference space: We employ two cascaded precoders: (1) a *fixed* precoder $\bar{\mathbf{P}} \in \mathbb{C}^{M \times M}$ located at the front-end; and (2) a zero-forcing precoder $\mathbf{B}_\alpha \in \mathbb{C}^{M \times S}$ which precedes the $\bar{\mathbf{P}}$. To differentiate with the precoder $\mathbf{P}$ used for the zero-forcing IA, we use different notation $\bar{\mathbf{P}}$. With this

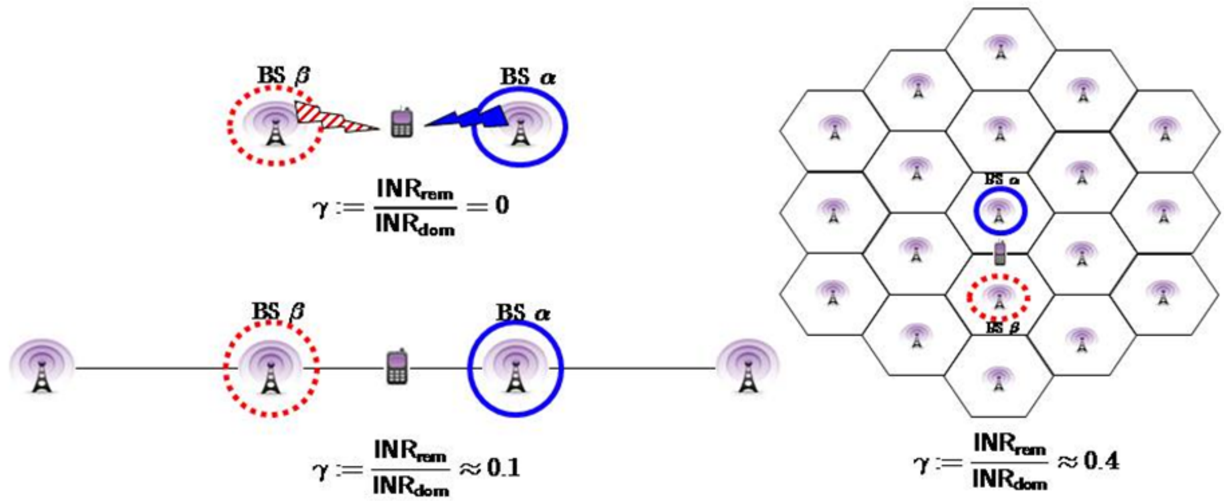


Fig. 4. Different layouts in a downlink cellular system. A parameter γ indicates the relative strength of the interference power from a dominant interferer to the remaining interference power (summed from the other BSs).

fixed precoder, we can color the interference space, to some extent, to be independent of the zero-forcing precoder. To see this, we first consider the covariance matrix of interference-plus-noise at user k in cell α:

$$\mathbf{\Phi}_k = (1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S}(\mathbf{G}_{\beta k}\bar{\mathbf{P}}\mathbf{B}_\beta\mathbf{B}_\beta^*\bar{\mathbf{P}}^*\mathbf{G}_{\beta k}^*), \quad (7)$$

where S is the total number of streams ($S \leq M$) and $\mathbf{B}_\beta$ indicates the zero-forcing precoder of a dominant interferer (BS β): $\mathbf{B}_\beta = [\mathbf{v}_{\beta 1}, \cdots, \mathbf{v}_{\beta S}] \in \mathbb{C}^{M\times S}$. Here we make several assumptions: noise power is normalized to 1 (without loss of generality); the total transmission power is equally allocated to each stream; and the aggregate interference except the dominant interference is white Gaussian. To be more accurate, we may include two or three dominant interferers in the process of computing $\mathbf{\Phi}_k$, assuming that the remaining interference except the multiple dominant interferers is white Gaussian. We will further discuss this issue in Section VII-C.

Since we consider uncoordinated systems, $\mathbf{B}_\beta$ is unknown to each user in cell α and therefore it is impossible to compute $\mathbf{\Phi}_k$. This motivates us to use the expected value of the covariance matrix averaged over $\mathbf{B}_\beta$: $\bar{\mathbf{\Phi}}_k := \mathbb{E}[\mathbf{\Phi}_k] = (1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S}(\mathbf{G}_{\alpha k}\bar{\mathbf{P}}\mathbb{E}[\mathbf{B}_\beta\mathbf{B}_\beta^*]\bar{\mathbf{P}}^*\mathbf{G}_{\alpha k}^*)$. Without the knowledge of $\mathbf{B}_\beta$, we can then control the coloredness of interference signals by carefully designing $\bar{\mathbf{P}}$. The idea is to differently weight the last $(M-S)$ columns of $\bar{\mathbf{P}}$ with a parameter κ ($0 \leq \kappa \leq 1$):

$$\bar{\mathbf{P}} = [\mathbf{f}_1, \cdots, \mathbf{f}_S, \kappa\mathbf{f}_{S+1}, \cdots,\ \kappa\mathbf{f}_M] \in \mathbb{C}^{M\times M}, \quad (8)$$

where $[\mathbf{f}_1, \cdots, \mathbf{f}_M]$ is an orthogonal matrix.

Before describing how to design κ and seeing how this colors interference signals, we will first explain how to compute $\mathbb{E}[\mathbf{B}_\beta\mathbf{B}_\beta^*]$ and how to decide the norm of each column vector of $\bar{\mathbf{P}}$ for meeting the transmit power constraint. In computing $\mathbb{E}[\mathbf{B}_\beta\mathbf{B}_\beta^*]$, we assume the statistics of $\mathbf{B}_\beta$. Since $\mathbf{B}_\beta$ is the zero-forcing precoder of BS β, it has the following form: $\mathbf{B}_\beta = \mathbf{H}^*\left(\mathbf{H}\mathbf{H}^*\right)^{-1}\mathsf{diag}\{\gamma_1, \cdots, \gamma_S\}$, where $\mathbf{H} := \left[\mathbf{u}_{\beta 1}^*\mathbf{H}_{\beta 1}\bar{\mathbf{P}}; \cdots; \mathbf{u}_{\beta S}^*\mathbf{H}_{\beta S}\bar{\mathbf{P}}\right]$. Note that $\mathbf{B}_\beta$ is coupled with $\bar{\mathbf{P}}$, so its statistics depend on κ. With a close observation of $\mathbf{B}_\beta$, one can see that the last $(M-S)$ rows of $\mathbf{B}_\beta$ is biased by a factor of κ. This motivates us to assume that each entry of $\mathbf{B}_\beta$ of the first S rows is i.i.d $\mathcal{CN}\left(0, \frac{1}{S+(M-S)\kappa^2}\right)$ and each entry of the last $(M-S)$ rows is i.i.d. $\mathcal{CN}\left(0, \frac{\kappa^2}{S+(M-S)\kappa^2}\right)$. Under this assumption, we can then compute $\mathbb{E}[\mathbf{B}_\beta\mathbf{B}_\beta^*]$ to get:

$$\begin{aligned}\bar{\mathbf{\Phi}}_k :=& \mathbb{E}[\mathbf{\Phi}_k] = (1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S+(M-S)\kappa^2}\times \\ &\left(\mathbf{G}_{\alpha k}\bar{\mathbf{P}}\begin{bmatrix}\mathbf{I}_S & \mathbf{0}\\ \mathbf{0} & \kappa^2\mathbf{I}_{M-S}\end{bmatrix}\bar{\mathbf{P}}^*\mathbf{G}_{\alpha k}^*\right).\end{aligned} \quad (9)$$

Considering the transmit power constraint, we can now decide the norm of each column vector of $\bar{\mathbf{P}}$: $||\mathbf{f}_i||^2 = \frac{S+(M-S)\kappa^2}{S+(M-S)\kappa^4}, \forall i$. Note that this choice satisfies the transmit power constraint, i.e., $\mathsf{trace}\left[\bar{\mathbf{P}}\mathbb{E}[\mathbf{B}_\beta\mathbf{B}_\beta^*]\bar{\mathbf{P}}^*\right] = S$.

Designing a coloring parameter κ: We now present how to design the coloring parameter κ. Two extreme cases give insights into this design. When the residual interference is negligible, i.e., $\gamma \ll 1$, the scheme should mimic the zero-forcing IA, so $\bar{\mathbf{P}}$ should be rank-deficient, i.e., $\kappa = 0$. In this case, the null space of the interference signals can be specified, independent of $\mathbf{B}_\beta$. As a result, the *expected* covariance matrix acts as the *actual* covariance matrix, thus inducing the same solution as the zero-forcing IA. At the other extreme ($\gamma \gg 1$), the scheme should mimic matched filtering. This motivates us to choose a unitary matrix $\bar{\mathbf{P}}$ (i.e., $\kappa = 1$) so that the $\bar{\mathbf{\Phi}}_k$ is close to $a\mathbf{I}$ for some scalar a. For an intermediate value of γ, we propose the following to sweep between the two cases:

$$\kappa = \min\left(\gamma^{1/4}, 1\right). \quad (10)$$

The use of the function $(\cdot)^{1/4}$ which relates γ to κ is our heuristic choice based on simulation results for some particular values of γ, SNR and other configurations. Specifically, for a 19 hexagonal cellular layout ($\gamma \approx 0.4$) and ($\mathsf{SNR} = 20$ dB$, M = 4, S = 3, K = 3$), we plot the sum-rate of the proposed scheme as a function of κ and then find κ

that maximizes the sum-rate (via a grid search). From this experiment, we conjecture the relationship between γ and κ. We find that the function $(\cdot)^{1/4}$ well matches the relationship, thus proposing this heuristic. One may optimize κ in a more precise manner. For example, one may choose optimal κ case-by-case for each configuration and with a finer grid-step-size.

In the above choice, κ varies with mobile location, since $\mathsf{INR}_{\mathsf{rem}}$ is a function of mobile location. This can be undesirable because it requires frequent adaptation of BS precoder which supports users from the cell center to the cell edge. Therefore, *we propose to fix* κ. In the interests of improving the worst-case performance (cell-edge performance), we fix κ, based on the cell-edge mobile location for a given network layout. For example, we use $\kappa \approx 0.57$ for the linear cell layout and $\kappa \approx 0.80$ for the 19 hexagonal wrap-around cell layout (see Fig. 4). Since our choice focuses on improving the cell-edge throughput, less performance gain is expected for cell-interior users.

Alternatively, we can have different κ factors, depending on whether the BS is precoding for cell-edge vs. cell-interior users. This would require different $\bar{\mathbf{P}}$ matrices, and would add to the complexity of the system, but would optimize performance for all users in the cell.

Designing a MMSE-like receiver: With the above $\bar{\mathbf{\Phi}}_k$, we then use the standard formula of an MMSE receiver: $\mathbf{u}_{\alpha k} = \frac{\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}}{||\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}||} \in \mathbb{C}^M$. Similar to the iterative matched filtering technique, we also employ an iterative approach to compute transmit-and-receive vector pairs.

B. Integration with a scheduler

We consider integration of our scheme with a scheduler: one of the important system issues that need to be considered in cellular systems. Designing the coloring parameter κ and controlling the number S of streams, our proposed scheme balances the degrees-of-freedom gain (IA gain) with matched-filtered power gain depending on the value of γ. Importantly, scheduler gain is closely coupled with these gains, as it can play significant role in providing beam-forming power gain. For instance, an opportunistic scheduler [11] exploits multi-user diversity to provide good signal separation and power gain, thus inducing the high SINR regime where degrees-of-freedom gain affects the performance more significantly than beam-forming power gain does. Hence, it is important to carefully design the scheme considering the integration with a scheduler, so as to well balance the degrees-of-freedom gain and power gain.

In this paper, we employ an opportunistic scheduler [11], which chooses a set of S users out of total K users such that the sum rate is maximized. We consider uncoordinated schedulers, i.e., scheduling information is not exchanged between different BSs.

C. Algorithm Description

We now describe an algorithm of the proposed IA scheme incorporating an opportunistic scheduler. Here is the algorithm.

1) (*Intialization*): Each user initializes its receive vector as follows: $\forall k \in \{1, \cdots, K\}$,

$$\mathbf{u}_{\alpha k}^{(0)} = \frac{\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(0)}}{||\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(0)}||} \in \mathbb{C}^M, \qquad (11)$$

where we set $\mathbf{v}_{\alpha k}^{(0)}$ as a maximum eigenvector of $\bar{\mathbf{P}}^*\mathbf{H}_{\alpha k}^*\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}$ to initially maximize beam-forming gain. Each user then feeds back the equivalent channel $\mathbf{u}_{\alpha k}^{(0)*}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}$ to its own BS.

2) (*Designing Transmit Vectors*): Fix a set $A \in \mathcal{K}$ where $\mathcal{K}$ is a collection of subsets of $\{1, \cdots, K\}$. As for the elements in $\mathcal{K}$, we consider all of the possible candidates that have cardinality S, i.e., $|\mathcal{K}| = \binom{K}{S}$. For the given A, with the feedback information, the BS computes zero-forcing transmit vectors

$$\mathbf{B}_\alpha := [\mathbf{v}_{\alpha k_1}^{(1)}, \cdots, \mathbf{v}_{\alpha k_S}^{(1)}] = \mathbf{H}^{(1)*}(\mathbf{H}^{(1)}\mathbf{H}^{(1)*})^{-1} \times \mathsf{diag}\left\{\gamma_1^{(1)}, \cdots, \gamma_S^{(1)}\right\} \in \mathbb{C}^{M \times S},$$

where $k_l \in A$, $\gamma_l^{(1)}$ is a normalization factor, and $\mathbf{H}^{(1)} := [\mathbf{u}_{\alpha k_1}^{(0)*}\mathbf{H}_{\alpha k_1}\bar{\mathbf{P}}; \cdots; \mathbf{u}_{\alpha k_S}^{(0)*}\mathbf{H}_{\alpha k_S}\bar{\mathbf{P}}] \in \mathbb{C}^{S \times M}$. Remember that the fixed precoder $\bar{\mathbf{P}}$ is designed so that each column vector of $\mathbb{E}[\bar{\mathbf{P}}\mathbf{B}_\alpha]$ is normalized. So $\bar{\mathbf{P}}\mathbf{B}_\alpha$ is not guaranteed to be normalized. Hence, the BS re-normalizes $\bar{\mathbf{P}}\mathbf{B}_\alpha$ with $\tilde{\gamma}_l^{(1)}$ so that each column vector of $\bar{\mathbf{P}}\mathbf{B}_\alpha\mathsf{diag}\left\{\tilde{\gamma}_1^{(1)}, \cdots, \tilde{\gamma}_S^{(1)}\right\}$ is normalized.

3) (*Opportunistic Scheduling*): The BS finds A^* such that

$$A^* = \arg\max_{A \in \mathcal{K}} \sum_{k \in A} \log\left(1 + \frac{\frac{\mathsf{SNR}}{S}||\tilde{\gamma}_k^{(1)}\mathbf{u}_{\alpha k}^{(0)*}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(1)}||^2}{1 + \mathsf{INR}_{\mathsf{rem}}}\right).$$

4) (*Iteration*): For the A^*, we iterate the following. The BS informs each user of $\mathbf{v}_{\alpha k}^{(i)}$ via precoded pilots. Each user updates the receive vector as follows:

$$\mathbf{u}_{\alpha k}^{(i)} = \frac{\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(i)}}{||\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(i)}||} \in \mathbb{C}^M, \quad k \in A^*.$$

Each user then feeds back the updated equivalent channel to its own BS. With this feedback information, the BS computes zero-forcing transmit vectors $\mathbf{v}_{\alpha k}^{(i+1)}$.

Remark 3: Although users can see out-of-cell interference, the scheduler at BS cannot compute it without some side-information from the users. Hence, we assume that the scheduler makes a decision assuming no dominant interference. Note that the denominator inside the logarithmic term contains only noise and residual interference. To reduce CSI overhead, we assume that a scheduler decision is made before the *iteration* step. ■

In practice, we may prefer not to iterate, since it requires more feedback information. Note that the feedback overhead is exactly the same as that of iterative matched-filtering (baseline). The only difference is that we use the fixed precoder $\bar{\mathbf{P}}$ and the MMSE-like receiver employing $\bar{\mathbf{\Phi}}_k$. *This requires little change to an existing cellular system supporting multi-user MIMO.*

V. Simulation Results

A. Setup

Through simulations, we evaluate the performance of the proposed scheme for downlink cellular systems. We consider one of the possible antenna configurations in the 4G standards [1], [2]: 4 transmit and 4 receive antennas. To minimize the change to the existing 4G systems, we consider using only antennas for the multiple dimensions, i.e., $M = 4$. We focus on three different cellular layouts, illustrated in Fig. 4.

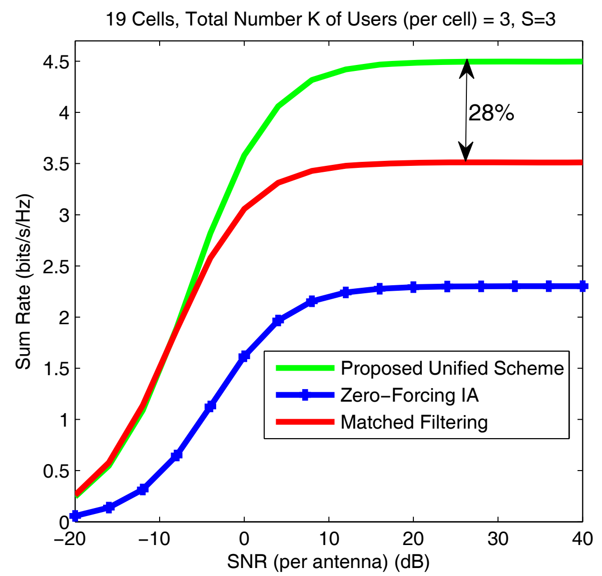
In the interests of improving the worst-case throughput performance, we consider a cell-edge mobile location. Specifically, we assume that all of the K users in each cell are placed at the mid-point between two adjacent cells. This simulation setup can reflect the scenarios where user locations, once chosen, are almost static, e.g., working places located in the cell-edge. On the other hand, one may be interested in simulating per-user throughput distribution assuming different user locations, so as to evaluate the system-wide benefits of the proposed scheme. In this case, we expect less performance gain of our proposed IA scheme, as it considers a single γ and the corresponding κ, which are based on cell-edge users. Evaluating this system-level performance more precisely is beyond the scope of this paper, but eventually this needs to be considered as future work.

We use the standard ITU-Ped path-loss model, with i.i.d. Rayleigh fading components for each of the antenna. We assume that inter-BS distance is 1 km and path-loss exponent is 3.76. As for an interference model, we exactly model the interference of the neighboring BS (the dominant interferer), while assuming that the aggregated interference of the remaining BSs is white Gaussian. This white Gaussian assumption on the residual interference provides the lower bound of the performance of all the schemes we will consider shortly. This is because each of the techniques can exploit the knowledge of interference, and the white interference is a worst case assumption.

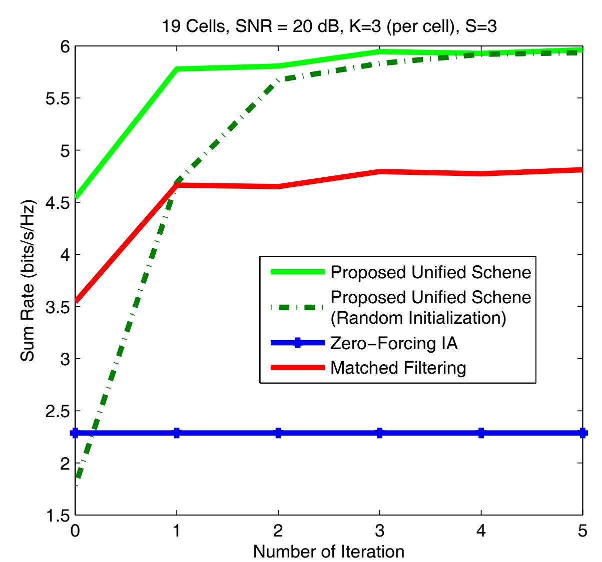
B. Performance

Fig. 5 shows the sum-rate performance for a 19 hexagonal cellular layout where $\gamma \approx 0.4$. We assume that total number K of users in each cell is 3 and consider the number $S = 3$ of streams. Note that the zero-forcing IA is worse than the matched filtering (baseline). This implies that when $\gamma \approx 0.4$ (residual interference is not negligible), boosting power gain gives better performance than mitigating dominant out-of-cell interference. However, the proposed unified IA technique outperforms both of them for all regimes. It gives approximately 28% throughput gain when SNR $= 20$ dB.

We also investigate the convergence of the proposed scheme. Note in Fig. 5(b) that the proposed scheme converges to the limits very fast, i.e., even one iteration is enough to derive most of the asymptotic performance gain. This means that additional iterations provide marginal gain, while requiring a larger overhead of CSI feedback. Another observation is that the converged limits of the proposed technique is invariant to the initial values of transmit-and-receive vectors. Note that random initialization induces the same limits as that of our carefully chosen initial values, but it requires more iterations to achieve the limits. Therefore, the initial values need to be carefully chosen to minimize the overhead of CSI feedback. Through simulations, we have observed the same convergence behavior in many other scenarios (different cellular layouts and different K, M and S), although it is not proved in this paper. So we conjecture that this convergence behavior occurs in general.



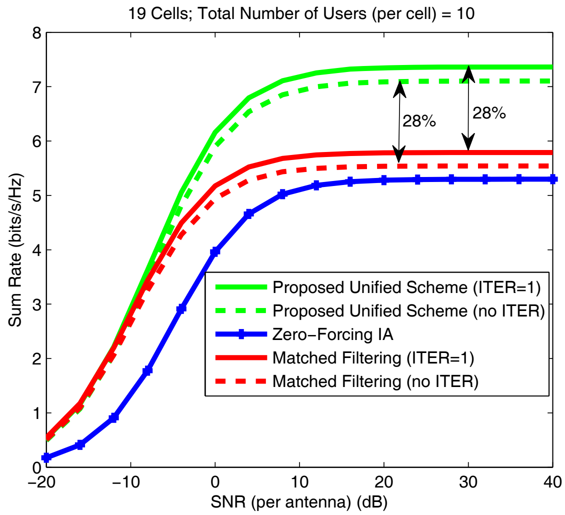
(a)



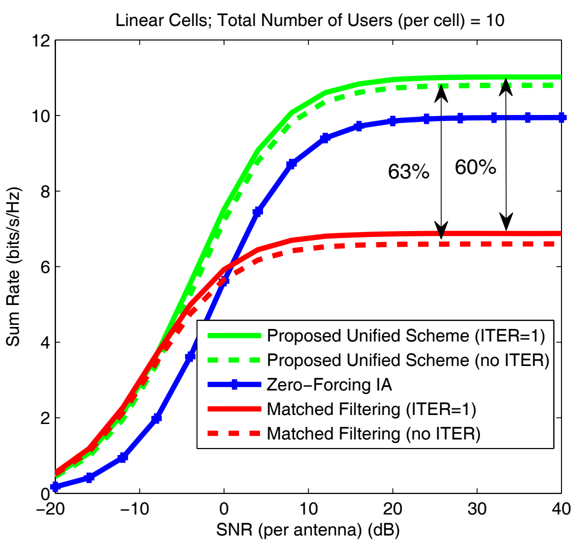
(b)

Fig. 5. The sum-rate performance for a 19 hexagonal cell layout where $M = 4$, the number K of users per cell is 3 and the number S of streams is 3: (a) as a function of SNR (no iteration); (b) as a function of the number of iteration.

Fig. 6 shows the sum-rate performance when considering a scheduler. We assume that $K = 10$ and consider an opportunistic scheduler. In fact, the number S of streams is related to the scheduling effect. For a large value of K, the opportunistic scheduler provides good signal separation and power gain, thereby inducing the high SINR regime where multiplexing gain is more significant than the beamforming



(a)



(b)

Fig. 6. The sum-rate performance of the schemes integrated with an opportunistic scheduler when the number K of users per cell is 10 and the number S of streams is 3: (a) 19 hexagonal cell layout; (b) linear cell layout. The opportunistic scheduler chooses a set of 3 users out of 10 such that the sum-rate is maximized.

power gain. In this case, using more streams provides better performance. We find through simulations that using three streams provides the best performance for a practical number of users per cell (around 10). Hence, we consider $S = 3$. The sum-rate reflects the 3 cell-edge users who are chosen at a time out of 10 via the scheduler.

As shown in Fig. 6 (a), as compared to the non-scheduler case, the performance of zero-forcing IA is significantly improved, although it is still worse than matched filtering. Zero-forcing IA can now achieve power gain with the scheduler. Notice that the power gain due to the scheduler is significant, thus making the additional matched-filter power gain marginal. Our proposed scheme still outperforms both schemes, providing approximately 28% over the matched filtering.

Fig. 6 (b) shows the sum-rate performance for a linear cellular layout where $\gamma \approx 0.1$. In this case, the residual interference is reduced to $\gamma \approx 0.1$, so mitigating dominant out-of-cell interference improves the performance more significantly than beam-forming does. The gain of the proposed scheme is significant, i.e., approximately 60% in the high SNR regime of interest. Notice that a crossover point between the zero-forcing IA and the matched filtering occurs at around SNR $= 0$ dB. The benefit of the zero-forcing IA is substantial.

*Remark 4 (**Comparison to Other Techniques**):* In addition to the matched-filtering scheme, as other baselines, one may consider resource partitioning and cooperative scheduling [16]. However, these techniques are not fair enough to be compared to our IA scheme, since these incur signalling overhead while our scheme does not. Resource partitioning requires explicit coordination of frequency resources for many neighboring cells, thus incurring signalling overhead. Cooperative scheduling [16] requires additional communication between different BSs to deliver user scheduling information across cells. On the contrary, our IA scheme does not require explicit coordination, as it adapts only the number of streams under frequency reuse of 1. While in this paper, detailed comparisons are not provided, doing comparative study needs to be done as future work especially for designing practical cellular systems [1], [2], where many system factors should be simultaneously taken into consideration with different weights of importance. In fact, this comparative study might give some insights into developing another scheme which combines the IA scheme and cooperative scheduling to provide the further performance gain.

VI. Macro-Pico Cellular Networks

We have observed that our scheme shows promise especially when dominant interference is much stronger than the remaining interference, i.e., $\gamma \ll 1$. Such scenario occurs often in heterogeneous networks [10] which use a mix of macro, pico, femto, and relay BSs to enable flexible and low-cost deployment. In this section, we focus on a scenario of the macro-pico cell deployment, illustrated in Fig. 7.

As shown in the figure, suppose that pico-BS is deployed at a distance d from the nearby macro-BS and a user is connected to the pico-BS. The pico-user can then see significant interference from the nearby macro-BS, and this interference can be much stronger than the aggregated interference from the remaining macro-BSs, especially when d is small. The interference problem can be further aggravated due to range extension techniques[1] [10] and the disparity between the transmit power levels of the macro-BS and the pico-BS. This motivates the need for intelligent interference management techniques. We show that our IA scheme can resolve this problem to provide substantial gain.

To show this, we evaluate the sum-rate performance of pico-users in the simple scenario shown in Fig. 7. We assume the 19 hexagonal wrap-around cellular layout, and on top of it we deploy one pico-BS, apart from the nearby macro-BS by a distance d. Based on [10], we consider the power levels

[1]Range extension extends the footprint of pico-cells by allowing more users to connect even if users do not see the pico-BS as the strongest downlink received power. The purpose for this is to better utilize cell-splitting and maximize cell offloading gain.

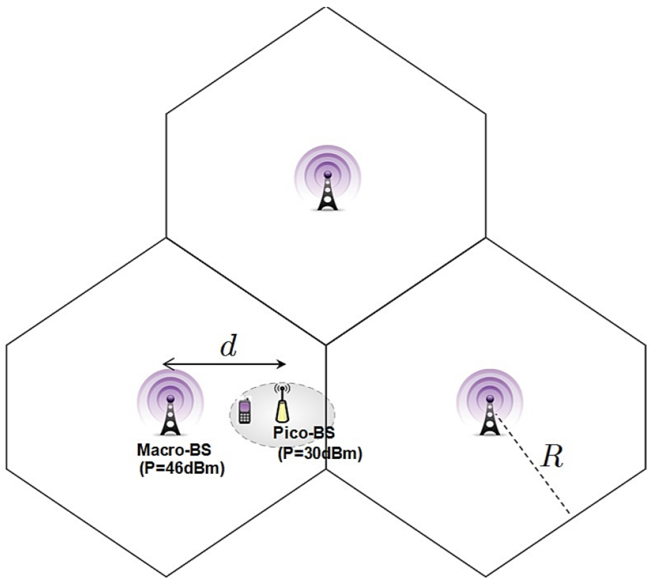
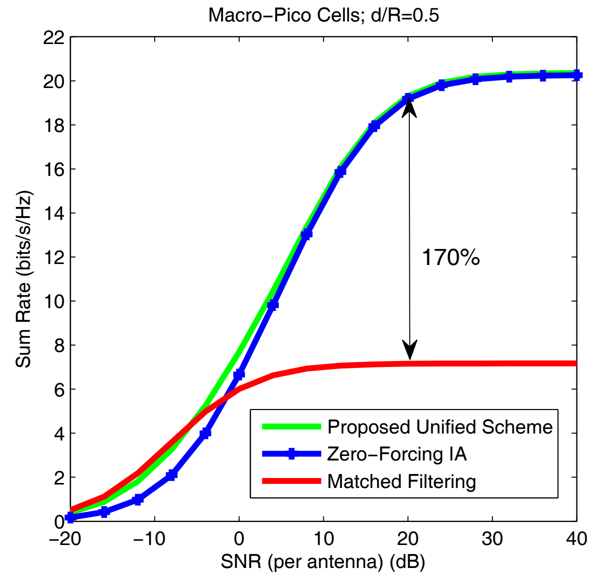
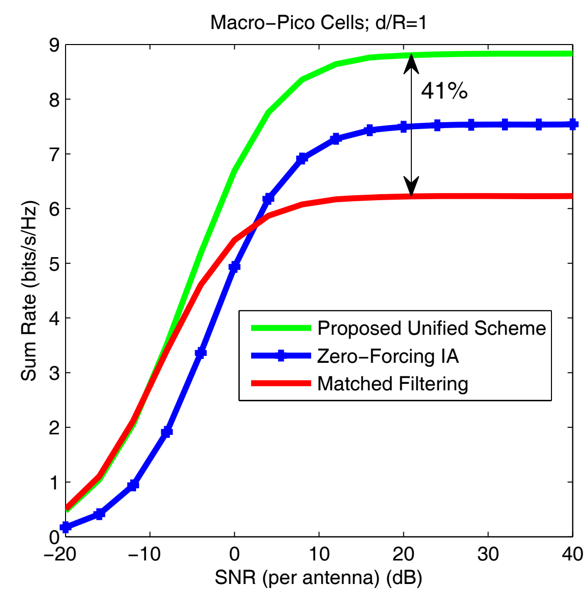


Fig. 7. Macro-pico cellular networks. The pico-user can see significant interference from the nearby macro-BS. The interference problem can be further aggravated when the pico-BS is close to the nearby macro-BS (small d) and the power levels of the two BSs are quite different.



(a)



(b)

Fig. 8. The sum-rate performance of pico-users for a macro-pico cell layout where a single pico-cell is deployed on top of 19 wrap-around macro cells (cell radius R) and the pico-BS is separated from the nearby macro-BS by a distance d: (a) $\frac{d}{R} = 0.5$; (b) $\frac{d}{R} = 1$. The number K of users per pico-cell (or macro-cell) is 10; the number S of streams is 3; and no iteration is performed. The sum-rate reflects the 3 pico-users chosen out of 10 via an opportunistic scheduler.

of 46 dBm and 30 dBm for the macro-BS and the pico-BS, respectively, so the difference is 16 dB. This scenario reflects the case where the pico-cell, once chosen, is fixed once and for all. Consistent with previous simulation setups, we consider a specific mobile location where the downlink received power from the pico-BS is the same as that from the nearby macro-BS. Due to the disparity of the power levels, the pico-users are closer to the pico-BS.[2] We assume a 4-by-4 antenna configuration, i.e., $M = 4$. We assume that each of the pico cell and macro-cells has $K = 10$ users placed at the specific location, and 3 users are chosen at a time out of 10 via the opportunistic scheduler. We assume an interference model where the precoder of the nearby macro-BS is actually computed and this interferes with the users of interest, while the aggregated interference of the remaining macro-BSs is white Gaussian.

Fig. 8 shows the sum-rate performance of the pico-users as a function of SNR. We assume that $S = 3$ and no iteration. Fig. 8 (a) considers the case of $\frac{d}{R} = 0.5$ where pico-users are interfered with by the nearby macro-BS. In this case, our IA scheme provides 170% gain over matched filtering. Fig. 8 (b) considers the case of $\frac{d}{R} = 1$ where the minimum gain of our scheme is expected. Even in this case, our proposed scheme gives approximately 41% gain over the matched filtering.

*Remark 5 (**Comparison to Resource Partitioning**):* In the macro-pico network scenario, as an alternative to our IA scheme, one may consider resource partitioning to resolve the interference problem. This is because unlike the conventional macro cellular networks containing many neighboring cells, this macro-pico network scenario has a fewer number of dominant interferers, thus making resource coordination simpler [17]. For example, we can use a frequency reuse of $\frac{1}{2}$ for the scenario in Fig. 7. So we provide simulation results and find that even in this case, our scheme shows respectable gain over resource partitioning. Fig. 9 shows the sum-rate performance of pico-users as a function of $\frac{d}{R}$ when SNR $= 20$ dB and $K = 10$. We use $S = 3$ for the IA schemes and the matched filtering, while for resource partitioning we optimize the number of streams to plot the best performance curve. In the resource partitioning, we use frequency reuse $\frac{1}{2}$ only between the the nearby macro-cell and the pico-cell, while

[2]In fact, this specific mobile location - where the downlink received power from the two BSs are the same - is a conservative setting. When employing the range extension technique that expands the footprint of pico-cells, one can expect a larger gain of our IA scheme, as the dominant interference power is stronger.

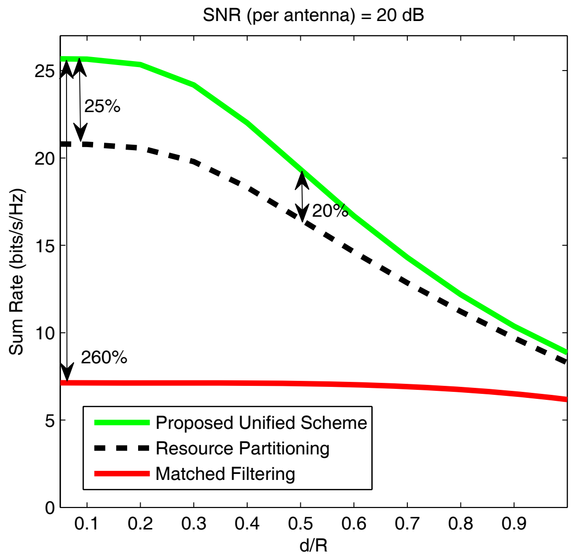


Fig. 9. Comparison to resource partitioning. The sum-rate performance as a function of $\frac{d}{R}$ for SNR = 20 dB.

using frequency reuse 1 for the other macro-cells. Notice that our scheme gives approximately 20% gain for $\frac{d}{R} = 0.5$. The smaller the ratio of $\frac{d}{R}$, the larger the gain, while for large $\frac{d}{R}$, the gain becomes marginal. ■

VII. Discussion

A. Asymmetric Antenna Configuration

We discuss the asymmetric antenna configuration where the BSs are equipped with more antennas, i.e., $M > N$. The extension to this asymmetric case is not straightforward, since more transmit antennas at BSs provide the possibility to null out interference at mobiles in other cells, thus requiring a sophisticated technique which well combines interference nulling with interference alignment.

In this section, we instead provide a simple and natural, but possibly suboptimal, variant of the proposed scheme. The scheme is to limit the number of streams with the minimum of M and N, i.e., $S \leq \min(M, N) = N$. Specifically, each BS sets the precoder $\bar{\mathbf{P}}$ as:

$$\bar{\mathbf{P}} = [\mathbf{f}_1, \cdots, \mathbf{f}_S, \kappa\mathbf{f}_{S+1}, \cdots, \kappa\mathbf{f}_M] \in \mathbb{C}^{M \times M}, \tag{12}$$

and sets the range of S as $S \leq N$. Other operations remain the same. Each user computes the expected covariance matrix by averaging over the transmitted signals from the other cell and then applies the standard MMSE formula for a receive vector. The BS then computes the zero-forcing transmit vectors with the feedback information. These steps can then be iterated.

Notice that in this scheme, interference alignment interpretation needs to be carefully made. For example, consider 4-by-2 antenna configuration in a two-cell layout. Our scheme allows each BS to send one stream out of two and therefore each user sees only one interference vector from the other cell. There is no aligned interference. Even in this configuration, however, interference alignment can be achieved if multiple subcarriers are incorporated, as will be discussed in the following section.

B. Using Subcarriers

Recall in our simulations that only antennas are employed for multiple dimensions. However, we can easily increase M by using multiple subcarriers. With this increase of M, we can make two interesting observations. The first observation is that the performance improves with an increase of M, since the dimension reserved for interference signals becomes negligible as M gets larger. Secondly, increasing M, we can make a chance to achieve interference alignment. To see this, consider 8-by-4 configuration incorporating two subcarriers with a 4-by-2 antenna configuration. We will show that unlike the 4-by-2 configuration, this 8-by-4 configuration enables interference alignment. Suppose there are two cells and each cell has three users. Our scheme allows each BS to transmit three streams out of four and thus each user sees five interfering vectors in total: three *out-of-cell* and two *intra-cell* interfering vectors. Notice the five interfering vectors are aligned onto a three dimensional linear subspace. This implies interference alignment.

C. Multiple Interferers

Our IA technique removes the interference from a single dominant interferer. However, a slight modification can deal with the case of multiple dominant interferers, to some extent. For example, consider a 19 hexagonal cell layout in Fig. 4 and suppose that mobiles are located at the middle point of three neighboring BSs. In this case, mobiles see the two dominant interferers. One simple way is to take multiple dominant interferers into account in the process of computing the expected covariance matrix. Specifically, we use:

$$\begin{aligned}\bar{\mathbf{\Phi}}_k := \mathbb{E}\Big[&(1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S}\mathbf{G}_{\beta k}\bar{\mathbf{P}}\mathbf{B}_\beta\mathbf{B}_\beta^*\bar{\mathbf{P}}^*\mathbf{G}_{\beta k}^* \\ &+\frac{\mathsf{SNR}}{S}\mathbf{G}_{\gamma k}\bar{\mathbf{P}}\mathbf{B}_\gamma\mathbf{B}_\gamma^*\bar{\mathbf{P}}^*\mathbf{G}_{\gamma k}^*\Big],\end{aligned} \tag{13}$$

where $\mathbf{G}_{\beta k}$ denotes cross-channel from BS β and $\mathbf{B}_\beta$ indicates the zero-forcing precoder of BS β. Similarly, we denote $(\mathbf{G}_{\gamma k}, \mathbf{B}_\gamma)$ for cell γ. For $\mathbf{B}_\beta$ and $\mathbf{B}_\gamma$, we assume that each entry of the first S rows is i.i.d. $\mathcal{CN}\left(0, \frac{1}{S+(M-S)\kappa^2}\right)$ and each entry of the last $(M-S)$ rows is i.i.d. $\mathcal{CN}\left(0, \frac{\kappa^2}{S+(M-S)\kappa^2}\right)$.

VIII. Conclusion

We have observed that the zero-forcing IA scheme is analogous to the zero-forcing receiver, and the iterative matched-filtering technique corresponds to the conventional matched-filter receiver. Based on this observation, we proposed a unified IA technique similar to an MMSE receiver that outperforms both techniques for all values of γ, where the power of the dominant interferer may be much greater or smaller than the power of the remaining aggregate interference.

Of practical importance is the fact that our proposed scheme can be implemented with small changes to an existing cellular system supporting multi-user MIMO, as it requires only a localized *within-a-cell* feedback mechanism. This technique can be extended to asymmetric antenna configurations and scenarios with more than one dominant interferer. Our technique also shows even greater performance gains for macro-pico cellular networks where the dominant interference is much stronger than the remaining interference.

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