Retrospective Interference Neutralization for the Two-Cell MIMO Interfering Multiple Access Channel

Bowei Zhang, Xin Hu, Weinong Wu, Jie Huang, Jing Wang and Wenjiang Feng

Abstract—**In this paper, we study the degrees of freedom (DoF) of the two-cell multiple-input multiple-output (MIMO) interfering multiple access channel (IMAC) with hybrid local channel state information (CSI) at the transmitter (CSIT). Hybrid CSIT means that part of the CSIT is delayed while part is instantaneous. The main contribution of this paper is that we propose a retrospective interference neutralization (RIN) method by using hybrid CSIT and obtain a new DoF result. The approach consists of two steps: 1) side-information learning and 2) retrospective interference transmission. In the first step, two cells of users are scheduled to transmit fresh symbols and each base station (BS) overhears the signals sent by the non-corresponding users. Each BS can learn the linear combination of interference symbols. In the second step, each user sends the previously transmitted symbols by using the beamforming matrix so that each BS can exploit the side-information to neutralize all interference symbols. Through theoretical analysis and numerical simulations, we first verify that the RIN method can obtain the theoretical DoF result. Furthermore, we show that with the help of hybrid CSIT, a higher DoF can be achieved compared with the existing retrospective interference alignment schemes based on completely delayed CSIT.**

Index Terms—**degrees of freedom, delayed CSIT, hybrid CSIT, interference alignment, interference neutralization.**

I. INTRODUCTION

Due to the broadcast nature of the wireless medium, simultaneous transmission from multiple nodes causes interference to each other. Interference is a major barrier to limit the capacity of multi-user wireless networks. Recently, interference alignment (IA) was shown to be able to achieve the information-theoretic maximum degrees of freedom (DoF) of some interference networks[1]-[2]. When relays are available in interference channel, it was found in [3-5] that another interference management technique, called interference neutralization (IN), can achieve a higher DoF than IA.

It is worth noting that the above DoF results were obtained under a requirement of instantaneous CSIT. In practical scenarios, it is unreasonable to ignore the impact of feedback delay. When the CSIT is delayed due to practical constraints, the conventional IA and IN is useless. To address this problem,

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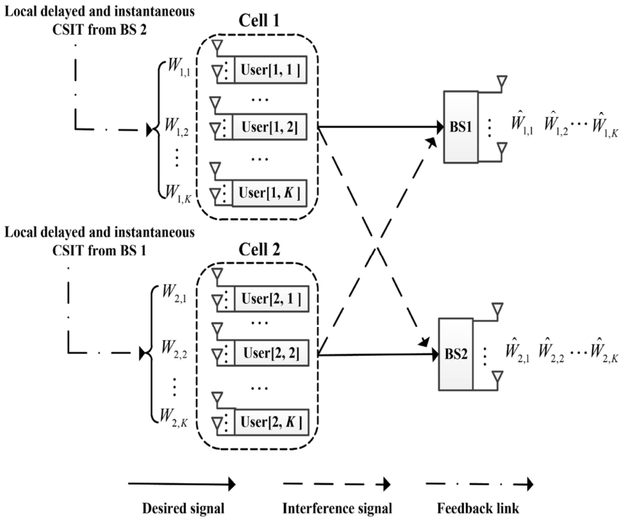

Fig.1 A two-cell MIMO IMAC with hybrid (delayed and local instantaneous) CSIT.

retrospective interference alignment (RIA) was proposed in [6-7] to show that RIA is still capable of increasing the DoF even when the CSIT is completely outdated. Subsequently, in [8], delayed CSIT was exploited to obtain a higher DoF than the time division multiple access (TDMA) scheme for the two-cell MIMO interfering multiple access channel (IMAC).

In this paper, we provide a new DoF result of the two-cell MIMO IMAC under an assumption that hybrid CSIT is available at transmitters. Here hybrid CSIT means that transmitters have a mix of delayed and limited amount of instantaneous CSI. The authors in [9] and [10], have shown that hybrid CSIT can obtain more DoF than the "delayed-only" CSIT for interference and X channels, respectively. By taking advantage of hybrid CSIT, we propose a retrospective interference neutralization (RIN) scheme for the two-cell MIMO IMAC. We show that the achievable sum-DoF is equal to $4M/3$ if $N < M \le KN/2$ and $M(1+1/(2\varphi+1))$ if $KN/2 < M < KN$, where M and N denote the number of antennas equipped at each base station (BS) and each user, respectively, and K denotes the number of users at each cell; $\varphi = \lceil M/(KN-M) \rceil$ represents the number of time slots that each user transmit the fresh symbols. It is shown that the RIN scheme can achieve a higher DoF than the best-known "delayed-only" result in [8] by using fewer time slots.

Notations: For any matrix $\mathbf{A}$, $\mathbf{A}^T$, $\mathbf{A}^{-1}$, $\mathbf{A}^H$, $\mathbf{A}^\dagger$ and *rank* ($\mathbf{A}$) denote the transpose, inverse of $\mathbf{A}$, Hermitian transpose, Moore–Penrose pseudo-inverse of **A** and the rank of **A**, respectively. $\mathbb{E}[\cdot]$ is the expectation operator. For convenience, we set $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$.

II. SYSTEM MODEL

We consider a MIMO IMAC with two cells and K ($K \geq 2$) users per cell as illustrated in Fig.1, where each BS and each user are equipped with M and N antennas, respectively. To be more realistic, we focus on a case with $M \geq N$, i.e., the number of antennas per BS is greater than or equal to the number of antennas per user. For convenience, we refer to the channel as a two-cell (M, N, K) MIMO IMAC. It is assumed that all nodes in the MIMO IMAC share the same frequency band. Owing to the simultaneous transmission, each BS receives the interference from the users in the other cell. For $k \in \mathcal{K}$ and $i \in \{1,2\}$, we denote the k-th user in the i-th cell as user [i, k]. User [i, k] intends to transmit the message $W^{[i,k]}$ to its corresponding BS.

When all users simultaneously send their signals at time slot t, the received signal $\mathbf{y}_l[t]$ at the l-th ($l \in \{1,2\}$) BS is given by

$$\mathbf{y}_l[t] = \sum_{i=1}^{2}\sum_{k=1}^{K} \mathbf{H}_l^{[i,k]}[t]\mathbf{x}^{[i,k]}[t] + \mathbf{n}_l[t] \tag{1}$$

where $\mathbf{H}_l^{[i,k]}[t]$ denotes the $M \times N$ channel matrix from user [i, k] to the l-th BS at time slot t; $\mathbf{x}^{[i,k]}[t]$ denotes the $N \times 1$ signal vector sent by the user [i, k] at time slot t satisfying an average power constraint $\mathbb{E}\left[\left\|\mathbf{x}^{[i,k]}[t]\right\|^2\right] \leq P$. $\mathbf{n}_l[t]$ denotes the $M \times 1$ additive white Gaussian noise (AWGN) vector with zero mean and variance σ^2 per entry. We assume that the channels vary independently at different time slot.

Similar to [6], we normalize delay to one time slot because our achievable results hold for arbitrary delay. Specifically, at time slot t, user [i, k] has access to the delayed local CSIT $\left\{\mathbf{H}_j^{[i,k]}[t']\right\}_{t'=1}^{t-1}$. At a particular time slot $\bar{t} = \left\{\mathbf{H}_j^{[i,k]}[t']\right\}_{t'=1}^{\bar{t}}$, the instantaneous CSIT is available at each user, where $i, j \in \{1,2\}$, $k \in \mathcal{K}$, $i \neq j$. In addition, each BS only needs to know local instantaneous CSIR, which is more relaxed than that demanded in [8]. It is assumed that all CSI can be obtained through a noiseless feedback link.

The sum-DoF of the network is defined as the pre-log coefficient of network sum rate in high signal-to-noise ratio (SNR) regime. In each time slot, the achievable rate from user [l, k] to the l-th BS can be expressed as:

$$R^{[l,k]}(SNR) = d^{[l,k]}\log(SNR) + o\left(\log(SNR)\right) \tag{2}$$

Where $d^{[l,k]}$ is the achievable DoF of user [l, k], $l \in \{1,2\}$, $k \in \mathcal{K}$. Therefore, the sum rate of the l-th BS can be written as

$$R_l(SNR) = \sum_{k=1}^{K} R^{[l,k]}(SNR) \tag{3}$$

The sum-DoF of the two-cell MIMO IMAC can be given by

$$\mathrm{DoF}_{sum} = \sum_{l=1}^{2}\sum_{k=1}^{K} d^{[l,k]} = \sum_{l=1}^{2}\sum_{k=1}^{K} \lim_{SNR\to\infty} \frac{R^{[l,k]}(SNR)}{\log(SNR)} \tag{4}$$

Since noise does not affect DoF, we neglect noise terms in the following discussions.

III. PROPOSED METHOD BASED ON HYBRID CSIT

In this section, we first use a simple example to illustrate the core idea behind our method. Then, we extend our approach into a general MIMO IMAC.

A. Example of (M, N, K)=(2, 2, 2)

Throughout this example, we will show that the sum-DoF of 4 can be achieved for (2, 2, 2) MIMO-IMAC using hybrid CSIT. The RIN scheme involves two steps: side-information learning and retrospective interference transmission. Next we explain how each of these steps is performed to achieve the stated sum-DoF.

1) Side-information learning: This step consists two time slots. In the first time slot, user [1,1] and user [1,2] send signals $\mathbf{x}^{[1,1]}[1] = [a_1\ a_2]^T$ and $\mathbf{x}^{[1,2]}[1] = [b_1\ b_2]^T$ to their corresponding BS (i.e., BS 1), while users in cell 2 keep silence. The received signal at each BS is given by:

$$\begin{aligned}\mathbf{y}_l[1] &= \mathbf{H}_l^{[1,1]}[1]\mathbf{x}^{[1,1]}[1] + \mathbf{H}_l^{[1,2]}[1]\mathbf{x}^{[1,2]}[1] \\ &= \mathbf{L}_l[1](a_1, a_2, b_1, b_2)\end{aligned} \tag{5}$$

where $\mathbf{L}_l[t](\cdot)$ denotes the linear combination of symbols that is received by the l-th BS at time slot t. In the second time slot, user [2,1] and user [2,2] send signals $\mathbf{x}^{[2,1]}[1] = [d_1\ d_2]^T$ and $\mathbf{x}^{[2,2]}[1] = [e_1\ e_2]^T$, while users in cell 1 keep silence. The received signal at each BS is given by:

$$\begin{aligned}\mathbf{y}_l[2] &= \mathbf{H}_l^{[2,1]}[2]\mathbf{x}^{[2,1]}[2] + \mathbf{H}_l^{[2,2]}[2]\mathbf{x}^{[2,2]}[2] \\ &= \mathbf{L}_l[2](d_1, d_2, e_1, e_2)\end{aligned} \tag{6}$$

At each time slot of the side-information step, each BS obtains two linear independent equations (each BS has 2 antennas) with four variables and we need to provide two more linear independent equations to resolve the desired symbols. Note that if BS 1 and BS2 knows the linear combinations of $\mathbf{L}_2[1](a_1, a_2, b_1, b_2)$ and $\mathbf{L}_1[2](d_1, d_2, e_1, e_2)$, respectively, they will have enough equations to decode all desired symbols. The key idea of step 2 is to provide the interference-free linear independent equations $\mathbf{L}_2[1](a_1, a_2, b_1, b_2)$ to BS 1 and $\mathbf{L}_1[2](d_1, d_2, e_1, e_2)$ to BS 2.

2) Retrospective interference transmission: We use the third time slot for the retrospective interference transmission. In the third time slot, each user has knowledge of both current and outdated local CSIT thanks to feedback. User [1, k] and user [2, k] ($k \in \{1,2\}$) simultaneously send a linear combination of the previously transmitted symbols by using linear beamforming matrix as

$$\mathbf{x}^{[1,k]}[3] = \mathbf{V}^{[1,k]}[3]\mathbf{H}_2^{[1,k]}[1]\mathbf{x}^{[1,k]}[1],\ k \in \{1,2\} \tag{7}$$

$$\mathbf{x}^{[2,k]}[3] = \mathbf{V}^{[2,k]}[3]\mathbf{H}_1^{[2,k]}[2]\mathbf{x}^{[2,k]}[2],\ k \in \{1,2\} \tag{8}$$

Then, the received signal at each BS is given by:

$$\begin{aligned}\mathbf{y}_l[3] = &\sum_{k=1}^{2}\mathbf{H}_l^{[1,k]}[3]\mathbf{V}^{[1,k]}[3]\mathbf{H}_2^{[1,k]}[1]\mathbf{x}^{[1,k]}[1] \\ &+ \sum_{k=1}^{2}\mathbf{H}_l^{[2,k]}[3]\mathbf{V}^{[2,k]}[3]\mathbf{H}_1^{[2,k]}[2]\mathbf{x}^{[2,k]}[2]\end{aligned} \tag{9}$$

The key idea of the interference neutralization step is to exploit the hybrid CSIT at each user and the side-information at each BS so that the received interference symbols at time slot 3 and side-information of the previous time slots can be added up to zero at each BS. It is noteworthy that the main difference between the traditional interference neutralization and the retrospective interference neutralization is that the former can eliminate interference in the air with the help of the relay that has global CSI, whereas the latter utilizes the received interference and does not need the aid of relay. For user [2, k] ($k \in \{1,2\}$), we construct the 2×2 interference neutralization matrix $\mathbf{V}^{[2,k]}[3]$ so that the received interference symbols at time slot 3 can be neutralized by using the side-information at BS 1, i.e.,

$$\sum_{k=1}^{2}\mathbf{H}_1^{[2,k]}[3]\mathbf{V}^{[2,k]}[3]\mathbf{H}_1^{[2,k]}[2]\mathbf{x}^{[2,k]}[2] + \mathbf{L}_1[2](d_1,d_2,e_1,e_2)=\mathbf{0} \quad (10)$$

In order to satisfy (10), the following condition should be satisfied:

$$\mathbf{H}_1^{[2,k]}[3]\mathbf{V}^{[2,k]}[3]\mathbf{H}_1^{[2,k]}[2]+\mathbf{H}_1^{[2,k]}[2]=\mathbf{0} \quad (11)$$

Then, we design $\mathbf{V}^{[2,k]}[3]$ as:

$$\mathbf{V}^{[2,k]}[3]=-\left(\mathbf{H}_1^{[2,k]}[3]\right)^{-1}, k\in\{1,2\} \quad (12)$$

Since $\mathbf{H}_1^{[2,k]}[t]$ is a 2×2 channel matrix, $\left(\mathbf{H}_1^{[2,k]}[3]\right)^{-1}$ and $\mathbf{V}^{[2,k]}[3]$ exist and (10) holds.

For user[1, k], we construct the interference neutralization matrix $\mathbf{V}^{[1,k]}[3]$ to eliminate the interference symbols at BS 2 as follows:

$$\mathbf{H}_2^{[1,k]}[3]\mathbf{V}^{[1,k]}[3]\mathbf{H}_2^{[1,k]}[1]+\mathbf{H}_2^{[1,k]}[1]=\mathbf{0}, k\in\{1,2\} \quad (13)$$

Similar to (10), (13) holds. As a result, BS 1 and BS 2 obtain interference-free linear independent combinations of $\mathbf{L}_2[1](a_1,a_2,b_1,b_2)$ and $\mathbf{L}_1[2](d_1,d_2,e_1,e_2)$. Without the retrospective interference transmission, step 2 will take two time slots to provide three interference-free linear independent equations for each BS, which yields DoF loss.

3) Decoding: We explain the decoding procedure for BS 1. Concatenating the received signals in three time slots, the equivalent input-output relationship at BS 1 is

$$\underbrace{\begin{bmatrix}\mathbf{y}_1[1]\\ \mathbf{y}_1[3]+\mathbf{y}_1[2]\end{bmatrix}}_{\bar{\mathbf{y}}_1}=\underbrace{\begin{pmatrix}\mathbf{H}_1^{[1,1]}[1] & \mathbf{H}_1^{[1,2]}[1]\\ \bar{\mathbf{H}}_2^{[1,1]}[1] & \bar{\mathbf{H}}_2^{[1,2]}[1]\end{pmatrix}}_{\bar{\mathbf{H}}_1}\begin{pmatrix}\mathbf{x}^{[1,1]}[1]\\ \mathbf{x}^{[1,2]}[1]\end{pmatrix} \quad (14)$$

where $\bar{\mathbf{H}}_2^{[1,k]}[1]=\mathbf{H}_1^{[1,k]}[3]\mathbf{V}^{[1,k]}[3]\mathbf{H}_2^{[1,k]}[1]$, $k\in\{1,2\}$; $\bar{\mathbf{y}}_1$ is a 4×1 vector, $\bar{\mathbf{H}}_1$ is a 4×4 matrix. Since all channel values are generic, $rank(\bar{\mathbf{H}}_1)=4$. Therefore, BS 1 can decode 4 desired symbols. Similarly, BS 2 can decode 4 desired symbols in three time slots by using the same method. Consequently, a total of 8 desired symbols have been transmitted in three time slots in the network, implying that the sum-DoF of 8/3 is achieved.

4) Sum-DoF gains: For the (2,2,2) MIMO IMAC, the RIA scheme in [8] can achieve the sum-DoF of 12/5 in 5 time slots. Since the RIN scheme attains the sum-DoF of 8 in 3 time slots, we utilizes fewer time slots to obtain 11.1% DoF gains over the RIA scheme in this network.

B. The general configuration

We now present the achievable DoF results for the general (M, N, K) MIMO IMAC in Theorem 1.

Theorem 1: For the two-cell (M, N, K) MIMO IMAC with hybrid CSIT where $N<M<KN$, the achievable sum-DoF is

$$\text{DoF}_{\text{sum}}=\begin{cases}\frac{4M}{3}, & N<M\le KN/2\\ M(1+\frac{1}{2\varphi+1}), & KN/2<M<KN\end{cases} \quad (15)$$

where $\varphi=\lceil M/(KN-M)\rceil$ represents the number of time slots used by each user to transmit the fresh symbols.

Proof: We prove Theorem 1 by using the proposed RIN scheme. In order to reach the maximal sum-DoF by using the RIN scheme, we should design different transmission strategies according to different system configurations. We first consider the case of $KN/2<M<KN$. In the following, we describe each transmissions in detail.

We first consider the side-information learning step. This step consists of two phases and each phase contains φ time slots. The number of φ time slots is determined on the values M, N, K. The i-th ($i\in\{1,2\}$) phase is dedicated to users in the i-th cell and user [i, k] ($k\in\mathcal{K}$) simultaneously sends $\mathbf{x}^{[i,k]}[t]=\left[x_1^{[i,k]},x_2^{[i,k]},\cdots,x_N^{[i,k]}\right]^T[t]$ over its own N transmit antennas at time slot t. Note that the final transmission (phase 3) only contains one time slot, we only can provide M new linear independent equations in phase 3. Due to the condition of $KN/2<M<KN$, we can find φ so that the condition of $\varphi M+M\le KN\varphi$ can be satisfied. Since each BS can decode at most $\varphi M+M$ desired symbols in $2\varphi+1$ time slots, users in the i-th cell only transmit $\varphi M+M$ fresh symbols in the i-th phase.

During phase 1, all users in cell 1 transmit $\varphi M+M$ fresh symbols and $KN\varphi-\varphi M-M$ zero elements in total and users in cell 2 keep silence. The received signal at each BS is given by:

$$\mathbf{y}_l[t]=\mathbf{H}_l^{[1,1]}[t]\mathbf{x}^{[1,1]}[t]+\cdots+\mathbf{H}_l^{[1,K]}[t]\mathbf{x}^{[1,K]}[t] \triangleq \mathbf{L}_l[t](\mathbf{x}^{[1,1]},\cdots,\mathbf{x}^{[1,K]}) \quad (16)$$

where $t\in\{1,2,\ldots,\varphi\}\triangleq\mathcal{T}_1$, $\mathbf{L}_l[t](\cdot)$ denotes the linear combination of symbols that is received by the l-th BS at time slot t. In phase 1, BS 1 receives the desired symbols and BS 2 overhears the interference symbols for use later (in phase 3). For each time slot, BS 1 has M linearly independent equations with KN variables. Due to the condition of $KN>M$, BS 1 cannot decode the desired symbols. In phase 1, if BS 1 knows $\mathbf{L}_2[1](\mathbf{x}^{[1,1]},\cdots,\mathbf{x}^{[1,K]})$ overheard by BS 2, it can decode all desired symbols.

During phase 2, all users in cell 2 transmit $\varphi M+M$ fresh symbols and the received signal at each BS is given by:

$$\mathbf{y}_l[2]=\mathbf{H}_l^{[2,1]}[2]\mathbf{x}^{[2,1]}[2]+\cdots+\mathbf{H}_l^{[2,K]}[2]\mathbf{x}^{[2,K]}[2] \triangleq \mathbf{L}_l[2](\mathbf{x}^{[2,1]},\cdots,\mathbf{x}^{[2,K]}) \quad (17)$$

where $t\in\{\varphi+1,\varphi+2,\cdots,2\varphi\}\triangleq\mathcal{T}_2$. Similarly, if BS 2 knows $\mathbf{L}_1[t](\mathbf{x}^{[2,1]},\cdots,\mathbf{x}^{[2,K]})$ ($t\in\mathcal{T}_2$), it can decode all desired symbols.

For the retrospective interference transmission, we use one time slot. Without loss of generality, we assume time slot $2\varphi+1$ has instantaneous CSIT. For simplicity, let us denote

$\bar{\varphi} = 2\varphi + 1$ in subsequent equation expression. In phase 3, each user has knowledge of both current and outdated local CSIT. User [1, k] and user [2, k] ($k \in \mathcal{K}$) simultaneously send a superposition of the linear combination of previously transmitted symbols by using linear beamforming matrix $\mathbf{V}^{[1,k]}[3]$ and $\mathbf{V}^{[2,k]}[3]$, respectively. Then, the received signal at each BS is given by:

$$\begin{aligned}\mathbf{y}_l[\bar{\varphi}] = &\sum_{k=1}^{K} \mathbf{H}_l^{[1,k]}[\bar{\varphi}]\mathbf{V}^{[1,k]}[\bar{\varphi}]\sum_{t=1}^{\varphi}\mathbf{H}_2^{[1,k]}[t]\mathbf{x}^{[1,k]}[t] \\ &+\sum_{k=1}^{K}\mathbf{H}_l^{[2,k]}[\bar{\varphi}]\mathbf{V}^{[2,k]}[\bar{\varphi}]\sum_{t=\varphi+1}^{2\varphi}\mathbf{H}_1^{[2,k]}[t]\mathbf{x}^{[2,k]}[t]\end{aligned} \tag{18}$$

For user [i, k] ($i \in \{1,2\}$, $k \in \mathcal{K}$), we construct the $N \times M$ interference neutralization matrix $\mathbf{V}^{[i,k]}[\bar{\varphi}]$ so that the received interference symbols at time slot $2\varphi+1$ can be neutralized by using the side-information at BS 1 and BS2, respectively, i.e.,

$$\begin{aligned}&\sum_{k=1}^{K}\mathbf{H}_1^{[2,k]}[\bar{\varphi}]\mathbf{V}^{[2,k]}[\bar{\varphi}]\sum_{t=\varphi+1}^{2\varphi}\mathbf{H}_1^{[2,k]}[t]\mathbf{x}^{[2,k]}[t] \\ &\quad+\sum_{t=\varphi+1}^{2\varphi}\mathbf{L}_1[t](\mathbf{x}^{[2,1]},\cdots,\mathbf{x}^{[2,K]}) = \mathbf{0}\end{aligned} \tag{19}$$

$$\begin{aligned}&\sum_{k=1}^{K}\mathbf{H}_2^{[1,k]}[\bar{\varphi}]\mathbf{V}^{[1,k]}[\bar{\varphi}]\sum_{t=1}^{\varphi}\mathbf{H}_2^{[1,k]}[t]\mathbf{x}^{[1,k]}[t] \\ &\quad+\sum_{t=1}^{\varphi}\mathbf{L}_2[t](\mathbf{x}^{[1,1]},\cdots,\mathbf{x}^{[1,K]}) = \mathbf{0}\end{aligned} \tag{20}$$

In order to satisfy (19) and (20), the following conditions should be satisfied:

$$\mathbf{H}_1^{[2,k]}[\bar{\varphi}]\mathbf{V}^{[2,k]}[\bar{\varphi}]\mathbf{H}_1^{[2,k]}[t] + \mathbf{H}_1^{[2,k]}[t] = \mathbf{0}, k \in \mathcal{K}, t \in \mathcal{T}_2 \tag{21}$$

$$\mathbf{H}_2^{[1,k]}[\bar{\varphi}]\mathbf{V}^{[1,k]}[\bar{\varphi}]\mathbf{H}_2^{[1,k]}[t] + \mathbf{H}_2^{[1,k]}[t] = \mathbf{0}\ k \in \mathcal{K}, t \in \mathcal{T}_1 \tag{22}$$

Since $\mathbf{H}_l^{[i,k]}[t]$ is a $M \times N$ channel matrix and $M > N$, $\mathbf{H}_l^{[i,k]}[t]^{\dagger}$ exists, where $\mathbf{H}_l^{[i,k]}[t]^{\dagger} = \left(\mathbf{H}_l^{[i,k]}[t]^H \mathbf{H}_l^{[i,k]}[t]\right)^{-1}\mathbf{H}_l^{[i,k]}[t]^H$. We can design $\mathbf{V}^{[2,k]}[\bar{\varphi}] = -\mathbf{H}_1^{[2,k]}[\bar{\varphi}]^{\dagger}$ and $\mathbf{V}^{[1,k]}[\bar{\varphi}] = -\mathbf{H}_2^{[1,k]}[\bar{\varphi}]^{\dagger}$ so that (21) and (22) can be satisfied, As a result, BS 1 and BS 2 eliminate all interference symbols.

Next we show the decoding procedure for BS 1. Concatenating the received desired signals in $2\varphi+1$ time slots, the equivalent input-output relationship at BS 1 is shown in (23).

$$\underbrace{\begin{bmatrix}\mathbf{y}_1[1]\\ \mathbf{y}_1[2]\\ \vdots \\ \mathbf{y}_1[\varphi] \\ \mathbf{y}_1[\bar{\varphi}] + \sum_{t\in\mathcal{T}_2}\mathbf{y}_1[t]\end{bmatrix}}_{\bar{\mathbf{y}}_1} = \underbrace{\begin{pmatrix}\mathbf{A}[1] & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{A}[2] & \mathbf{0} & \vdots \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{A}[\varphi] \\ \mathbf{B}[1] & \mathbf{B}[2] & \cdots & \mathbf{B}[\varphi]\end{pmatrix}}_{\bar{\mathbf{H}}_1}\bar{\mathbf{x}}_1 \tag{23}$$

where $\bar{\boldsymbol{H}}_2^{[1,k]}[t] = \boldsymbol{H}_1^{[1,k]}[\bar{\varphi}]\boldsymbol{V}^{[1,k]}[\bar{\varphi}]\boldsymbol{H}_2^{[1,k]}[t]$, $\boldsymbol{A}[t] = \left[\boldsymbol{H}_1^{[1,1]}[t]\cdots\boldsymbol{H}_1^{[1,K]}[t]\right]$, $\boldsymbol{B}[t] = \left[\bar{\boldsymbol{H}}_2^{[1,1]}[t]\cdots\bar{\boldsymbol{H}}_2^{[1,K]}[t]\right]$, $\bar{\boldsymbol{x}}_1 = \left[\boldsymbol{x}^{[1,1]}[1]^T\cdots\boldsymbol{x}^{[1,K]}[\varphi]^T\right]^T$, $k \in \mathcal{K}, t \in \mathcal{T}_1$. $\bar{\mathbf{y}}_1$ is a $(\varphi+1)M \times 1$ vector, $\bar{\mathbf{H}}$ is a $(\varphi+1)M \times (\varphi+1)M$ matrix, $\bar{\boldsymbol{x}}$ is a $(\varphi+1)M \times 1$ vector. Since all channel values are generic, $rank(\bar{\mathbf{H}}) = (\varphi+1)M$. Therefore, BS 1 can decode $(\varphi+1)M$ desired symbols. Similarly, BS 2 can decode $(\varphi+1)M$ desired symbols in $2\varphi+1$ time slots by using the same method. Consequently, a total of $2(\varphi+1)M$ desired symbols have been transmitted in $2\varphi+1$ time slots in the network, implying that the sum-DoF of $M(1+1/2\varphi+1)$ is achieved. Since the sum-DoF decreases as the parameter φ increases and the condition $\varphi M + M \le KN\varphi$ should be satisfied, we select the minimum values of φ , i.e., $\varphi = \lceil M/(KN-M)\rceil$.

For the case of $N < M \le KN/2$, we can select φ =1 to satisfy the condition of $\varphi M + M \le KN\varphi$, i.e., each phase only contains one time slot. The sum-DoF of $4M/3$ can be directly obtained by using the same method with the case of $KN/2 < M < KN$. We thus complete the proof of Theorem 1.

IV. DoF Comparison and Simulation Results

A. DoF Comparison

We first compares the DoF result obtained when there is only delayed CSIT and the one obtained when there is hybrid CSIT. The case with only delayed CSIT uses the RIA scheme in [8] and the achievable sum-DoF is $M\left(1+1/(2\eta+1)\right)$ when $K \le M \le KN - N/2$, where $\eta = \lceil 2M/N\rceil$. According to the results in the *Theorem 1*, we can compute the sum-DoF gain from the hybrid CSIT over the delayed CSIT, which is

$$\text{DoF}_{gain} = \begin{cases} M\left(\dfrac{1}{3} - \dfrac{1}{2\eta+1}\right), & N < M \le KN/2 \\ M\left(\dfrac{1}{2\varphi+1} - \dfrac{1}{2\eta+1}\right), & KN/2 \le M \le KN - N/2 \end{cases} \tag{24}$$

where $\varphi = \lceil M/(KN-M)\rceil$. Since η is larger than or equal to 2 in the case of $N < M \le KN/2$ and φ is less than η in the case of $KN/2 \le M < KN - N/2$, the RIN scheme can utilize fewer time slots to attain a higher DoF than the RIA scheme under the feasible condition of RIA scheme.

B. Numerical simulation

We provide numerical results to evaluate the sum rate performance of the proposed RIN scheme. We demonstrate that the RIN scheme can exactly obtain the achievable DoF derived in Theorem 1. The channel is modeled as i.i.d. (independent identically distributed) complex Gaussian distribution with zero mean and unit variance. The numerical results are averaged over 10000 independent Monte Carlo runs.

We first explain how to compute the sum rate of the two-cell MIMO IMAC by applying the proposed RIN scheme. We calculate R_1 as a representative. According to (23), the received signal at BS 1 can be described as

$$\bar{\mathbf{y}}_1 = \bar{\mathbf{H}}\bar{\mathbf{x}} + \bar{\mathbf{n}}_1 \tag{25}$$

where $\bar{\mathbf{n}}_1 = \left[\mathbf{n}_1[1]\,\mathbf{n}_1[2]\cdots\mathbf{n}_1[\varphi]\right]^T$. According to [11-12], we can calculate the sum rate R_1 by (26)

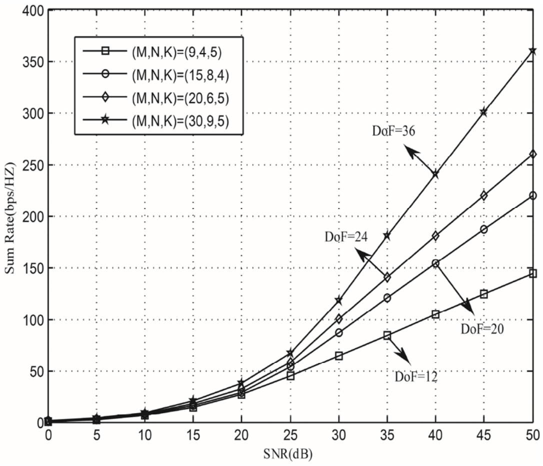

Fig.2 The sum rate and DoF of the proposed RIN scheme.

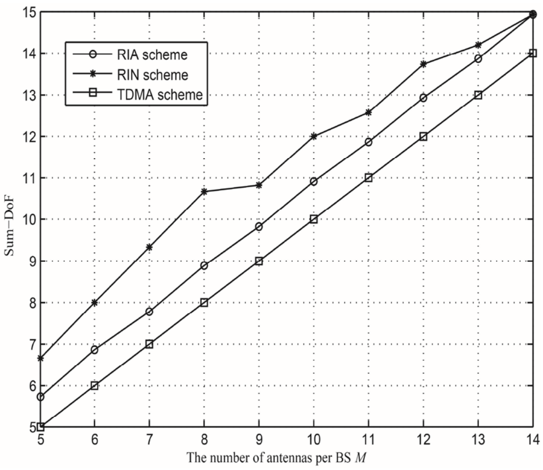

Fig.3 Comparison of sum-DoF among the proposed RIN scheme, the SNC scheme and the TDMA scheme

$$R_1 = \log_2\left[\det\left(\mathbf{I}+\overline{\mathbf{H}}\mathbb{E}\left(\overline{\mathbf{x}}\left(\overline{\mathbf{x}}\right)^H\right)\left(\overline{\mathbf{H}}\right)^H\mathbb{E}\left(\overline{\mathbf{n}}_1\left(\overline{\mathbf{n}}_1\right)^H\right)^{-1}\right)\right] \quad (26)$$

Fig.2 illustrates the sum rate and DoF results of the proposed RIN scheme with different system configurations. For the case of $N < M \le KN/2$, the curves of (9,4,5) and (15,8,4) are plotted. For the case of $KN/2 < M < KN$, the curves of (20,6,5) and (30,9,5) are plotted. The slopes of the sum rate curves at high SNR are equal to DoF/lg2 according to the Shannon capacity formula. Checking the case of $N < M \le KN/2$, we can observe that (9,4,5) and (15,8,4) obtain 12 and 20 DoF, respectively. The DoF results match with the theoretical DoF of $4M/3$ well at the high SNR regime. Similarly, For the curves of (20,6,5) and (30,9,5), the DoF results match with the theoretical DoF of $M\left(1+1/(2\varphi+1)\right)$ ($\varphi = \lceil M/(KN-M)\rceil = 2$), which verifies the theoretic results shown in Theorem 1.

To show the superiority of the proposed RIN scheme, we plot the achievable DoF achieved by different schemes in Fig.3. The system configuration (M, N, K) is chosen based on Theorem 1, where $M \in [5,14]$, N=4 and K=4. We can observe that the RIN scheme attains a higher DoF than the RIA scheme and the TDMA scheme. The DoF gain comes from the fact that exploiting hybrid CSIT can transmit more interference-free symbols. Additionally, the RIN scheme can utilize the signal space at each BS more efficiently than the RIA scheme do so that the RIN scheme can eliminate more interference symbols than the RIA scheme. For the different number of N and the same number of M, we can obtain the same result. It is worth note that the DoF gain will be reduced in the presence of channel estimation errors [13]. However, the sum DoF of the RIN scheme is still higher than the TDMA scheme when channel estimation errors exist.

V. CONCLUSION

We proposed a RIN method to obtain the new achievable DoF of the two-cell MIMO IMAC with delayed and limited amount of instantaneous CSIT (hybrid CSIT). Through theoretical analysis and numerical simulations, we showed that the proposed RIN method can obtain the theoretical DoF results. Furthermore, it was shown that the proposed RIN method can provide significant performance gain over the conventional TDMA scheme and the RIA scheme in terms of DoF, which highlights the benefits brought by the hybrid CSIT for uplink cellular networks.

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