Beamforming Design with Proactive Interference Cancelation in MISO Interference Channels

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***Abstract*—In this paper, we design coordinated beamforming at base stations (BSs) to facilitate interference cancelation at users in interference networks, where each BS is equipped with multiple antennas and each user is with a single antenna. By assuming that each user can select the best decoding strategy to mitigate the interference, either canceling the interference after decoding when it is strong, or treating it as noise when it is weak, we optimize the beamforming vectors that maximize the sum-rate for the networks under different interference scenarios, and find the solutions of beamforming with closed-form expressions. The inherent design principles are then analyzed, and the performance gain over passive interference cancelation is demonstrated through simulations in multi-cell heterogeneous cellular networks.**

I. Introduction

One of the key features of the fifth generation cellular networks is ultra dense and heterogeneous [1], where the interference generated by different base stations (BSs) is more complicated. Depending on the locations, the users may experience different levels of interference.

For multi-input-multi-output (MIMO) interference channels, the beamforming optimization for each BS is not an easy task, because the achievable rate of each user depends on the beamforming of all BSs. Simple linear transceiver such as the zero-forcing based coordinated beamforming (ZF-CB) tries to circumvent this problem by separating the signal and the interference in orthogonal subspaces. If each coordinated BS does not have more antennas than the number of users in the network, ZF-CB cannot remove all the interference. On the other hand, if the interference is very weak or very strong, it is a waste of spatial resource to provide an orthogonal subspace for each interference. In fact, for weak interference channels, treating the interference as noise is optimal [2]. For strong interference channels, interference cancelation can achieve the capacity [3]. Under other levels of interference, it remains unknown for how to design an optimal transceiver.

In [4], six interference scenarios for a single antenna two-cell network were characterized, where the users respectively experience very strong, strong, mixed 1, mixed 2, weak, and very weak interference. For each scenario, a corresponding transmission scheme to achieve the capacity or the best known achievable rate was designed, and the concept of proactive interference cancelation was proposed for strong and mixed interference scenarios. The basic idea of proactive interference cancelation is to guarantee strong interference to be decodable and hence can be thoroughly canceled at the receiver by designing the transmitter. This is distinct from existing interference cancelation scheme, which waits for the opportunity until the interference becomes strong enough to be decodable. In [5], the idea was extended to MIMO interference channels in mixed interference scenario, where a coordinated precoding method was developed to facilitate proactive interference cancelation. Since the sum-rate expression is a non-convex function of the precoding matrices, an iterative solution was found through convex relaxation.

In this paper, we consider transmission scheme design for multi-input-single-output (MISO) interference channels. In [6], a parameterization of the beamforming that achieves the Pareto boundary of the achievable rate region was proposed, where a brute-force searching is required to find the solutions. In [7], a more efficient method was proposed to find the Pareto-optimal beamforming vectors, which however needs to solve a cubic equation or to perform a scalar line searching.

Considering that closed-form transceivers are highly desirable for practical systems, we employ an alternative approach to design the coordinated beamforming that assists proactive interference cancelation for MISO interference channels. Specifically, we assume that each receiver is able to choose the best decoding strategy to mitigate the interference, either decoding the interference first and then canceling it when it is strong, or treating it as noise when it is weak. To maximize the sum-rate, the strong interference might need to be further strengthened to increase the interference-to-signal-plus-noise ratio (ISNR), and the weak interference might need to be further weakened to increase the signal-to-interference-plus-noise ratio (SINR). Inspired by such an intuition, we formulate the optimization problem for designing linear beamforming that maximizes the sum-rate with given decoding methods under different interference scenarios. Beamforming vectors with explicit expressions are then provided. Simulation results show that the proposed transmission scheme is superior to existing schemes in heterogeneous networks (HetNets).

II. System Model and Transmission Scheme

In this section, we introduce the system model and the transmission scheme with proactive interference cancelation.

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A. System Model

Consider a HetNet, where one macro-cell coexists with pico-cells in the same frequency band. To obtain a closed-form solution and gain useful insight, we consider a two-cell MISO network consisting of one macro-cell and one pico-cell in the optimization, and then extend the designed beamforming to multi-cell networks.

We assume that BS_1 serves user 1 and BS_2 serves user 2, and each BS knows the channel information from itself to both users. The i-th BS is equipped with M_i antennas, and each user is equipped with a single antenna.

The symbol received at user i is

$$y_i = \mathbf{h}_{ii}^H \mathbf{v}_i x_i + \mathbf{h}_{ij}^H \mathbf{v}_j x_j + n_i, \quad i,j \in \{1,2\}, \quad j \neq i, \quad (1)$$

where $\mathbf{h}_{ji} \in \mathbb{C}^{M_i}$ denotes the channel vector from BS_i to user j, x_i is the symbol transmitted by BS_i with power $\mathbb{E}[|x_i|^2] = P_i$, $\mathbf{v}_i \in \mathbb{C}^{M_i}$ is the transmit beamforming vector at BS_i with unit norm $\|\mathbf{v}_i\| = 1$, and n_i is the Gaussian white noise at user i with zero mean and unit variance.

B. Transmission Scheme

The transmission scheme with proactive interference cancelation includes transmit beamforming and decoding.

We first decide the decoding methods for two users according to interference scenarios as follows. (a) When both users suffer weak interference, the desired signals are decoded directly by treating the interference as noise at both users. (b) When one user suffers strong interference while the other suffers weak interference, the strong interference is decoded and subtracted before the desired signal is decoded, and the weak interference is simply treated as noise. (c) When both users suffer strong interference, both users first decode and subtract the interference, and then decode the desired signals.

Since we do not know whether the interference is strong or weak before beamforming, we will find the optimal beamforming vectors for each of the three decoding methods, and then choose the scheme that achieves the highest sum-rate.

III. Problem Formulation

Given the decoding method at each user, we can obtain the sum-rate as a function of the beamforming vector, from which we can formulate the optimization problem to find the beamforming that maximizes the sum-rate.

(a) Both users treat the interference as noise: When both users are subject to weak interference that is not able to be decoded correctly, the interference can be treated as noise at each user. If the SINR at each user is high, i.e., $\text{SINR}_i \gg 1$, where

$$\text{SINR}_i = \frac{P_i |\mathbf{h}_{ii}^H \mathbf{v}_i|^2}{P_j |\mathbf{h}_{ij}^H \mathbf{v}_j|^2 + 1}, \quad i,j \in \{1,2\}, \quad j \neq i, \quad (2)$$

then the achievable sum-rate can be approximated as

$$R^{\text{weak}}(\mathbf{v}_1, \mathbf{v}_2) = \sum_{i=1}^{2} \log_2 (1 + \text{SINR}_i) \approx \sum_{i=1}^{2} \log_2 (\text{SINR}_i). \quad (3)$$

This approximation will lead to at most 1 bps/Hz loss in achievable rate of each user in this scenario, because

$$\log_2(1+t) - \log_2 t = \log_2(1+t^{-1}) \leq 1 \quad (t \geq 1). \quad (4)$$

(b) One user decodes the interference: This is a scenario of mixed interference. When user 1 suffers strong interference while user 2 experiences weak interference, the strong interference should be decoded and canceled at user 1 and the weak interference at user 2 can be treated as noise. Similarly to the previous case, we assume high SINR at user 2, i.e., $\text{SINR}_2 \gg 1$. At user 1, the interference should be much stronger than the desired signal and the noise in order to be decodable, hence we can apply a high ISNR assumption, i.e., $\text{ISNR}_1 \gg 1$, where

$$\text{ISNR}_i = \frac{P_j |\mathbf{h}_{ij}^H \mathbf{v}_j|^2}{P_i |\mathbf{h}_{ii}^H \mathbf{v}_i|^2 + 1}, \quad i,j \in \{1,2\}, \quad j \neq i. \quad (5)$$

User 1 decodes and subtracts the interference caused by BS_2 and then the desired signal from BS_1 is decoded in an interference-free environment, thus the achievable rate of user 1 is $\log_2\left(1 + P_1 |\mathbf{h}_{11}^H \mathbf{v}_1|^2\right)$. The achievable rate of user 2 is upper bounded by $\log_2(1 + \text{ISNR}_1)$ and $\log_2(1 + \text{SINR}_2)$ simultaneously, since the signal from BS_2 should be decodable both at user 1 and user 2. Similarly to the previous case, under the assumption of high ISNR_1 and SINR_2, the achievable sum-rate can be approximated as

$$R^{\text{mixed1}}(\mathbf{v}_1, \mathbf{v}_2) \approx \log_2\left(1 + P_1 |\mathbf{h}_{11}^H \mathbf{v}_1|^2\right) + \log_2\left(\min\left(\text{ISNR}_1, \text{SINR}_2\right)\right). \quad (6)$$

If user 1 treats the interference as noise and user 2 decodes it, the achievable sum-rate can be approximated similarly to (6) as

$$R^{\text{mixed2}}(\mathbf{v}_1, \mathbf{v}_2) \approx \log_2\left(1 + P_2 |\mathbf{h}_{22}^H \mathbf{v}_2|^2\right) + \log_2\left(\min\left(\text{ISNR}_2, \text{SINR}_1\right)\right). \quad (7)$$

(c) Both users decode the interference: When both users suffer strong interference, they decode and cancel the interference first and then decode their desired signals. Since the interference should be much stronger than the desired signal and the noise, it is reasonable to assume high ISNR at each user, i.e., $\text{ISNR}_i \gg 1, i = 1,2$.

To ensure the interference caused by BS_1 to be decodable at user 2, the achievable rate of user 1 should be upper bounded by $\log_2(1 + \text{ISNR}_2)$. Similarly, the achievable rate of user 2 should be upper bounded by $\log_2(1+\text{ISNR}_1)$. After decoding the interference, each user decodes the desired signal without interference. Therefore, the achievable rate of user i is also upper bounded by $\log_2\left(1 + P_i |\mathbf{h}_{ii}^H \mathbf{v}_i|^2\right)$. Then, the achievable sum-rate can be approximated as

$$R^{\text{strong}}(\mathbf{v}_1, \mathbf{v}_2) \approx \sum_{i=1, j\neq i}^{2} \log_2\left(\min\left(\text{ISNR}_j, 1 + P_i |\mathbf{h}_{ii}^H \mathbf{v}_i|^2\right)\right). \quad (8)$$

The approximation in case (c) will lead to at most 1 bps/Hz per-user rate loss as in case (a), and in case (b) it will loss at most 1 bps/Hz at only one user.

Among these cases, the best achievable scheme will be selected as the final transmission scheme. Such a problem to find the optimal beamforming can be formulated as

$$\max_{\mathbf{v}_1,\mathbf{v}_2} \ \max\left(R^{\text{weak}}, R^{\text{mixed1}}, R^{\text{mixed2}}, R^{\text{strong}}\right), \tag{9a}$$

$$\mathbf{s.t.} \quad \|\mathbf{v}_i\| = 1, \quad \mathbf{v}_i \in \mathbb{C}^{M_i}, i = 1, 2. \tag{9b}$$

IV. Beamforming Design With Closed Form

In this section, we strive to find a closed-form solution of problem (9). To this end, we need to find the beamforming vectors that respectively maximize the achievable sum-rates in four scenarios, R^{weak}, R^{mixed1}, R^{mixed2} and R^{strong}.

A. Both Users Treat the Interference as Noise

For the scenario where both users treat the interference as noise, the achievable sum-rate R^{weak} in (3) is rewritten as

$$\log_2\left(\frac{P_1|\mathbf{h}_{11}^H\mathbf{v}_1|^2}{P_1|\mathbf{h}_{21}^H\mathbf{v}_1|^2+1}\cdot\frac{P_2|\mathbf{h}_{22}^H\mathbf{v}_2|^2}{P_2|\mathbf{h}_{12}^H\mathbf{v}_2|^2+1}\right). \tag{10}$$

The maximization of (10) can be achieved by solving the generalized Rayleigh quotient problem as follows

$$\max_{\mathbf{v}_i} \ \frac{P_i\mathbf{v}_i^H\mathbf{h}_{ii}\mathbf{h}_{ii}^H\mathbf{v}_i}{\mathbf{v}_i^H\mathbf{B}_{ji}\mathbf{v}_i}, \tag{11}$$

whose solution is given by generalized eigenvalue decomposition

$$\mathbf{h}_{ii}\mathbf{h}_{ii}^H\mathbf{v}_i = \lambda_i\mathbf{B}_{ji}\mathbf{v}_i, \tag{12}$$

where $\mathbf{B}_{ji} = P_i\mathbf{h}_{ji}\mathbf{h}_{ji}^H + \mathbf{I}_{M_i}$ and λ_i is the unique nonzero eigenvalue of $\mathbf{B}_{ji}^{-1}\mathbf{h}_{ii}\mathbf{h}_{ii}^H$. Considering the unit-norm constraint of the beamforming vector, we can obtain

$$\mathbf{v}_i^{\text{weak}} = \frac{\mathbf{B}_{ji}^{-1}\mathbf{h}_{ii}}{\|\mathbf{B}_{ji}^{-1}\mathbf{h}_{ii}\|}, \quad i = 1, 2, \tag{13}$$

which is one of the generalized eigenvectors associated to λ_i. Note that this result was also obtained in [8]. From the optimization problem, we can see that the beamforming vector is to maximize the signal-to-leakage-plus-noise ratio (SLNR).

B. One User Decodes the Interference

For the scenario where user 1 suffers strong interference and user 2 experiences weak interference (the scenario where user 1 experiences weak interference and user 2 suffers strong interference is similar and hence omitted), from (6) the achievable sum-rate R^{mixed} can be expressed as

$$\log_2\left(\min\left(P_2|\mathbf{h}_{12}^H\mathbf{v}_2|^2, P_2|\mathbf{h}_{22}^H\mathbf{v}_2|^2\frac{P_1|\mathbf{h}_{11}^H\mathbf{v}_1|^2+1}{P_1|\mathbf{h}_{21}^H\mathbf{v}_1|^2+1}\right)\right). \tag{14}$$

Since $\mathbf{v}_1$ appears only in the second term of the minimum function above, the optimal solutions of $\mathbf{v}_1$ and $\mathbf{v}_2$ that maximize (14) can be found successively. Specifically, we can first find $\mathbf{v}_1$ by solving the generalized Rayleigh quotient problem as follows

$$\max_{\mathbf{v}_1} \ \frac{\mathbf{v}_1^H\mathbf{B}_{11}\mathbf{v}_1}{\mathbf{v}_1^H\mathbf{B}_{21}\mathbf{v}_1}, \tag{15}$$

whose solution is the generalized eigenvector associated to the largest generalized eigenvalue $\lambda_{\max}$, which is

$$\mathbf{B}_{11}\mathbf{v}_1 = \lambda_{\max}\mathbf{B}_{21}\mathbf{v}_1. \tag{16}$$

Thus, we can obtain

$$\mathbf{v}_1^{\text{mixed}} = \nu_{\max}(\mathbf{B}_{21}^{-1}\mathbf{B}_{11}), \tag{17}$$

where $\nu_{\max}(\mathbf{A})$ is the unit-norm eigenvector corresponding to the largest eigenvalue of $\mathbf{A}$.

Then, we find the solution of $\mathbf{v}_2$. Substituting $\lambda_{\max}$ into (14), we can obtain the optimization problem for $\mathbf{v}_2$ as follows

$$\max_{\mathbf{v}_2} \ \min\left(P_2|\mathbf{h}_{12}^H\mathbf{v}_2|^2, P_2|\mathbf{h}_{22}^H\mathbf{v}_2|^2\lambda_{\max}\right). \tag{18}$$

Since $\lambda_{\max}$ is a positive real number, (18) can be further simplified as

$$\max_{\mathbf{v}_2} \ \min\left(|\mathbf{h}_{12}^H\mathbf{v}_2|, |\sqrt{\lambda_{\max}}\mathbf{h}_{22}^H\mathbf{v}_2|\right). \tag{19}$$

To better understand problem (19), we provide its geometric explanation in Fig. 1. Since $\mathbf{v}_2$ is a unit-norm vector in $\mathbb{C}^{M_2}$, finding the solution of problem (19) is equivalent to finding a direction vector that maximizes the minimum of projections of $\mathbf{h}_{12}$ and $\sqrt{\lambda_{\max}}\mathbf{h}_{22}$ on it.

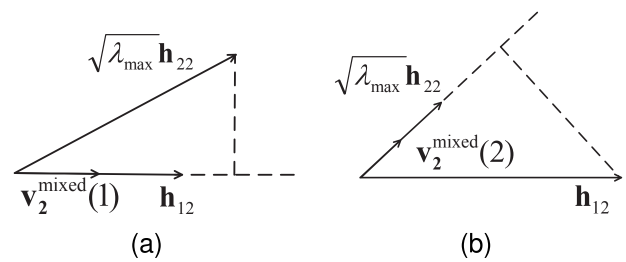

Fig. 1. (a) $\sqrt{\lambda_{\max}}|\mathbf{h}_{22}^H\mathbf{h}_{12}| \geq \|\mathbf{h}_{12}\|^2$; (b) $|\mathbf{h}_{12}^H\mathbf{h}_{22}| \geq \sqrt{\lambda_{\max}}\|\mathbf{h}_{22}\|^2$.

Case 1: If the projection of $\sqrt{\lambda_{\max}}\mathbf{h}_{22}$ on the direction vector $\frac{\mathbf{h}_{12}}{\|\mathbf{h}_{12}\|}$ is bigger than $\|\mathbf{h}_{12}\|$, i.e., $\sqrt{\lambda_{\max}}|\mathbf{h}_{22}^H\mathbf{h}_{12}| \geq \|\mathbf{h}_{12}\|^2$ as shown in Fig. 1(a), (19) is upper bounded by $\|\mathbf{h}_{12}\|$, which is the maximum of $|\mathbf{h}_{12}^H\mathbf{v}_2|$. Then the optimal solution is

$$\mathbf{v}_2^{\text{mixed}}(1) = \frac{\mathbf{h}_{12}}{\|\mathbf{h}_{12}\|}. \tag{20}$$

Case 2: If the projection of $\mathbf{h}_{12}$ on the direction vector $\frac{\sqrt{\lambda_{\max}}\mathbf{h}_{22}}{\|\sqrt{\lambda_{\max}}\mathbf{h}_{22}\|}$ exceeds $\|\sqrt{\lambda_{\max}}\mathbf{h}_{22}\|$, i.e., $|\mathbf{h}_{12}^H\mathbf{h}_{22}| \geq \sqrt{\lambda_{\max}}\|\mathbf{h}_{22}\|^2$ as shown in Fig. 1(b), the function in (19) is upper bounded by $\sqrt{\lambda_{\max}}\|\mathbf{h}_{22}\|$, which is the maximum of $|\sqrt{\lambda_{\max}}\mathbf{h}_{22}^H\mathbf{v}_2|$. The optimal solution is

$$\mathbf{v}_2^{\text{mixed}}(2) = \frac{\mathbf{h}_{22}}{\|\mathbf{h}_{22}\|}. \tag{21}$$

Case 3: Besides these two cases, the optimal solution will be obtained when the following equality holds,

$$|\mathbf{h}_{12}^H\mathbf{v}_2| = |\sqrt{\lambda_{\max}}\mathbf{h}_{22}^H\mathbf{v}_2|, \tag{22}$$

which is due to the nature of the maximization of the minimum function and the continuity of the two terms. The solution will be located in a two-dimensional subspace of $\mathbb{C}^{M_2}$ spanned by $\mathbf{h}_{12}$ and $\mathbf{h}_{22}$. (The proof is omitted due to the lack of space.)

To find the solution of $\mathbf{v}_2$ from (22), we need to consider two subcases based on the projection angle of $\mathbf{h}_{12}$ and $\mathbf{h}_{22}$, as shown in Fig. 2.

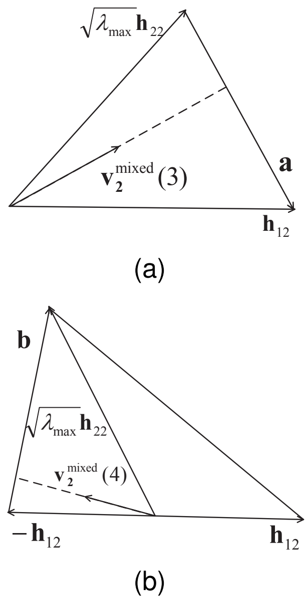

Fig. 2. (a) $\Re(\mathbf{h}_{12}^H\mathbf{h}_{22}) > 0$; (b) $\Re(\mathbf{h}_{12}^H\mathbf{h}_{22}) \leq 0$.

Case 3(a): If the real part of $\mathbf{h}_{12}^H\mathbf{h}_{22}$ is positive, i.e., $\Re(\mathbf{h}_{12}^H\mathbf{h}_{22}) > 0$, the solution of $\mathbf{v}_2$ is in the direction of the altitude of the acute triangle as shown in Fig. 2(a). Denote $\mathbf{a} \triangleq \mathbf{h}_{12} - \sqrt{\lambda_{\max}}\mathbf{h}_{22}$, which is the third edge of the triangle. Let $\mathbf{h}_{12} + \alpha\mathbf{h}_{22}$ denote an arbitrary vector in the the two-dimensional subspace, where α is a weighting coefficient. Since $\mathbf{v}_2^{\text{mixed}}$ is perpendicular to $\mathbf{a}$, by solving the equation $\mathbf{a}^H(\mathbf{h}_{12} + \alpha\mathbf{h}_{22}) = 0$, we obtain the optimal weighting coefficient as $\alpha^* = -\frac{\mathbf{a}^H\mathbf{h}_{12}}{\mathbf{a}^H\mathbf{h}_{22}}$. Then, the solution is

$$\mathbf{v}_2^{\text{mixed}}(3) = \frac{\mathbf{h}_{12} + \alpha^*\mathbf{h}_{22}}{\|\mathbf{h}_{12} + \alpha^*\mathbf{h}_{22}\|}. \tag{23}$$

Case 3(b): If $\Re(\mathbf{h}_{12}^H\mathbf{h}_{22}) \leq 0$, the solution of $\mathbf{v}_2$ is in the direction of the altitude of the complementary triangle, as shown in Fig. 2(b). Denote $\mathbf{b} \triangleq \mathbf{h}_{12} + \sqrt{\lambda_{\max}}\mathbf{h}_{22}$, which is the third edge of the complementary triangle. Similarly to Case 3(a), since $\mathbf{v}_2^{\text{mixed}}$ is perpendicular to $\mathbf{b}$, by solving $\mathbf{b}^H(\mathbf{h}_{12} + \beta\mathbf{h}_{22}) = 0$, we obtain the optimal weighting coefficient as $\beta^* = -\frac{\mathbf{b}^H\mathbf{h}_{12}}{\mathbf{b}^H\mathbf{h}_{22}}$ and obtain the solution in this subcase as

$$\mathbf{v}_2^{\text{mixed}}(4) = \frac{\mathbf{h}_{12} + \beta^*\mathbf{h}_{22}}{\|\mathbf{h}_{12} + \beta^*\mathbf{h}_{22}\|}. \tag{24}$$

C. Both Users Decode the Interference

In strong interference scenario, we maximize the achievable sum-rate R^{strong} in (8), which can be written as

$$\log_2\left(\prod_{i=1,j\neq i}^{2} \min\left(\frac{P_i|\mathbf{h}_{ji}^H\mathbf{v}_i|^2}{P_j|\mathbf{h}_{jj}^H\mathbf{v}_j|^2+1}, 1 + P_i|\mathbf{h}_{ii}^H\mathbf{v}_i|^2\right)\right). \tag{25}$$

Denote $f_1(\mathbf{v}_1) \triangleq P_1|\mathbf{h}_{21}^H\mathbf{v}_1|^2$, $f_2(\mathbf{v}_2) \triangleq P_2|\mathbf{h}_{12}^H\mathbf{v}_2|^2$, and $g(\mathbf{v}_1,\mathbf{v}_2) \triangleq \left(1 + P_1|\mathbf{h}_{11}^H\mathbf{v}_1|^2\right)\left(1 + P_2|\mathbf{h}_{22}^H\mathbf{v}_2|^2\right)$. By expanding the product in (25), the maximization of (25) can be simplified as

$$\max_{\mathbf{v}_1,\mathbf{v}_2} \min\left(g(\mathbf{v}_1,\mathbf{v}_2), f_1(\mathbf{v}_1), f_2(\mathbf{v}_2), \frac{f_1(\mathbf{v}_1)f_2(\mathbf{v}_2)}{g(\mathbf{v}_1,\mathbf{v}_2)}\right), \tag{26}$$

whose solution is the maximum of the solutions to the following three subproblems.

$$\max_{\mathbf{v}_1,\mathbf{v}_2} \quad g(\mathbf{v}_1,\mathbf{v}_2), \tag{27a}$$

$$\textbf{s.t.} \quad g(\mathbf{v}_1,\mathbf{v}_2) \leq \min\left(f_1(\mathbf{v}_1), f_2(\mathbf{v}_2)\right). \tag{27b}$$

$$\max_{\mathbf{v}_1,\mathbf{v}_2} \quad \frac{f_1(\mathbf{v}_1)f_2(\mathbf{v}_2)}{g(\mathbf{v}_1,\mathbf{v}_2)}, \tag{28a}$$

$$\textbf{s.t.} \quad g(\mathbf{v}_1,\mathbf{v}_2) \geq \max\left(f_1(\mathbf{v}_1), f_2(\mathbf{v}_2)\right). \tag{28b}$$

$$\max_{\mathbf{v}_1,\mathbf{v}_2} \quad \min\left(f_1(\mathbf{v}_1), f_2(\mathbf{v}_2)\right), \tag{29a}$$

$$\textbf{s.t.} \min\left(f_1(\mathbf{v}_1), f_2(\mathbf{v}_2)\right) \leq g(\mathbf{v}_1,\mathbf{v}_2) \leq \max\left(f_1(\mathbf{v}_1), f_2(\mathbf{v}_2)\right). \tag{29b}$$

It is hard to solve these three optimization subproblems directly since the constraints are non-convex. To obtain beamforming vectors with explicit expressions, we find the solutions in the following way and allow a suboptimal solution.

Case 1: We first maximize (27a) without any constraints, and the solution is given by

$$\mathbf{v}_i^{\text{strong}}(1) = \frac{\mathbf{h}_{ii}}{\|\mathbf{h}_{ii}\|}, \quad i = 1, 2. \tag{30}$$

Then we substitute (30) into (27b) to check whether the constraint is satisfied.

If (27b) can be satisfied, $\mathbf{v}_i^{\text{strong}}(1)$ in (30) is the optimal solution of problem (27). Moreover, it must be the global optimal solution of problem (26), since the maximization values of the objective functions of problems (28) and (29) must be smaller than the objective function in (27a), which is determined by (28b) and (29b).

If (27b) cannot be satisfied, the optimal solution of problem (27) is obtained when the equality in (27b) holds, which can be found from problem (29).

Case 2: Next we maximize (28a) without any constraints, which is a generalized Rayleigh quotient problem. Similarly to (13), we can obtain

$$\mathbf{v}_i^{\text{strong}}(2) = \frac{\mathbf{B}_{ii}^{-1}\mathbf{h}_{ji}}{\|\mathbf{B}_{ii}^{-1}\mathbf{h}_{ji}\|}, \quad i = 1, 2. \tag{31}$$

Substitute (31) into (28b) to check whether the constraint is satisfied. If (28b) can be satisfied, $\mathbf{v}_i^{\text{strong}}(2)$ in (31) is the optimal solution of problem (28), which must be the global optimal solution of problem (26) as well. If (28b) cannot be satisfied, the optimal solution of problem (28) is obtained when the equality in (28b) holds. The problem can be included into problem (29) as well.

TABLE I
SUMMARY OF OPTIMAL BEAMFORMING VECTORS AND DESIGN PRINCIPLES

Scenarios	Sum-Rates	Beamforming Vectors		Design Principles	
Weak interference	R^{weak}	$\mathbf{v}_i^{\text{weak}} = \frac{\mathbf{B}_{ji}^{-1}\mathbf{h}_{ii}}{\|\mathbf{B}_{ji}^{-1}\mathbf{h}_{ii}\|}$		$\max \frac{\text{SNR}_i}{1+\text{INR}_j}$	
Mixed interference	R^{mixed}	$\mathbf{v}_1^{\text{mixed}} = \nu_{\max}(\mathbf{B}_{21}^{-1}\mathbf{B}_{11})$	Case 1: $\mathbf{v}_2^{\text{mixed}}(1) = \frac{\mathbf{h}_{12}}{\|\mathbf{h}_{12}\|}$	$\max \frac{1+\text{SNR}_1}{1+\text{INR}_2}$	max INR_1
			Case 2: $\mathbf{v}_2^{\text{mixed}}(2) = \frac{\mathbf{h}_{22}}{\|\mathbf{h}_{22}\|}$		max SNR_2
			Case 3(a): $\mathbf{v}_2^{\text{mixed}}(3) = \frac{\mathbf{h}_{12}+\alpha^*\mathbf{h}_{22}}{\|\mathbf{h}_{12}+\alpha^*\mathbf{h}_{22}\|}$		max min$(\text{INR}_1, \text{SNR}_2)$
			Case 3(b): $\mathbf{v}_2^{\text{mixed}}(4) = \frac{\mathbf{h}_{12}+\beta^*\mathbf{h}_{22}}{\|\mathbf{h}_{12}+\beta^*\mathbf{h}_{22}\|}$		
Strong interference	R^{strong}	Case 1: $\mathbf{v}_i^{\text{strong}}(1) = \frac{\mathbf{h}_{ii}}{\|\mathbf{h}_{ii}\|}$		max SNR_i	
		Case 2: $\mathbf{v}_i^{\text{strong}}(2) = \frac{\mathbf{B}_{ii}^{-1}\mathbf{h}_{ji}}{\|\mathbf{B}_{ii}^{-1}\mathbf{h}_{ji}\|}$		$\max \frac{\text{INR}_j}{1+\text{SNR}_i}$	
		Case 3: $\mathbf{v}_i^{\text{strong}}(3) = \frac{\mathbf{h}_{ji}}{\|\mathbf{h}_{ji}\|}$		max INR_j	

Case 3: Besides these two cases, the solution of problem (26) is obtained by solving the subproblem (29). If we remove the constraint in (29b), a simple solution can be obtained as

$$\mathbf{v}_i^{\text{strong}}(3) = \frac{\mathbf{h}_{ji}}{\|\mathbf{h}_{ji}\|}, \quad i = 1, 2. \tag{32}$$

This solution is optimal when it satisfies constraint (29b), otherwise it is suboptimal.

D. Interpretation and Extension

The beamforming vectors optimized for the typical interference scenarios are summarized in Table I, where in each scenario the users apply different decoding methods. From the previous optimization procedure and the expression of each optimal beamforming vector, we can interpret the principle behind the optimal beamforming design for each scenario.

In weak interference scenario, the beamforming vectors at both BSs essentially maximize the SLNR, as we have explained in section IV-A.

In mixed interference scenario where user 1 is subject to strong interference, the beamforming vector at BS_1 also maximizes the SLNR since BS_1 generates weak interference; while the beamforming vector at BS_2 depends on how strong the interference BS_2 might generate. Specifically, when the interference caused by BS_2 is not very strong, the beamforming vector is to match the cross-link channel $\mathbf{h}_{12}$ in order to maximize the INR_1, i.e., to strengthen the interference. When the interference from BS_2 is very strong, the beamforming vector only needs to match the direct-link channel $\mathbf{h}_{22}$ such that maximizes the SNR_2. When the interference level is in between, we need to find a trade-off between maximizing INR_1 and maximizing SNR_2.

In strong interference scenario, the beamforming vector at each BS depends on the interference level. When the interference is very strong, the beamforming only maximizes the SNR. When the interference is not very strong, the beamforming should maximize the INR. When the interference level is in between, the beamforming is to maximize the leakage-to-signal-plus-noise ratio.

***Extension*:** In a practical scenario where one macro-cell coexists with multiple pico-cells, we can first select a pico-BS closest to the macro-user as pico-BS_1, then design the beamforming vectors for the macro-BS and pico-BS_1 using the above principles as if there are only two cells. For other pico-BSs, the beamforming vectors are designed according to the particular interference scenario considering the already-determined beamforming vector and data rate of the macro-BS. For example, if pico-user 2 is subject to weak interference from the macro-BS, the beamforming vector of pico-BS_2 can be designed as in the weak interference scenario, i.e., maximizing the SLNR. If pico-user 2 suffers strong interference from the macro-BS but causes negligible interference to the macro-user, the beamforming of pico-BS_2 should guarantee the interference from the macro-BS to be decodable at pico-user 2, i.e., pico-BS_2 might proactively mismatch its direct-link channel to keep the required ISNR.

V. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed beamformers with proactive interference cancelation (PIC) in HetNets by comparing with other schemes.

To show the performance of the scheme that treats the interference as noise, we simulate the achievable rate of maximal SLNR scheme [8], which is optimal for weak interference scenario. To compare with spatially orthogonal transmission, the performance of ZF-CB is shown. To demonstrate the performance gain of PIC over passive interference cancelation, we simulate a scheme that employs matched filter at each BS and interference cancelation at each user (MF-IC).

In the simulation, all BSs are equipped with two antennas, and each BS serves one user. The radiuses of the macro-cell and each pico-cell are 500 m and 60 m, respectively. The transmit powers of the macro-BS and each pico-BS are 46 dBm and 30 dBm, respectively. The noise power is determined by the cell-edge SNR of the macro-cell, which is set as 5 dB. The path loss follows 3GPP channel model [9], and the small-scale channel is subject to Rayleigh fading. All the simulation results are obtained from 1000 channel realizations.

To show the performance under different interference scenarios, we first consider a two-cell HetNet and fix the position of the macro-user at 250 m away from the macro-BS, and move the pico-BS from the macro-cell center to the macro-cell edge while keep the relative position between the pico-BS and the pico-user fixed. The average sum-rates of the considered transmission schemes are shown in Fig. 3. Comparing the sum-rates achieved in different interference scenarios, we can see that as the pico-BS moves, the system successively experiences mixed 2, strong, mixed 1, and weak interference scenarios. Since both the beamforming designs and the decoding methods are different under different interference scenarios, the trend of the average sum-rate of PIC varies in Fig. 3. In all scenarios, PIC outperforms the other schemes. The maximal SLNR scheme is inferior to PIC in all scenarios except for the weak interference scenario. The average sum-rate of ZF-CB is nearly constant in all interference scenarios, because the interference is orthogonal in spatial subspace to the desired signal. MF-IC has a similar trend with PIC, but is inferior to PIC due to passively waiting for proper opportunities of canceling the interference.

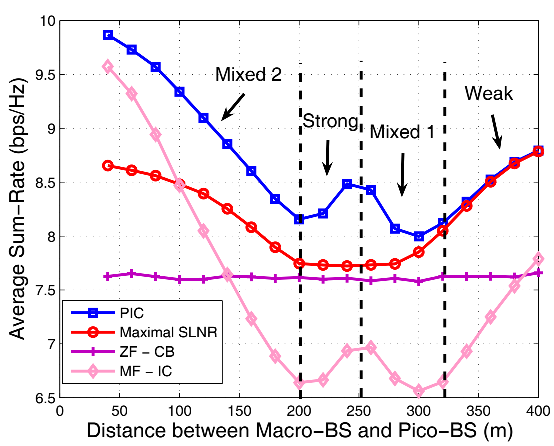

Fig. 3. Average sum-rates of different schemes in a two-cell HetNet when the pico-BS moves from macro-cell center to macro-cell edge.

Next, to illustrate the performance of PIC in practical HetNet, we consider a scenario where 20 pico-cells are randomly deployed in the macro-cell with a 120 m minimum distance among the pico-BSs. In this simulation, the position of the macro-user is still fixed at 250 m away from the macro-BS and the relative position between each pico-BS and its serving pico-user is fixed. Fig. 4 shows the average and the cell-edge per-user rates of the four schemes. Note that the cell-edge per-user rate is a statistic average counted from the worst served 5% users, which does not imply the users are really located in cell-edge. It is shown that PIC outperforms all the other schemes, especially in terms of cell-edge performance. For example, the cell-edge per-user rate of PIC is almost 6 times as that of MF-IC, which reveals the potential of proactive interference cancelation in multi-cell HetNets.

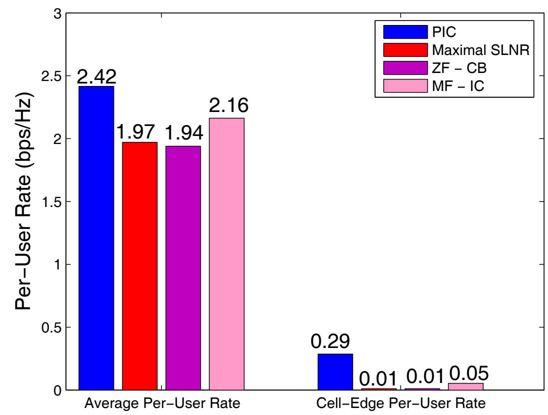

Fig. 4. Average per-user rate versus cell-edge per-user rate with 20 pico-cells coexisted with the macro-cell.

VI. Conclusion

In this paper, we proposed a transmission scheme for MISO interference channels. Specifically, we optimized the transmit beamforming that maximizes the achievable sum-rate, given the best decoding methods for weak, mixed and strong interference scenarios. Closed-form solutions of the optimal beamforming were obtained and the underlying design principles were interpreted. By proactively strengthening the interference with the optimized beamforming to ensure the interference to be correctly decoded and then subtracted at the receiver, the proposed scheme outperforms existing schemes of passive interference cancelation and zero-forcing beamforming, as demonstrated by simulation results.

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