Sum Rate Enhancement by Maximizing SGINR in an Opportunistic Interference Alignment Scheme

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***Abstract*— In this paper, we consider an opportunistic interference alignment scheme exploiting multiuser diversity in the interference-limited uplink cellular networks. The spatial degrees of freedom afforded by multiple receive antennas are partitioned into the signal dimension and interference dimension. We propose a method to enhance the sum rate by maximizing the signal to generated interference and noise ratio (SGINR) in each user. When multiple antennas are available in each user, we also propose a transmit beamforming scheme at each user in the direction to further maximize SGINR. We show that the proposed methods greatly improve the sum rate compared to the conventional opportunistic scheme.**

***Index Terms*—Uplink cellular network, inter-cell interference, opportunistic interference alignment, SGINR, user scheduling, beamforming, sum rate.**

I. Introduction

The capacity of the interference channel is not fully known even in the simplest two user interference channel. Recently, interference alignment (IA) was proposed as a degree of freedom (DOF) optimal scheme [1]. The basic idea is to restrict all the undesired interference from other communication links into a pre-determined subspace which is independent of the desired signal subspace. However, the scheme demands that each transmitter should have global knowledge of channel state information of other communication links and large dimension of time, frequency or spatial expansions.

One of the most common systems with the interference channel is a multi-cell cellular network. The key challenge in cellular networks is to handle the inter-cell interference [2], [3]. Especially in the uplink multi-cell communication, the SINR at a base station depends on the selected users in other cells, which is generally not known to the base station. Due to this coupled nature, user selection in each cell is challenging.

To handle the inter-cell interference in uplink user scheduling, the opportunistic interference alignment (OIA) scheme was proposed [4], [5]. The basic idea is to exploit multiuser diversity to opportunistically align undesired inter-cell interference to a pre-determined interference subspace. Specifically, each base station (BS) broadcasts its pre-designed interference directions, *e.g.,* orthonormal random vectors, to all the users in the system. Then, each user computes the amount of its generating interference that affects the other BSs, and sends it back to its home cell BS. The OIA does not require global channel state information, time/frequency expansion, and a number of iterations, thereby resulting in easier implementation. Furthermore, in [6], the authors mathematically proved that the OIA-based user scheduling scheme achieves the optimal DOF in wireless multi-cell uplink networks as the number of users in a cell increases. However, the conventional OIA scheme was proposed for achieving the optimal DOF metric and its sum-rate performance can be improved by modifying the scheduling criterion.

In this paper, we consider the OIA scheme in an interference-limited uplink cellular network. We propose a scheme to enhance the sum rate by maximizing the signal to generated interference and noise ratio (SGINR) in each user. The basic idea of SGINR was proposed in [7]–[9]. When multiple antennas are available in users, we also propose transmit beamforming at each user to further maximize SGINR. We show that the proposed schemes greatly improve the sum rate compared to the conventional ones.

In summary, the main contribution of this paper is the development of a scheme that maximizes SGINR and utilizes transmit beamforming in the OIA scheme to enhance the sum rate of the system .

This paper is organized as follows. In Section II, we describe the system model and develop the sum rate of the system. In Section III, we describe the conventional schemes. In Section IV, we propose a scheme to enhance the sum rate of the system by considering joint scheduling and transmit beamforming based on SGINR metric. In Section V, we show numerical results. We conclude in Section VI.

II. System Model

We consider an uplink time division duplex (TDD) cellular system with N_{BS} cells as in Fig. 1. Each cell has one base station (BS) and N_{US} users. Each base station is equipped with N_{R} receive antennas and each user has N_{T} transmit antennas. A channel from user-j in cell-i to BS-k is denoted as $H_{ij}^{(k)}$ which is an $N_{\text{R}} \times N_{\text{T}}$ matrix. We assume that the channels are reciprocal between the uplink and the downlink. Each entry of the channel matrix is assumed to follow a complex Gaussian distribution $\mathcal{CN}(0,1)$,[1] and all the entries are assumed to be mutually independent of one another.

[1] $\mathcal{CN}(\mu,\sigma^2)$ denotes a circularly symmetric complex Gaussian distribution with mean μ and variance σ^2.

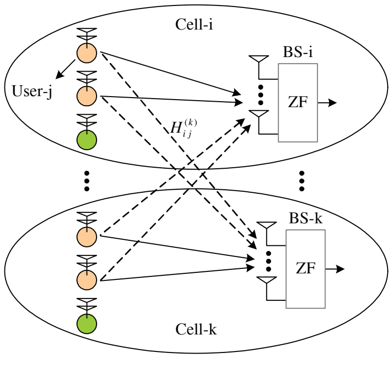

Fig. 1. System block diagram for an uplink cellular system.

Let $\mathcal{S}_i$ and $\mathcal{I}_i$ denote the signal subspace and the interference subspace of BS-i where $1 \leq i \leq N_{\text{BS}}$. We assume that $\mathcal{S}_i$ and $\mathcal{I}_i$ are orthogonal and that the dimension of each subspace is N_{SG} and N_{IN} respectively. Let $\mathbf{u}_{im}$ and $\mathbf{v}_{in}$ denote the orthonormal basis vectors for $\mathcal{S}_i$ and $\mathcal{I}_i$ respectively, where $1 \leq m \leq N_{\text{SG}}$, $1 \leq n \leq N_{\text{IN}}$, $1 \leq N_{\text{SG}} \leq N_{\text{R}}$ and $N_{\text{SG}} + N_{\text{IN}} = N_{\text{R}}$. We assume that these vectors are available to users through the broadcast system message. At each scheduling instant, user selection and data transmission consist of five stages; (i) broadcast of the basis vectors for the signal dimension in each BS (ii) feedback of one analog value from each user which is based on the SGINR metric, (iii) selection of N_{ST} users at each BS based on the feedback received from all the users in the cell, (iv) uplink data transmission of the selected users employing transmit beamforming, and (v) signal detection at each BS.

Specifically, in the first stage, BS-i broadcasts the basis vectors $\mathbf{u}_{im}$ for the signal dimension. These are randomly and independently generated in each BS. In the second stage, user-j in cell-i measures the downlink channel coefficients from all the BSs (*i.e.,* $H_{ij}^{(k)}$ for $1 \leq k \leq N_{\text{BS}}$). For the proposed method, the user computes a certain matrix K_{ij} based on the measured channel coefficients and finds the appropriate eigenvalue L_{ij} from K_{ij}. Although K_{ij} and L_{ij} are developed based on the SGINR metric, the method of development can be applied to the conventional metric, *e.g.,* GIN (generated interference to other cells) or SNR (signal to noise ratio) metric. Then, the user feeds back the eigenvalue to its own BS. Details of feedback information will be elaborated in Section IV. In the third stage, BS-i selects N_{ST} users, each of whom is denoted as $\pi_i(\ell)$ for $1 \leq \ell \leq N_{\text{ST}}$. A set of the selected users at BS-i is denoted as Π_i. The scheduling policy for user selection will be given in Section IV. Suppose in the third stage that user-j is selected in cell-i. In the fourth stage, the selected user computes the beamforming vector $\mathbf{w}_{ij}$, which is used to transmit data x_{ij}. In the fifth stage, BS-i employs a zero-forcing (ZF) receiver utilizing the basis vectors $\mathbf{v}_{in}$ for the interference dimension to retrieve each message of the selected users treating others as noise.

Let ρ_{ij} denote the signal to noise ratio (SNR) of user-j at BS-i. Let $\eta_{ij}^{(k)}$ denote the interference to noise ratio (INR) of user-j in cell-i to BS-k. Then, the received signal in BS-i satisfies the equation

$$\mathbf{y}_i = \sum_{j \in \Pi_i} \sqrt{\rho_{ij}}\, H_{ij}^{(i)} \mathbf{w}_{ij}\, x_{ij} + \sum_{\substack{k=1 \\ k \neq i}}^{N_{\text{BS}}} \sum_{j \in \Pi_k} \sqrt{\eta_{kj}^{(i)}} H_{kj}^{(i)} \mathbf{w}_{kj}\, x_{kj} + \mathbf{z}_i \tag{1}$$

where x_{ij} denotes the transmitted message from user-j in cell-i and $\mathbf{z}_i$ denotes the additive white Gaussian noise (AWGN) vector at BS-i which follows $\mathcal{CN}(\mathbf{0}, \mathbf{I}_{N_{\text{R}}})$. Here, $\mathbf{I}_{N_{\text{R}}}$ denotes the $N_{\text{R}} \times N_{\text{R}}$ identity matrix. We assume that the zero-forcing detection is employed at each base station for message detection. The ZF matrix is constructed including the interference subspace as follows:

$$\mathbf{H}_i^{\dagger} = (\mathbf{H}_i^{\text{H}} \mathbf{H}_i)^{-1} \mathbf{H}_i^{\text{H}}, \quad \text{where} \quad \mathbf{H}_i = \Big[H_{i\pi_i(1)}^{(i)} \mathbf{w}_{i\pi_i(1)}, \cdots,$$
$$H_{i\pi_i(N_{\text{ST}})}^{(i)} \mathbf{w}_{i\pi_i(N_{\text{ST}})}, \mathbf{v}_{i1}, \cdots, \mathbf{v}_{iN_{\text{IN}}} \Big]. \tag{2}$$

The messages for the desired users are retrieved by multiplying $\mathbf{H}_i^{\dagger}$ to the received signal and extracting the first N_{ST} elements in the resulting vector as follows:

$$[\hat{x}_{i\pi_i(1)}, \cdots, \hat{x}_{i\pi_i(N_{\text{ST}})}] = \mathbf{D}\mathbf{H}_i^{\dagger}\mathbf{y}_i, \tag{3}$$

where $\mathbf{D}$ denotes $N_{\text{ST}} \times N_{\text{R}}$ matrix obtained by the first N_{ST} rows of $\mathbf{I}_{N_{\text{R}} \times N_{\text{R}}}$.

A. Sum rate of the system

The signal after ZF processing for the received signal in (1) is given by

$$\mathbf{H}_i^{\dagger}\mathbf{y}_i = \begin{bmatrix} \sqrt{\rho_{i\pi_i(1)}}\; x_{i\pi_i(1)} \\ \vdots \\ \sqrt{\rho_{i\pi_i(N_{\text{ST}})}}\; x_{i\pi_i(N_{\text{ST}})} \\ \mathbf{0}_{(N_{\text{R}} - N_{\text{ST}}) \times 1} \end{bmatrix} + \mathbf{H}_i^{\dagger} \times$$
$$\left(\sum_{\substack{k=1 \\ k \neq i}}^{N_{\text{BS}}} \sum_{j \in \Pi_k} \sqrt{\eta_{kj}^{(i)}} H_{kj}^{(i)} \mathbf{w}_{kj}\, x_{kj} + \mathbf{z}_i \right) \tag{4}$$

It is shown in Appendix A that the instantaneous $\text{SINR}_{i\pi_i(\ell)}$ for the selected user $\pi_i(\ell)$ in cell-i is given by

$$\frac{\rho_{i\pi_i(\ell)}}{\left\langle \mathbf{H}_i^{\dagger} \sum_{k=1, k \neq i}^{N_{\text{BS}}} \sum_{j \in \Pi_k} \eta_{kj}^{(i)} H_{kj}^{(i)} \mathbf{w}_{kj} (H_{kj}^{(i)} \mathbf{w}_{kj})^{\text{H}} \mathbf{H}_i^{\dagger\,\text{H}} + (\mathbf{H}_i^{\text{H}} \mathbf{H}_i)^{-1} \right\rangle_{\ell\ell}} \tag{5}$$

where $<\cdot>_{\ell\ell}$ denotes the ℓ^{th} diagonal element of a matrix. Then, the sum rate per cell can be obtained by taking an average over all $H_{kj}^{(i)}$'s as

$$R_{\text{SUM}} = \frac{1}{N_{\text{BS}}} \sum_{i=1}^{N_{\text{BS}}} \sum_{\ell=1}^{N_{\text{ST}}} \mathbb{E}[\log_2(1 + \text{SINR}_{i\pi_i(\ell)})]. \tag{6}$$

III. Conventional schemes without transmit beamforming

In this section, we briefly take a look at how the feedback information L_{ij} is computed when we do not consider transmit beamforming as in [4], *i.e.,* single-input and multiple-output case (SIMO). Thus in (1), we have $\mathbf{w}_{ij} = 1$ and $H_{ij}^{(k)} = \mathbf{h}_{ij}^{(k)}$ *i.e.,* in a vector form of $N_{\text{R}} \times 1$.

A. Selecting the users with the large in-cell channel power (Max-SNR)

One simple scheme for user selection is that each base station selects the users with the good channel condition within a cell. The feedback information for a user-j in cell-i is simply the magnitude of a channel to BS-i as follows:

$$L_{ij} = \left\| \mathbf{h}_{ij}^{(i)} \right\|^2. \tag{7}$$

Then, users feedback L_{ij} to their own base station and BS-i selects N_{ST} users $\pi_i(\ell), 1 \le \ell \le N_{\text{ST}}$, who have one of the *largest*-N_{ST} L_{ij}'s out of N_{US} values as follows:

$$\pi_i(\ell) = j, \quad s.t. \quad L_{ij} = L_{i[\ell]},\ N_{\text{US}} - N_{\text{ST}} + 1 \le \ell \le N_{\text{US}}, \tag{8}$$

where $L_{i[\ell]}$ denotes the order statistics of L_{ij} in j such that $L_{i[1]} \le \cdots \le L_{i[N_{\text{US}}]}$.

B. Minimizing the generated interference [4] (Min-GIN)

To make interferences from other cells align in each cell in an opportunistic way, a scheme to minimize the generated interference was proposed in [4]. For a metric to measure the interference to BS-k from user-j in cell-i, the leakage is defined as

$$L_{ij}^{(k)} = \left\| \sum_{m=1}^{N_{\text{SG}}} (\mathbf{u}_{km}^{\text{H}} \mathbf{h}_{ij}^{(k)}) \mathbf{u}_{km} \right\|^2 = \sum_{m=1}^{N_{\text{SG}}} \left| \mathbf{u}_{km}^{\text{H}} \mathbf{h}_{ij}^{(k)} \right|^2. \tag{9}$$

We see that this metric is the 2-norm of the channel $\mathbf{h}_{ij}^{(k)}$ projected to the subspace $\mathcal{S}_k$. The total generated interference is given by

$$L_{ij} = \sum_{k=1, k\neq i}^{N_{\text{BS}}} L_{ij}^{(k)}. \tag{10}$$

Then, users feedback L_{ij} to their own base station and BS-i selects N_{ST} users $\pi_i(\ell), 1 \le \ell \le N_{\text{ST}}$, who have one of the *smallest*-N_{ST} L_{ij}'s out of N_{US} values as follows:

$$\pi_i(\ell) = j, \quad s.t. \quad L_{ij} = L_{i[\ell]},\ 1 \le \ell \le N_{\text{ST}}. \tag{11}$$

IV. Proposed scheme with joint scheduling and transmit beamforming based on SGINR(Max-SGINR)

In this section, we propose a scheme to enhance the sum rate by maximizing SGINR of each user when multiple antennas are available to each user. To this end, we utilize the SGINR metric and develop a transmit beamforming vector for each user, so that we construct the strategy of joint scheduling and transmit beamforming, which justifies the procedure of the system operation in Section II.

Transmit beamforming affects the SINR at all the receivers in the network by influencing the received interference signal. Thus, we need joint optimization to find the optimal transmit beamforming weights to maximize SINR in each receiver, which is usually very complicated. Instead, the SLNR (signal to leakage and noise ratio) or SGINR metric was proposed in [7]–[9], which enables separate optimization for each transmit beamforming vector and thus reduces the computational complexity greatly. It was shown that the metric works well especially in the high SINR case [7]–[9].

We note that the conventional scheme in Section III-B does not consider how good is a channel of a selected user within its own cell. To improve the sum rate, we propose that each base station should select users who have a large component projected to its own signal subspace in addition to generating small interferences to other cells, *i.e.,* the large SGINR. Considering the concept of SGINR [7], we can compute the SGINR of user-j in cell-i as follows;

$$\text{SGINR}_{ij} = \frac{\rho_{ij} \sum_{m=1}^{N_{\text{SG}}} |\mathbf{u}_{im}^{\text{H}} H_{ij}^{(i)} \mathbf{w}_{ij}|^2}{1 + \sum_{k=1,k\neq i}^{N_{\text{BS}}} \eta_{kj}^{(i)} \sum_{m=1}^{N_{\text{SG}}} |\mathbf{u}_{km}^{\text{H}} H_{ij}^{(k)} \mathbf{w}_{ij}|^2}. \tag{12}$$

We note in (12) that the numerator represents the 2-norm of the signal component projected to the signal subspace $\mathcal{S}_i$ of user-j's own BS-i (*i.e.,*$H_{ij}^{(i)} \mathbf{w}_{ij} \to \mathcal{S}_i$), and the denominator represents the noise power and the sum of 2-norm of the generated interference components projected to the signal subspace $\mathcal{S}_k$ of the interfering BS-k (*i.e.,*$H_{ij}^{(k)} \mathbf{w}_{ij} \to \mathcal{S}_k$), when a transmit beamforming vector $\mathbf{w}_{ij}$ is used. After some manipulation of (12), we can rewrite SGINR_{ij} as

$$\frac{\rho_{ij} \mathbf{w}_{ij}^{\text{H}} H_{ij}^{(i)\text{H}} \{ \sum_{m=1}^{N_{\text{SG}}} \mathbf{u}_{im} \mathbf{u}_{im}^{\text{H}} \} H_{ij}^{(i)} \mathbf{w}_{ij}}{\mathbf{w}_{ij}^{\text{H}} \left(\mathbf{I} + \sum_{k=1,k\neq i}^{N_{\text{BS}}} \eta_{kj}^{(i)} H_{ij}^{(k)\text{H}} \{ \sum_{m=1}^{N_{\text{SG}}} \mathbf{u}_{km} \mathbf{u}_{km}^{\text{H}} \} H_{ij}^{(k)} \right) \mathbf{w}_{ij}}. \tag{13}$$

The objective of joint user scheduling and transmit beamforming is to maximize SGINR_{ij} in (13). The problem of finding the optimal $\mathbf{w}_{ij}$ to maximize SGINR_{ij} in (13) can be solved using the Rayleigh-Ritz theorem related to the generalized eigenvalue problem [10]. Several similar examples are also found in [7], [8]. To formulate the problem more specifically, let us define $K_{\text{SGINR},ij}$ as

$$K_{\text{SGINR},ij} = \rho_{ij} \left(\mathbf{I} + \sum_{k=1,k\neq i}^{N_{\text{BS}}} \eta_{kj}^{(i)} H_{ij}^{(k)\text{H}} \{ \sum_{m=1}^{N_{\text{SG}}} \mathbf{u}_{km} \mathbf{u}_{km}^{\text{H}} \} H_{ij}^{(k)} \right)^{-1}$$
$$\times H_{ij}^{(i)\text{H}} \{ \sum_{m=1}^{N_{\text{SG}}} \mathbf{u}_{im} \mathbf{u}_{im}^{\text{H}} \} H_{ij}^{(i)} \overset{(a)}{=} V_{ij} \Lambda_{ij} V_{ij}^{\text{H}}, \tag{14}$$

where (a) follows from the eigenvalue decomposition. Then, the problem of finding the optimal transmit beamforming vector to maximize SGINR_{ij} in (13) can be written as [10]

$$\mathbf{w}_{ij}^{\text{o}} = \arg\max_{\mathbf{w}_{ij}} \mathbf{w}_{ij}^{\text{H}} K_{\text{SGINR},ij} \mathbf{w}_{ij}, \tag{15}$$

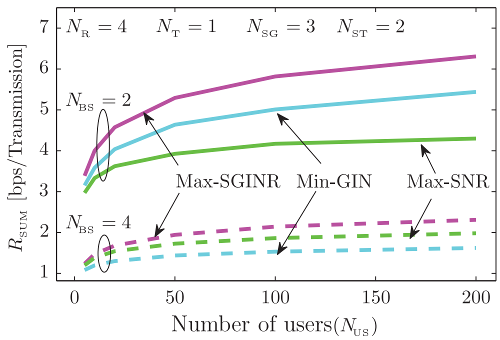

Fig. 2. Sum rate comparison of Max-SGINR, Min-GIN, and Max-SNR schemes. ($N_T = 1$)

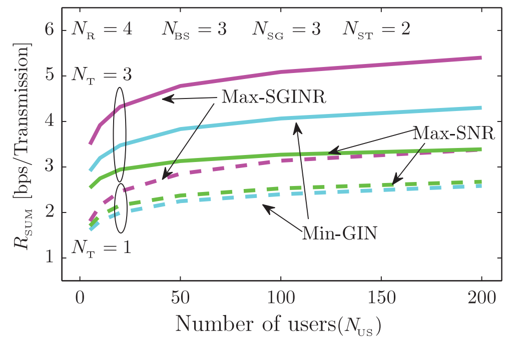

Fig. 3. Effect of transmit beamforming combined with user scheduling. ($N_{BS} = 3$)

and the solution is obtained through the eigenvector corresponding to the largest eigenvalue of $K_{\mathrm{SGINR},ij}$. Thus, feedback information for user-j in cell-i can be found as

$$L_{ij} = \max_{1 \le \ell \le N_T} <\Lambda_{ij}>_{\ell\ell} \,. \tag{16}$$

Based on this feedback information, each base station selects N_{ST} users who have the *largest* L_{ij}'s out of N_{US} values as follows:

$$\pi_i(\ell) = j, \quad s.t. \quad L_{ij} = L_{i[\ell]},\ N_{US} - N_{ST} + 1 \le \ell \le N_{US}. \tag{17}$$

Finally, selected users utilize $\mathbf{w}_{ij}^{o}$ in (15) as their transmit beamforming vector, which justifies the system operation procedure in Section II.

V. Numerical Results

In this section, we present simulation results for the proposed scheme and compare its performance with the conventional schemes. The common system parameters are as follows: $N_R = 4$, $N_{SG} = 3$, $N_{ST} = 2$, SNR = INR = 10dB. The other parameters are shown in each figure.

In Fig. 2, we show the sum rate results of the proposed Max-SGINR scheme in Section IV and compare them with two other conventional schemes, Min-GIN and Max-SNR in Section III. The sum rate is depicted as a function of the number of users (N_{US}). We find that the Max-SGINR scheme is the best among three schemes with both $N_{BS} = 2$ and $N_{BS} = 4$. In this figure, we do not assume transmit beamforming since $N_T = 1$. Thus, the gain comes from the scheduling policy based on maximizing SGINR.

In Fig. 3, we demonstrate the effect of transmit beamforming combined with user scheduling. We can see that all of Max-SGINR, Min-GIN, and Max-SNR schemes obtain the transmit beamforming gain when we increase N_T to 3 from 1. However, we note that the gain in the Max-SGINR scheme and the Min-GIN scheme is much larger than that of the Max-SNR scheme, which implies that transmit beamforming should be devised considering generated interference in the cellular network.

VI. Conclusion

In this paper, we proposed a method to enhance the sum rate by maximizing the SGINR in each user. When multiple antennas are available in each user, we also proposed a strategy of joint user scheduling and transmit beamforming to further maximize SGINR. We show that the proposed methods greatly improve the sum rate compared to the conventional opportunistic scheme.

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Appendix A
Derivation of SINR

Let $A \triangleq \sum_{k=1,k\neq i}^{N_{BS}} \sum_{j\in \Pi_k} \sqrt{\eta_{kj}^{(i)}} H_{kj}^{(i)} \mathbf{w}_{kj} x_{kj}$ in (4). Then, covariance of A is given by

$$\mathrm{cov}(A, A) = \sum_{k=1,k\neq i}^{N_{BS}} \sum_{j\in \Pi_k} \eta_{kj}^{(i)} H_{kj}^{(i)} \mathbf{w}_{kj} \left(H_{kj}^{(i)} \mathbf{w}_{kj}\right)^{\mathrm{H}} \tag{18}$$

because $\mathbb{E}[x_{kj} x_{\ell m}^*] = \delta_{k\ell}\delta_{jm}$ where $\delta_{k\ell}$ denotes the Kronecker delta. Since $\mathrm{cov}(\mathbf{z}_i, \mathbf{z}_i) = \mathbf{I}_{N_R \times N_R}$ from the complex Gaussian noise assumption, covariance of $\mathbf{H}_i^{\dagger}(A + \mathbf{z}_i)$, *i.e.*, $\mathrm{cov}\left(\mathbf{H}_i^{\dagger}(A + \mathbf{z}_i), \mathbf{H}_i^{\dagger}(A + \mathbf{z}_i)\right)$ is given from (18) by

$$\mathbf{H}_i^{\dagger} \sum_{k=1,k\neq i}^{N_{BS}} \sum_{j\in \Pi_k} \eta_{kj}^{(i)} H_{kj}^{(i)} \mathbf{w}_{kj} (H_{kj}^{(i)} \mathbf{w}_{kj})^{\mathrm{H}} \mathbf{H}_i^{\dagger^{\mathrm{H}}} + (\mathbf{H}_i^{\mathrm{H}} \mathbf{H}_i)^{-1} \tag{19}$$

The SINR of the selected user $\pi_i(\ell)$ in (4) is given by

$$\mathrm{SINR}_{i\ell} = \frac{\rho_{i\pi_i(\ell)}}{\left\langle \mathrm{cov}\left(\mathbf{H}_i^{\dagger}(A + \mathbf{z}_i), \mathbf{H}_i^{\dagger}(A + \mathbf{z}_i)\right)\right\rangle_{\ell\ell}}, \tag{20}$$

which reduces to (5) from (19).

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