This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

Downlink Interference Alignment

Changho Suh
Wireless Foundations
University of California at Berkeley
Email: chsuh@eecs.berkeley.edu

Minnie Ho
Intel Labs
Intel Corporation
Email: minnie.ho@intel.com

David Tse
Wireless Foundations
University of California at Berkeley
Email: dtse@eecs.berkeley.edu

***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 minimal 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 show through simulations that our technique provides respectable gain under a more realistic scenario: it gives approximately 20% gain for a 19 hexagonal wrap-around-cell layout.**

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 WiMAX [1] and 3GPP-LTE [2], require at least a doubling in cell-edge throughput over previous 3G systems [2]. Given the disparity between average and cell-edge spectral efficiencies (ratios of about 4:1) [1], 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], [5], [6] has focused on K point-to-point interfering links, it has also been shown in [7], [8], [9] that IA can be used to improve the cell-edge user throughput in a cellular network. Especially, it was shown in [7] that *near interference-free throughput* performance can be achieved in the cellular network.

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.

This work was supported by a gift from Intel and a grant CNS-0722032 from the National Science Foundation.

We propose a new IA technique for downlink cellular systems that addresses many of these practical concerns. Unlike the uplink IA, 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 builds on the idea of the IA technique in [7] that aims for a two-isolated cell layout and can thus cancel interference only from one neighboring BS. We observe that the IA technique in [7] may give 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 these two scenarios, 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 20% gain in cell-edge throughput performance for a 19 hexagonal wrap-around-cell layout, as compared to a standard multi-user MIMO technique. Also our scheme is easily combined with a widely-employed opportunistic scheduler [10] for significant multi-user-diversity gain.

II. Review of Uplink Interference Alignment

We begin by reviewing uplink IA [7]. Fig. 1 illustrates an example for the case of two isolated cells α and β. Suppose there are K users in each cell and each user (e.g., user k in cell α) sends one symbol (or 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: $M =$ (# of subcarriers)$\times$(# of antennas). Let S be the number of streams and in this case $S = K$, as all of the users are sending their own symbols. In this paper, we assume that each BS has the same number of dimensions: M-by-M symmetric configuration. We extend to the asymmetric case in the full version of this paper [11].

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. Due to the randomness in wireless channels, the transmitted vectors are likely to

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

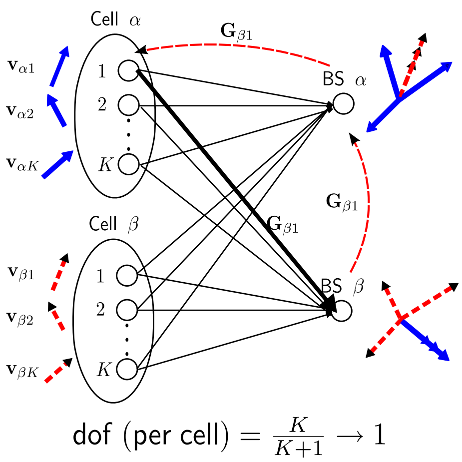

Fig. 1. Uplink interference alignment

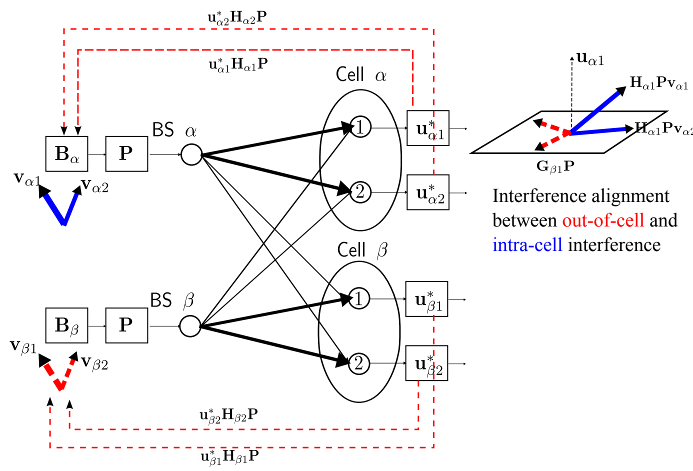

Fig. 2. Downlink interference alignment

be linearly independent at the desired BS. Note that for $M = K + 1$, the desired signals span a K-dimensional space while the interference signals only occupy a one-dimensional subspace. Hence, each BS can recover K desired signals using $K+1$ dimensions. The performance in the interference-limited regime can be captured by a notion of degrees-of-freedom (dof). Here, dof per cell $= \frac{K}{K+1}$, so as K grows 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, *backhaul cooperation* is required to convey such channel knowledge. Fig. 1 shows a way to obtain this CSI, where $\mathbf{G}_{\beta 1} \in \mathbb{C}^{M \times M}$ indicates the cross-channel from user 1 of cell α to BS β. On the contrary, in the downlink, we show that IA can be applied without backhaul cooperation.

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 [7] says that the dof of the uplink is the same as that of the downlink. Hence, dof per cell $= \frac{K}{K+1} = \frac{2}{3}$. To achieve this, each BS needs to send two symbols (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.

We first set a M-by-S fixed precoder matrix $\mathbf{P}$ at BS α and BS β, respectively. Unlike conventional precoding, before the fixed precoder, each BS (e.g., BS α) uses one more precoder $\mathbf{B}_\alpha = [\mathbf{v}_{\alpha 1}, \mathbf{v}_{\alpha 2}]$, where $\mathbf{v}_{\alpha k}$ indicates a transmitted vector intended for user k in cell α. These two precoders spread two data streams ($S = 2$) over three-dimensional resources $M = 3$. The received signal of user k in cell α is then given by

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

where $\mathbf{H}_{\alpha k} \in \mathbb{C}^{3\times 3}$ indicates direct-channel from BS α to user k of cell α, and $\mathbf{G}_{\beta k} \in \mathbb{C}^{3\times 3}$ denotes cross-channel from BS β. We assume that noise is additive white Gaussian and without loss of generality assume that it has unit power, i.e., $\mathbf{z}_{\alpha k} \sim \mathcal{CN}(0, \mathbf{I})$.

Now 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.

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 $\mathbf{B}_\alpha$:

$$\mathbf{B}_\alpha = [\mathbf{v}_{\alpha 1}, \mathbf{v}_{\alpha 2}] = \begin{bmatrix} \mathbf{u}^*_{\alpha 1}\mathbf{H}_{\alpha 1}\mathbf{P} \\ \mathbf{u}^*_{\alpha 2}\mathbf{H}_{\alpha 2}\mathbf{P} \end{bmatrix}^{-1} \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix}, \quad (1)$$

where γ_k is a normalization factor for $||\mathbf{v}_{\alpha k}|| = 1$. Considering user 1's received signal, this zero-forcing precoder guarantees user 2's transmitted signal $\mathbf{H}_{\alpha 1}\mathbf{P}\mathbf{v}_{\alpha 2}$ to lie 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 $= \frac{2}{3}$.

Interpretation: A series of these operations enables interference alignment. Let us call this scheme *zero-forcing IA*. To see this, let us observe the interference plane of user 1 in cell α. Note that there are three interference vectors: two *out-of-cell* interference vectors and one *intra-cell* interference vector.

978-1-4244-5638-3/10/$26.00 ©2010 IEEE

These three vectors 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 to reserve only two dimensions (not three) for the interference, thus saving one dimension.

While the downlink dof is the same as that of the uplink, the way interference is aligned is quite different. Note in Fig. 1 that in uplink IA, interference alignment is achieved among out-of-cell interference vectors only. On the other hand, in downlink IA, interference alignment is achieved between out-of-cell and intra-cell interference vectors at multiple users *at the same time*.

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 actually transmitted vectors*, i.e., user k in cell α can compute $\mathbf{u}_{\alpha k}$ without knowing $\mathbf{B}_{\beta}$. 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 stark contrast to the uplink IA which requires 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 for downlink 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 10. As a baseline scheme, we use a *matched filter receiver*: one of the standard multi-user MIMO techniques [12], [13]. The scheme uses the dominant left-singular vector of the direct-channel as a receive vector. 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.

Note that the transmit and receive vectors are interconnected, i.e., a receive vector is a function of a transmit vector and vice versa. One way to compute the transmit-and-receive vector pairs is to employ an iterative algorithm [12], [13]. We call this scheme *iterative matched filtering*. Refer to the full version of this paper [11] for further details. Unlike the matched filtering, the receive vector in the zero-forcing IA is irrelevant to the transmit vectors, thus requiring no iteration. Hence, for fair comparison of CSI overhead, we avoid the iterative procedure for the baseline and this is reflected in the simulation of Fig. 3. In the simulation, we consider an opportunistic scheduler in an effort to take into account system aspects. The opportunistic scheduler chooses a set of $S = 3$ users out of $K = 10$ such that the sum rate is maximized.

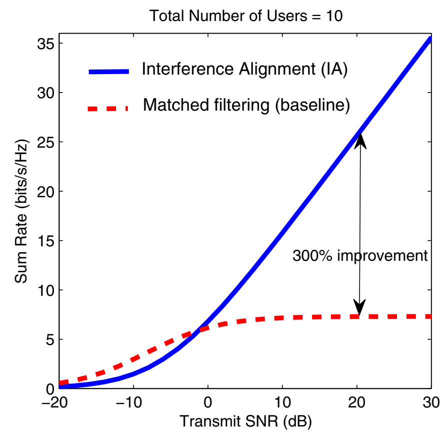

Fig. 3. Performance of downlink interference alignment in 2-isolated cell layout for 4-by-4 antenna configuration ($M = 4$).

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 IA scheme provides the asymptotically optimal performance, since it achieves the optimal dof [7]. This gain is due to the fact that in the two-isolated cell case, there exists only a single interferer and our IA scheme completely removes the interference. 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 (BS) to the remaining interference power (summed from the other BSs):

$$\gamma := \frac{\mathsf{INR}_{\mathsf{rem}}}{\mathsf{INR}_{\mathsf{dom}}}, \tag{2}$$

where $\mathsf{INR}_{\mathsf{dom}}$ and $\mathsf{INR}_{\mathsf{rem}}$ denote the ratios of the dominant and aggregate interference power over the power of the noise, 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 the 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 and the matched-filtered power gain depending on the value of γ.

IV. Proposed New IA Scheme

The zero-forcing IA and matched filtering schemes remind us of 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. The idea is to *color* an interference signal space by using two cascaded precoders: (1) a *fixed* precoder $\bar{\mathbf{P}} \in \mathbb{C}^{M\times M}$ located at the front-end; (2) a zero-forcing precoder $\mathbf{B}_\alpha \in \mathbb{C}^{M\times S}$ which precedes the $\bar{\mathbf{P}}$. With the fixed precoder, we can color the interference space, to some extent, to be independent of actually transmitted vectors. To see this, consider the covariance matrix of interference-plus-noise at user k in cell α:

$$\mathbf{\Phi}_k = (1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S}(\mathbf{G}_{\beta k}\bar{\mathbf{P}}\mathbf{B}_\beta\mathbf{B}_\beta^*\bar{\mathbf{P}}^*\mathbf{G}_{\beta k}^*), \quad (3)$$

where S is the total number of streams assigned to the scheduled users in the cell ($S \le M$) and $\mathbf{B}_\beta$ indicates the zero-forcing precoder of a dominant interferer (BS β). Assume that the aggregate interference except the dominant interference is white Gaussian.[1] Without loss of generality, we assume that Gaussian noise power is normalized to 1. Assume the total transmission power is equally allocated to each stream.

Since we consider uncoordinated systems, $\mathbf{B}_\beta$ is unknown to users in cell α. This motivates us to take the expectation of the covariance matrix over $\mathbf{B}_\beta$:

$$\bar{\mathbf{\Phi}}_k := \mathbb{E}[\mathbf{\Phi}_k] = (1+\mathsf{INR}_{\mathsf{rem}})\mathbf{I} + \frac{\mathsf{SNR}}{S}(\mathbf{G}_{\beta k}\bar{\mathbf{P}}\bar{\mathbf{P}}^*\mathbf{G}_{\beta k}^*), \quad (4)$$

where we assume that each entry of $\mathbf{B}_\beta$ is i.i.d. $\mathcal{CN}(0, \frac{1}{S})$.

Now we control the coloredness of interference signals by differently weighting the last $(M-S)$ columns of $\bar{\mathbf{P}}$ with a parameter κ ($0 \le \kappa \le 1$):

$$\bar{\mathbf{P}} = [\mathbf{f}_1, \cdots, \mathbf{f}_S, \kappa\mathbf{f}_{S+1}, \cdots, \kappa\mathbf{f}_M] \in \mathbb{C}^{M\times M}, \quad (5)$$

where $[\mathbf{f}_1, \cdots, \mathbf{f}_M]$ is a unitary matrix. Two extreme cases give insights into designing κ. 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., $\kappa = 0$. Note in this case that 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 of 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 $\bar{\mathbf{P}}$ so that the $\bar{\mathbf{\Phi}}_k$ is as close as the scaled identity matrix. One way for smoothly sweeping between the two cases is to set:

$$\kappa = \min\left(\sqrt{\gamma}, 1\right). \quad (6)$$

Note that for $\gamma \ll 1$, $\kappa \approx 0$, thus making the $\bar{\mathbf{P}}$ rank-deficient. For $\gamma \gg 1$, κ is saturated as 1, thus making the $\bar{\mathbf{P}}$ a unitary matrix.

Considering system aspects, however, the κ needs to be carefully chosen. In the above choice, the 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. For example, we can fix κ based on the case of $\mathsf{SNR} = 20$ dB, a cell-edge mobile location, and a fixed network layout, e.g., $\gamma \approx 0.4$ and $\kappa \approx 0.64$ for the 19 hexagonal wrap-around cell layout. See [11] for detailed calculations.

With the $\bar{\mathbf{\Phi}}_k$, we then use the standard formula of an MMSE receiver. Similar to the iterative matched filtering technique, we also employ an iterative approach to compute transmit-and-receive vector pairs.

<Proposed New IA Scheme>

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

$$\mathbf{u}_{\alpha k}^{(0)} = \frac{\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(0)}}{||\bar{\mathbf{\Phi}}_k^{-1}\mathbf{H}_{\alpha k}\bar{\mathbf{P}}\mathbf{v}_{\alpha k}^{(0)}||}, \quad (7)$$

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 beamforming 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 $A \subset \mathcal{K}$ where $\mathcal{K}$ is a collection of subsets $\subset \{1, \cdots, K\}$ that has cardinality $|\mathcal{K}| = \binom{K}{S}$. For the given A, with the feedback information, the BS computes zero-forcing transmit vectors:

$$[\mathbf{v}_{\alpha k_1}^{(1)}, \cdots, \mathbf{v}_{\alpha k_S}^{(1)}] = \mathbf{H}^{(1)*}(\mathbf{H}^{(1)}\mathbf{H}^{(1)*})^{-1}\mathsf{diag}\{\gamma_1^{(1)}, \cdots, \gamma_S^{(1)}\},$$

where $k_l \in A$, $\gamma_l^{(1)}$ is a normalization factor, and

$$\mathbf{H}^{(1)} := \begin{bmatrix} \mathbf{u}_{\alpha k_1}^{(0)*}\mathbf{H}_{\alpha k_1}\bar{\mathbf{P}} \\ \vdots \\ \mathbf{u}_{\alpha k_S}^{(0)*}\mathbf{H}_{\alpha k_S}\bar{\mathbf{P}} \end{bmatrix} \in \mathbb{C}^{S\times M}. \quad (8)$$

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

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

4) (*Iteration*): For the A^*, we iterate the following. The BS informs each user of $\mathbf{v}_{\alpha k}^{(i)}$ via precoded pilots. With $\mathbf{v}_{\alpha k}^{(i)}$, each user updates the receive vector $\mathbf{u}_{\alpha k}^{(i)}$ and then feeds back the updated equivalent channel to its own

[1]To be more accurate, we may consider two or three dominant interferers to compute the $\mathbf{\Phi}_k$. See [11] for details.

BS. With this feedback information, the BS computes zero-forcing transmit vectors $\mathbf{v}_{\alpha k}^{(i+1)}$.

Remarks: To reduce CSI overhead, we assume that a scheduler decision is made before the *iteration* step. In practice, we may not prefer 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 by employing the $\bar{\mathbf{\Phi}}_k$. *This requires little changes to an existing cellular system supporting multi-user MIMO.*

V. Simulation Result

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 multiple dimensions, i.e., $M = 4$. Since the cell-edge throughput performance is of our main interest, we consider a specific mobile location (the mid-point between two adjacent cells). We assume that the total number K of users in each cell is 10 and the 10 users are placed at the mid-point. 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 [1], [2].

Fig. 4 shows the sum-rate throughput performance for 19 hexagonal cellular systems. We consider the number $S = 3$ of streams and employ an opportunistic scheduler.[2] Note that the zero-forcing IA scheme is worse than the matched filtering (baseline). This implies that when 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 20% throughput gain in the high SNR regime.[3]

VI. Conclusion and Discussion

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.

[2]We find through simulations that using three streams provides the best performance in terms of sum rate for a practical number of users K (around 10). See [11] for detailed simulation results.

[3]We also investigate the convergence of the proposed scheme in the full version [11], where it is shown 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.

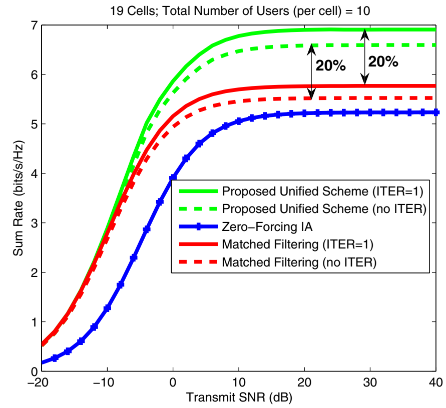

Fig. 4. The sum rate performance of the proposed IA scheme for 19 hexagonal cell layout where $K = 10$ and $S = 3$.

In the full version [11], we also find that our scheme has the potential to provide substantial performance for heterogeneous networks [14] e.g., macro-pico cellular networks where pico-users can be significantly interfered with by the nearby macro-BS. Simulation results in [11] shows that for these networks our IA scheme can give around 30% to 200% gain over the matched filtering. See [11] for the detailed simulation results.

References

[1] *IEEE, 802.16m-08/0004r2, "IEEE802.16m Evaluation Methodology Document (EMD)"*, Jul. 2008.

[2] *3GPP TR 25.814 V7.1.0, "Physical Layer Aspects for Evolved Universal Terrestrial Radio Access"*, Oct. 2007.

[3] M. A. Maddah-Ali, S. A. Motahari, and A. K. Khandani, "Communication over MIMO X channels: Interference alignment, decomposition, and performance analysis," *IEEE Transactions on Information Theory*, vol. 54, pp. 3457–3470, Aug. 2008.

[4] V. R. Cadambe and S. A. Jafar, "Interference alignment and the degree of freedom for the K user interference channel," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3425–3441, Aug. 2008.

[5] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "Approaching the capacity of wireless networks through distrubted interference alignment," *Proc. of IEEE GLOBECOM*, Dec. 2008.

[6] S. W. Peters and R. W. Heath, "Interference alignment via alternating minimization," *Proc. of IEEE ICASSP*, Apr. 2009.

[7] C. Suh and D. Tse, "Interference alignment for cellular networks," *Allerton Conference on Communication, Control, and Computing*, Sep. 2008.

[8] G. Caire, S. A. Ramprashad, H. C. Papadopoulos, C. Pepin, and C. E. W. Sundberg, "Multiuser MIMO downlink with limited inter-cell cooperation: Approximate interference alignment in time, frequency and space," *Allerton Conference on Communication, Control, and Computing*, Sep. 2008.

[9] R. Tresch and M. Guillaud, "Cellular interference alignment with imperfect channel knowledge," *Proc. of IEEE ICC*, Jun. 2009.

[10] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, 1st ed., Cambridge, 2005.

[11] C. Suh, M. Ho, and D. Tse, "Downlink interference alignment," *submitted to the IEEE Transactions on Communications (arXiv:1003.3707)*, May 2010.

[12] Z. Pan, K.-K. Wong, and T.-S. Ng, "Generalized multiuser orthogonal space-division multiplexing," *IEEE Trans. on Wireless Communications*, vol. 3, no. 6, pp. 1969–1973, Nov. 2004.

[13] D. Gesbert, M. Kountouris, R. W. Heath, C.-B. Chae, and T. Salzer, "From single user to multiuser communications: Shifting the MIMO paradigm," *IEEE Signal Processing Magazine*, vol. 24, no. 5, Oct. 2007.

[14] *Qualcomm Incorporated, "LTE Advanced: Heterogeneous Networks"*, Feb. 2010.