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Partial Interference Alignment Scheme for Three-Tier Downlink Heterogeneous Networks

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ABSTRACT The introduction of the relay in heterogeneous networks (HetNets) can enhance cell-edge signals, but it will also bring coexistence of multiple interference which is composed of co-tier, cross-tier and cross time slot (caused by the half-duplex mode of the relay) interference, resulting in the ineffectiveness of the existing interference alignment (IA) schemes. To solve the above problem, the partial IA scheme, which achieves IA in the case of limited antennas by rationally designing the order and method of eliminating interference, is proposed in this paper. First, we align the interference from other base stations (BSs) into the interference space generated by pico BS to reduce the interference dimension of the relay, and then solve the interference between BSs and users by null space and concatenated precoding schemes. Furthermore, the feasibility condition of antenna configuration is analyzed. The simulation results show that the proposed scheme is superior to the traditional IA scheme in sum rate, and the performance of the proposed scheme is further improved as the relay transmission power increases.

INDEX TERMS Cross time slot interference, heterogeneous networks, interference alignment, partial connectivity.

I. INTRODUCTION

With the development of 5G mobile communication, the number of wireless terminals would increase dramatically, proposing higher requirements on the transmission rate and utilization of spectrum resources [1], [2]. Heterogeneous networks (HetNets) is based on the traditional cellular network, deploying more pico base stations (PBSs) inside the macro base station (MBS) to improve the coverage of the cell, which is one of the key network technologies to achieve 5G coverage and capacity improvement. All base stations in HetNets use the same frequency spectrum, which would cause serious interference. The interference in HetNets can be divided into cross-tier interference and co-tier interference [3], in which the interference between base stations and users of the same tier is called co-tier interference and the interference between base stations and users of different tier is named as cross-tier interference respectively.

Interference alignment (IA) is considered to be an effective interference management method, which divides the received signal space into the desired subspace and the interference subspace. By designing the precoding and decoding matrix, IA can align the interference signal from the undesired transmitter to the interference signal subspace at the receiver, so as to receive the desired signal without interference in the desired signal subspace [1], [4], [5]. Therefore, IA can achieve high multiplexing gain and degrees of freedom (DoF) the channel. Reference [6] proposes an efficient interference-aware frequency resource-sharing scheme in the D2D communications which aims to maximize system throughput by IA. And IA method and apparatus for an interference-aware resource-sharing scheme for multiple

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D2D group communications are provided in [7]. According to the requirements of channel state information (CSI), interference alignment algorithms can be divided into IA algorithms based on perfect CSI, IA algorithms based on imperfect CSI [8]–[11] and blind interference alignment which does not require CSI [12]–[14].

In-depth research has been conducted to solve interference problems in HetNets through IA. References [15]–[17] propose a Min-WLI algorithm which targets the least residual interference in the system and a Max-SINR algorithm which targets the maximum signal-to-interference and noise ratio of the received signal. In these algorithms, the precoding matrix and the interference suppression matrix are calculated through repeated iterations of both sides of the transceiver, which would result in high calculation complexity. The authors of [18] group PBSs and design the selective IA scheme to solve the co-tier interference between the same group of PBSs, but the co-tier interference between different groups is not solved. Considering the partial connectivity and heterogeneity of HetNets, a two-stage IA scheme is proposed to solve cross-tier interference and co-tier interference in a single-cell HetNet by rationally allocating antenna resources of base stations and users [19]. In order to eliminate the cross-tier interference between two macro cells, [20] proposes a cross-tier IA schemes with interfering pair selection for the uplink HetNet of multi-macro cells, which eliminates the interference between macro users at the edge of the cell and the surrounding PBSs. Considering the power imbalance between MBS and PBS, [21] optimizes the overall network performance by ignoring some cross-tier interference in the case of medium signal-to-noise ratio (SNR). Reference [22] proposes a QoS priority-based coordinated scheduling and hybrid spectrum access scheme in two-tier HetNet to alleviate cross-tier interference. Reference [23] proposes the public safety users priority-based mobile personal cells user association scheme to reduce co-channel interference. For the two-tier HetNets which are oriented to the Internet of Things, [24] proposes two self-organizing cognitive IA solutions, which mainly eliminate the cross-tier interference caused by cognitive spectrum sharing and ensure the optimal capacity of small cells. Reference [25] deploys a D2D local area network in the service area of the MBS to form a HetNet, and proposes two D2D communication schemes based on IA to manage the co-tier and cross-tier interference.

The above IA schemes all focus on eliminating co-tier interference and cross-tier interference in HetNets. Due to path loss, macro users at the edge of HetNets would have low rates or even be unable to communicate normally. The relay can solve this issue by amplifying and forwarding the signals which are from the MBS. Some researchers concentrate on increasing the rates of edge users in networks by introducing relays to assist BSs. Reference [26] proposes a cross-slot interference alignment scheme to solve inter-cell interference and intra-cell interference due to relay in a two-cell network. Reference [27] proposes an interference alignment scheme for the multiple-input-multiple-output (MIMO) uplink cellular network with the help of a relay, and analyzes the DoF performance of the proposed IA scheme. The introduction of relay in HetNets can enhance cell-edge signals, but it can also bring coexistence of multiple interference which is composed of co-tier, cross-tier and cross time slot (caused by the half-duplex mode of the relay) interference, resulting in more complicated types and amounts of interference in the network, and existing IA schemes cannot eliminate all interference. Hence, it is necessary to propose a new IA scheme to manage the co-tier, cross-tier and cross time slot interference in the relay HetNets.

In this paper, we focus on the three-tier downlink partially connected relay HetNet, which is composed of one MBS, two PBSs and an amplify-and-forward (AF) relay with half-duplex mode, and propose the partial IA scheme. Different from the "three-tier HetNet" in [28] which consists of macro, pico and femto tiers, the term "three-tier HetNet" in this paper refers to MBS, PBSs and relay. Since the proposed scheme can handle the co-tier, cross-tier and cross time slot interference at the same time, we simply refer to it as the CCSIA scheme. The main contributions of this paper are as follows:

1) Construct a HetNet model in which MBS, PBS and relay coexist, and analyze the interference in the network.
2) Propose the partial IA scheme, which achieves IA in the case of fewer antennas by rationally designing the order and method of eliminating interference. First, we align the interference from other BSs into the interference space generated by PBS to reduce the interference dimension of the relay, and then solve the interference between BSs and users by null space and concatenated precoding scheme. Furthermore, path loss is also taken into account.
3) Analyze the feasibility condition of the proposed scheme and deduce the number of antennas needed to achieve IA.
4) Prove the effectiveness of the proposed scheme through a lot of simulations on different system parameters. The simulation results show that the proposed scheme is superior to the traditional IA scheme in sum rate, and as the relay transmission power increases, the performance of the proposed scheme is further improved.

The structure of this paper is as follows. The section II introduces the system and channel model and analyzes the received signals at different nodes. The section III elaborates the scheme proposed in this paper and proves the feasibility of the scheme. The section IV gives the experimental results of the proposed scheme and compares the experimental results with the traditional IA schemes. The section V summarizes this paper.

Notations: Lowercase and uppercase in bold such as $\mathbf{a}$ and $\mathbf{A}$ denote vectors and matrices. $\mathbf{A}^H$, rank($\mathbf{A}$), span($\mathbf{A}$) and null($\mathbf{A}$) represent the conjugate transpose, rank, the space spanned by the column vectors and null space of the matrix $\mathbf{A}$.

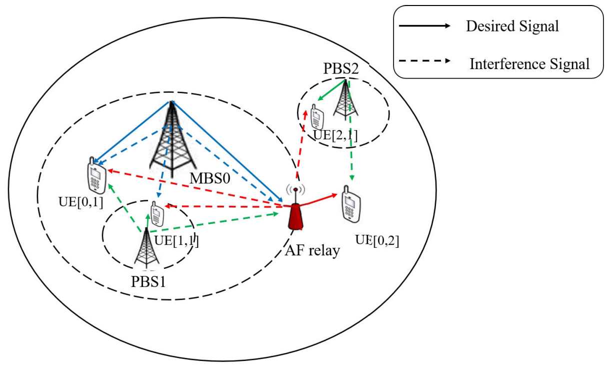

FIGURE 1. System model of the three-tier downlink MIMO HetNet.

II. SYSTEM MODEL

The system model we consider is the three-tier downlink MIMO HetNet, which is composed of one MBS, two PBSs and one AF relay with half-duplex mode. The specific model is shown in Fig. 1, where the solid line represents the desired signal, the dashed line represents the interference signal, and the blue, green and red lines represent the transmitted signals of MBS, PBS and relay, respectively. The MBS serves two users, that is, the central macro user (CMU) directly served by MBS and the edge macro user (EMU) served through a two-hop link constructed by the AF relay. According to [26], there is no direct link between the EMU and the MBS and the considered HetNet can be modeled as a partially connected system. The PBS1 is located within the service range of the MBS, and is simultaneously interfered by MBS and relay, while the PBS2 is within the service range of the AF relay and can merely be interfered by the relay. The distance relationships between the users and the BSs are shown in Table. 2. Due to the existence of path loss and the low transmission power of the PBSs, we consider that PBSs are partially connected without mutual interference, and at the same time, the interference signal from PBS1 to EMU could be ignored, as well as the interference signal from PBS2 to CMU. We denote the BSs by j = 0, 1, 2, R, where j = 0 represents the MBS0 equipped with M_b antennas, j = 1 and j = 2 respectively represent PBS1 and PBS2 equipped with M_s antennas, and j = R represents the AF relay equipped with M_r antennas. UE[j,i] represents the i-th user served by the j-th BS. Only MBS serves two users (UE[0,1] represents the CMU, UE[0,2] represents the EMU), and the rest of BSs just serve one user (PBS1 serves UE[1,1], PBS2 serves UE[2,1]). In this case, each user is equipped with N antennas so as to receive N_s desired data streams.

There are three types of interference in the system, i.e., the cross-tier interference (form MBS to UE[1,1]), the co-tier interference (the UE[0,2]'s desired signal to UE[0,1]) and the cross time slot interference (form relay to UE[2,1]). Due to the half-duplex mode, the relay cannot receive and forward the signal at the same time, thus the entire transmission process is divided into two time slots. The communication process of UE[0,2] is as follows. In the time slot 1, the MBS0 sends the combined signals which consist of the desired signal for UE[0,1] and UE[0,2] to the relay, and in the second time slot, the relay amplifies and forwards the received signals to the UE[0,2]. Note that EMU only receives signals in the second time slot, the remaining users receive signals in double time slots. In particular, we assume that the Gaussian channel model is static during a whole transmission period. The AF relay only forwards the received signals through a processing matrix without decoding them. We assume that all BSs and users have the global CSI.

The analysis of the received signals of users in the two time slots is as follows. In time slot 1, MBS0 transmits N_s data streams to the users it serves, namely UE[0,1] and UE[0,2], and the combined signals transmitted to UE[0,2] are received at the relay R. At the same time, PBS1 and PBS2 transmit N_s data streams to their intended users UE[1,1] and UE[2,1], respectively. Therefore, the received signals of different nodes at this moment are as follows:

$$\mathbf{y}_{t1}^{[0,1]} = \sqrt{g_0^{[0,1]}}\mathbf{H}_0^{[0,1]}(\mathbf{V}^{[0,1]}\mathbf{s}_{t1}^{[0,1]} + \mathbf{V}^{[0,2]}\mathbf{s}_{t1}^{[0,2]}) + \sqrt{g_1^{[0,1]}}\mathbf{H}_1^{[0,1]}\mathbf{V}^{[1,1]}s_{t1}^{[1,1]} + \mathbf{n}_{t1}^{[0,1]}, \tag{1}$$

$$\mathbf{y}_{t1}^{[1,1]} = \sqrt{g_1^{[1,1]}}\mathbf{H}_1^{[1,1]}\mathbf{V}^{[1,1]}\mathbf{s}_{t1}^{[1,1]} + \sqrt{g_0^{[1,1]}}\mathbf{H}_0^{[1,1]}(\mathbf{V}^{[0,1]}\mathbf{s}_{t1}^{[0,1]} + \mathbf{V}^{[0,2]}\mathbf{s}_{t1}^{[0,2]}) + \mathbf{n}_{t1}^{[1,1]}, \tag{2}$$

$$\mathbf{y}_{t1}^{[2,1]} = \sqrt{g_2^{[2,1]}}\mathbf{H}_2^{[2,1]}\mathbf{V}^{[2,1]}\mathbf{s}_{t1}^{[2,1]} + \mathbf{n}_{t1}^{[2,1]}, \tag{3}$$

$$\mathbf{y}_{t1}^{R} = \sqrt{g_0^{R}}\mathbf{H}_0^{R}(\mathbf{V}^{[0,1]}\mathbf{s}_{t1}^{[0,1]} + \mathbf{V}^{[0,2]}\mathbf{s}_{t1}^{[0,2]}) + \sqrt{g_1^{R}}\mathbf{H}_1^{R}\mathbf{V}^{[1,1]}\mathbf{s}_{t1}^{[1,1]} + \sqrt{g_2^{R}}\mathbf{H}_2^{R}\mathbf{V}^{[2,1]}\mathbf{s}_{t1}^{[2,1]} + \mathbf{n}_{t1}^{R}, \tag{4}$$

where $\mathbf{H}_j^{[l,i]} \in \mathbb{C}^{N\times M_j}, i, j, l \in \{0, 1, 2\}$ and $\mathbf{H}_j^{R} \in \mathbb{C}^{M_R\times M_j}, i, j, l \in \{0, 1, 2\}$ respectively represent the channel matrix from BS j to UE[l, i] and the channel matrix from BS j to relay R, and the number of antennas of BS j is represented by M_j. The elements of $\mathbf{H}_j^{[l,i]}$ are drawn from independent identically distributed complex Gaussian random variables with zero mean and unit variance. Similarly, $\sqrt{g_j^{[l,i]}}$ and $\sqrt{g_j^{R}}$ represent the long-term path gain from BS j to UE[l, i] and the long-term path gain from BS j to relay R, respectively. The specific values of path loss are shown in Table 1. $\mathbf{V}^{[l,i]} \in \mathbb{C}^{M\times N_S}, l, i \in \{0, 1, 2\}$, $\mathbf{V}^{[l,i]H}\mathbf{V}^{[l,i]} = \mathbf{I}_{N_s}$ is the precoding matrix of UE[l,i]. Similarly, $\mathbf{U}^{[l,i]} \in \mathbb{C}^{N\times N_S}, l, i \in \{0, 1, 2\}$, $\mathbf{U}^{[l,i]H}\mathbf{U}^{[l,i]} = \mathbf{I}_{N_s}$ is the receiving beamforming matrix of UE[l, i] to eliminate interference from undesired receivers. The specific design details of $\mathbf{V}^{[l,i]}$ and $\mathbf{U}^{[l,i]}$ will be presented in the next section. $\mathbf{s}_{t1}^{[l,i]} \in \mathbb{C}^{N_S\times 1}$ and $\mathbf{n}_{t1}^{[l,i]} \in \mathbb{C}^{N_S\times 1}$ respectively represent the desired signal of UE[l,i] and additive Gaussian white noise with variance σ^2 in time slot 1. Taking (2) as an example, the first term on the right side of the equation represents the desired signal of UE[1,1], the second term represents the interference signals from MBS0, and the last term is the noise in the course of transmission.

TABLE 1. Parameter settings.

Parameter	Assumption
Radius of cell	500 m
Radius of center area	300 m
Carrier frequency / Bandwidth	2 GHz/10 MHz
Maximum transmit power of MBS	46 dBm
Maximum transmit power of PBS	15 dBm
Maximum transmit power of relay	25 dBm
The number of antennas at BS0,1,2,R	4,2,2,2
The number of antennas at users	2
Degrees of freedom of each link	1
Antenna pattern	0 dB (omni-directional)
Channel model	3GPP SCM
Noise power spectral density	-174 dBm/Hz
Noise figure	9 dB
Path loss from MBS to users	128.1 + 37.6log10R [dB], R in km
Path loss from relay and PBS to users	140.7 + 36.7log10R [dB], R in km

In time slot 2, the relay amplifies and forwards the combined signal received in time slot 1 to UE[0,2] and other users would receive the interference signals from the relay at the same time. Taking UE[0,2] as an example, the received signals in this time slot are as follows:

$$\mathbf{y}_{t2}^{[0,2]} = \sqrt{g_R^{[0,2]}}\mathbf{H}_R^{[0,2]}\mathbf{G}\rho_R\mathbf{y}_{t1}^R + \sqrt{g_2^{[0,2]}}\mathbf{H}_2^{[0,2]}\mathbf{V}^{[2,1]}\mathbf{s}_{t2}^{[2,1]} + \mathbf{n}_{t2}^{[0,2]}, \quad (5)$$

$\mathbf{G} \in \mathbb{C}^{N\times M_R}$ and $\mathbf{y}_{t1}^R$ are the relay processing matrix and the received signals at relay R in time slot 1 respectively. $\rho^2{}_R = \frac{P_R}{g_0^R tr(\mathbf{A})\frac{P_0}{N_S}+N_S\sigma^2}$, $\mathbf{A} = \widetilde{\mathbf{H}}_0^R\mathbf{V}^{[0,1]}\mathbf{V}^{[0,1]H}\widetilde{\mathbf{H}}_0^{RH} + \widetilde{\mathbf{H}}_0^R\mathbf{V}^{[0,2]}\mathbf{V}^{[0,2]H}\widetilde{\mathbf{H}}_0^{RH}$ is the amplification factor of the relay, which can reverse the influence of the first hop fading and limit the output power of the relay when the first hop fading amplitude is low. In particular, P_R and P_0 are the transmission power of the relay and MBS0, respectively.

Since the relay works in half-duplex mode, in time slot 2, the relay only transmits signals to UE[0,2] and cannot receive signals from other BSs, so the MBS0 only sends the desired signal to UE[0,1] in this time slot. Therefore, the received signal of UE[0,1] is

$$\mathbf{y}_{t2}^{[0,1]} = \sqrt{g_0^{[0,1]}}\mathbf{H}_0^{[0,1]}\mathbf{V}^{[0,1]}\mathbf{s}_{t2}^{[0,1]} + \sqrt{g_1^{[0,1]}}\mathbf{H}_1^{[1,1]}\mathbf{V}^{[1,1]}\mathbf{s}_{t2}^{[1,1]} + \sqrt{g_R^{[0,1]}}\mathbf{H}_R^{[0,1]}\mathbf{G}^R\rho_R\mathbf{y}_{t1}^R + \mathbf{n}_{t2}^{[0,1]}. \quad (6)$$

III. THE PARTIAL INTERFERENCE ALIGNMENT SCHEME FOR THREE-TIER HetNet

In this paper, we consider that only the MBS is equipped with 4 antennas, the rest BSs and users are equipped with 2 antennas, which can be proved in section III-C. In order to make full use of the limited antennas, we need to rationally design the order and method of canceling interference.

According to (4), the relay would receive multiple interference signals from three BSs in time slot 1. Due to the half-duplex mode of relay, in time slot 2, the relay will cause more interference to each user when forwarding the signals. Therefore, a reasonable solution to the interference issue at the relay is the key to achieve IA in the three-tier HetNet model.

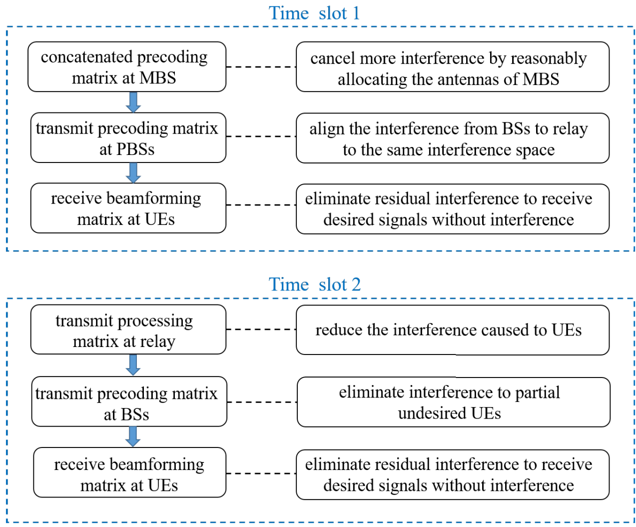

FIGURE 2. The flow diagram of the CCSIA scheme.

In our partial interference alignment (CCSIA) scheme, the interference from the BSs to the relay is first processed. We align the interference from MBS0 and PBS2 to relay into the interference space generated by PBS1 to relay, thereby reducing the interference dimension received by the relay. Then we cancel these interference signals by designing the processing matrices of the relay. Finally, we reasonably utilize the null space and concatenated precoding schemes to solve the interference problem between the BSs and users. The flow diagram of the CCSIA scheme is shown in Fig. 2.

A. INTERFERENCE ALIGNMENT SCHEME FOR TIME SLOT 1

1) TRANSMIT PRECODING MATRIX AT EACH BS

Considering that the number of antennas at MBS0 is larger than that of PBSs and relay, the concatenated precoding is adopted to cancel more interference by reasonably allocating the antennas of MBS0. Therefore, the concatenated precoding matrix at the MBS0 is $\mathbf{V}^0 = \mathbf{W}(\mathbf{V}^{[0,1]} + \mathbf{V}^{[0,2]})$, where $\mathbf{V}^{[0,1]}$ and $\mathbf{V}^{[0,2]}$ are the precoding matrix of UE[0,1] and UE[0,2], respectively, and $\mathbf{W}$ is used to cancel the interference from the MBS to the user served by PBS1. $\mathbf{W}$ is given as follows:

$$\mathbf{W} = null(\mathbf{H}_0^{[1,1]}). \quad (7)$$

As a consequence, the MBS0 transmits in the null space of the channel matrix from the MBS0 to the UE[1,1].

Meanwhile, the equivalent channel matrix from the MBS0 to other nodes is

$$\widetilde{\mathbf{H}}_0 = \mathbf{H}_0\mathbf{W}. \quad (8)$$

In order to avoid interfering the UE[0,1], the PBS1 should align the transmitted signal in the interference subspace of the UE[0,1], i.e., PBS1 can send the signal in the null space of the received signal space of UE[0,1] to achieve the target.

$$\mathbf{V}^{[1,1]} = null(\mathbf{U}^{[0,1]H}\mathbf{H}_1^{[0,1]}). \tag{9}$$

Afterwards, we design the second tier precoding matrix of the MBS and the precoding matrix of the remaining BSs. We calculate the precoding matrix to align the interference from MBS0 and PBS2 to the interference space generated by PBS1 at the relay. In this process, we can align multiple interference signals into one interference space, reducing the interference dimension suffered by the relay.

$$span(\mathbf{H}_0^R\mathbf{W}\widetilde{\mathbf{V}}^{[0,1]}) = span(\mathbf{H}_1^R\mathbf{V}^{[1,1]}). \tag{10}$$
$$span(\mathbf{H}_2^R\mathbf{V}^{[2,1]}) = span(\mathbf{H}_1^R\mathbf{V}^{[1,1]}). \tag{11}$$

Therefore, the precoding matrix of UE[0,1] and UE[2,1] can be obtained as

$$\text{span}(\mathbf{V}^{[0,1]}) = span(\mathbf{W}^{-1}(\mathbf{H}_0^R)^{-1}\mathbf{H}_1^R\mathbf{V}^{[1,1]}). \tag{12}$$
$$span(\mathbf{V}^{[2,1]}) = span((\mathbf{H}_2^R)^{-1}\mathbf{H}_1^R\mathbf{V}^{[1,1]}). \tag{13}$$

Similarly, the desired signal of UE[0,2] should be received in the null space of the interference space at the relay, i.e.,

$$\mathbf{V}^{[0,2]} = null(\mathbf{H}_1^R\mathbf{V}^{[1,1]}). \tag{14}$$

Thus, the concatenated precoding matrix for the MBS can be achieved as

$$\mathbf{V}_0 = \mathbf{W}(\mathbf{V}^{[0,1]} + \mathbf{V}^{[0,2]}). \tag{15}$$

2) RECEIVE BEAMFORMING MATRIX AT EACH USER

For UE[0,1], the interference from PBS1 has been canceled by the precoding matrix of PBS1, and it is only interfered by the undesired signal which is transmitted to UE[0,2] in the combined signal from the BS0. Therefore, the decoding matrix of UE[0,1] is as follows:

$$\mathbf{U}^{[0,1]} = null([\mathbf{H}_1^{[1,1]}\mathbf{W}\mathbf{V}^{[0,2]}]^H). \tag{16}$$

Similarly, the interference from MBS0 at UE[1,1] has been eliminated in the first tier precoding of MBS0. Therefore, UE[1,1] and UE[2,1] do not receive other interference. We perform singular value decomposition (SVD) on channel matrix to obtain the decoding matrix. Taking UE[1,1] as an example, the equivalent channel matrix from BS1 to UE[1,1] is $\widetilde{\mathbf{H}}_0^{[1,1]} = \mathbf{H}_0^{[1,1]}\mathbf{V}^{[1,1]}$, and the SVD is performed on $\widetilde{\mathbf{H}}_0^{[1,1]}$

$$\widetilde{\mathbf{H}}_0^{[1,1]} = \tilde{\mathbf{U}}^{[1,1]}\Lambda^{[1,1]}\tilde{\mathbf{V}}^{[1,1]H}. \tag{17}$$

Therefore, the precoding and decoding matrix of UE[1,1] are $\mathbf{V}^{[1,1]} = \mathbf{V}^{[1,1]}\tilde{\mathbf{V}}^{[1,1]}$ and $\mathbf{U}^{[1,1]} = \tilde{\mathbf{U}}^{[1,1]}$, respectively.

B. INTERFERENCE ALIGNMENT SCHEME FOR TIME SLOT 2

1) TRANSMIT PRECODING MATRIX AT EACH BS

After the processing of the time slot 1, the interference from MBS0 and PBS2 to the relay has been aligned to the interference space generated by PBS1 at the relay. Therefore, the processing matrix at the relay is designed to send signals in the null space of the interference, that is, only the desired signal of UE[0,2] remains at the relay

$$\mathbf{G} = null([\mathbf{H}_1^R\mathbf{V}^{[1,1]}]^H). \tag{18}$$

Due to the half-duplex mode, the relay cannot receive signals while sending signals to UE[0,2], all BSs do not need to consider eliminating interference to the relay. In particular, the interference at users caused by the forwarding signals of relay is canceled by the user's decoding matrix. Therefore, the precoding matrices of MBS0 and BS2 remain consistent in the two time slots, which are respectively expressed as (15) and (14).

As mentioned above, the PBS1 will not interfere with the relay and the precoding matrix of PBS1 is designed to transmit signals in the nullspace of the receiving space of UE[0,1], thereby eliminating cross-tier interference

$$\mathbf{V}^{[1,1]} = null(\mathbf{U}^{[0,1]H}\mathbf{H}_1^{[0,1]}). \tag{19}$$

2) RECEIVE BEAMFORMING MATRIX AT EACH USER

Since the number of interference at the relay is effectively controlled, after section III-B1, all users except UE[0,2] are only interfered by the relay. The interference from relay can be completely eliminated by the receive beamforming matrices at these users. This goal is fullfilled by enabling the users to receive in the null space of the transmission signals space from the relay to these users

$$\mathbf{U}^{[0,1]} = null([\mathbf{H}_R^{[0,1]}\mathbf{G}]^H). \tag{20}$$
$$\mathbf{U}^{[1,1]} = null([\mathbf{H}_R^{[1,1]}\mathbf{G}]^H). \tag{21}$$
$$\mathbf{U}^{[2,1]} = null([\mathbf{H}_R^{[2,1]}\mathbf{G}]^H). \tag{22}$$

The received signals of UE[0,2] contain the desired signal from the relay and the interference signal from PBS2, so we calculate the decoding matrix of UE[0,2] to receive the desired signal in the nullspace of the transmission signals space from the PBS2 to UE[0,2].

$$\mathbf{U}^{[0,2]} = null([\mathbf{H}_2^{[0,2]}\mathbf{V}^{[2,1]}]^H). \tag{23}$$

C. IA FEASIBILITY CONDITIONS

Proposition: In order to achieve IA, the number of antennas of each node in the model is as follows:

$$M_b \geq 4N_s$$
$$M_r, M_s, \geq 2N_s \tag{24}$$

Proof: First prove that the case of equal sign satisfies IA, that is, when $N_s = 1$ then $M_b = 4, M_r, M_s, N = 2$.

First, we determine the dimensions of the channel matrices based on the number of antennas of the BSs and the users, i.e., $\mathbf{H}_0^{[l,i]} \in \mathbb{C}^{2\times 4}$, $\mathbf{H}_1^{[l,i]}, \mathbf{H}_2^{[l,i]}, \mathbf{H}_R^{[l,i]} \in \mathbb{C}^{2\times 2}$. According to (7), the dimension of $\mathbf{H}_0^{[1,1]}$ is (2×4), the null space will be of dimension $(4 - 2)$. Hence, the linear precoding matrix $\mathbf{W} \in \mathbb{C}^{4\times 2}$ will always exist and the columns of this matrix will be the columns of the null space. Then in (8), the equivalent channel matrix of MBS0 becomes $\widetilde{\mathbf{H}}_0 \in \mathbb{C}^{2\times 2}$. Since $N_s = 1$, it is assumed that the dimension of each user's precoding matrix is $\mathbf{V}^{[l,i]} \in \mathbb{C}^{2\times 1}$. From (14), the dimension of the interference space is (1×2), so the dimension of the null space is $(2 \times (2-1))$, that is, a decoding matrix $\mathbf{U}^{[0,1]} \in \mathbb{C}^{2\times 1}$ is existed. Similarly, the precoding matrix $\mathbf{V}^{[1,1]}$, $\mathbf{V}^{[0,1]} \in \mathbb{C}^{2\times 1}$ in (11) and (13) can be obtained, satisfying our assumption. Therefore, the scheme in time slot 1 is feasible.

In time slot 2, the relay processing matrix is first analyzed. According to (15), due to $\mathbf{H}_1^R\mathbf{V}^{[1,1]} \in \mathbb{C}^{2\times 1}$, the dimension of the null space can be found to be $(2\times(2-1))$, so the number of antennas of the relay satisfies the condition, and a processing matrix $\mathbf{G} \in \mathbb{C}^{2\times 1}$ can be generated. Then, we verify that the decoding matrices exist, taking (17) as an example. Due to $\mathbf{G} \in \mathbb{C}^{2\times 1}$, $\mathbf{H}_R^{[0,1]} \in \mathbb{C}^{2\times 2}$, the dimension of the null space is $(2 \times (2-1))$, then when the number of antennas of the user is 2, the decoding matrix $\mathbf{U}^{[0,1]} \in \mathbb{C}^{2\times 1}$ must exist, which can cancel the interference from the relay. Similarly, it can be proved that when the number of antennas is 2, all users can eliminate interference and receive the desired signal by designing the receiving beamforming matrix.

Then, when the number of antennas increases, IA can be achieved, and there will be redundant antennas in the system.

Finally when the number of antennas decreases ($N_s = 1, M_r, M_s, N = 1, M_b = 3$), the scheme cannot be implemented.

Since the number of desired data streams of each user is 1, when the BSs and the users only have 1 antenna, the node can only receive or transmit the desired signal, so it cannot perform IA. Based on the above discussion, there will be a lot of interference in the system that cannot be eliminated. In this case, IA cannot be achieved.

In summary, the proposition has been proved.

IV. PERFORMANCE EVALUATION

In this section, we first compare the change of the achievable sum rate under different schemes with the SNR, where SNR is defined as the ratio of signal power to noise power. Then we analyze the number of antennas required by different schemes to implement IA. Afterwards, the influence of the relay transmission power on the achievable sum rate under different schemes is investigated. Moreover, we analyze the effect of the distance between the EMU and the MBS on the rate of EMU when SNR=25dB, and analyze the improvement of the proposed scheme at different distances.

In this paper, the comparison schemes are the Min-WLI scheme [15] and the Two stage IA scheme [19]. We assume that both conventional schemes meet the feasibility conditions. All rates calculated in this paper are the average rate of a single time slot. Due to the half-duplex mode of the relay, the EMU only receives signals in time slot 2, so the rate of the CCSIA scheme proposed in this paper is obtained by calculating the sum rate of two slots and dividing by 2. The MIN-WLI scheme is suitable for the scenario of fully connected K users, and the system model of this paper considers partially connected between PBSs. Therefore, the MIN-WLI scheme only calculates the rates of the users of MBS and PBS1, and PBS2 keeps silence and do not transmit data [14].

TABLE 2. Distance relationship.

	UE[0,1]	UE[0,2]	UE[1,1]	UE[2,1]	Relay R
MBS0	150m	400m	250m	—	300m
PBS1	100m	—	70m	—	100m
PBS2	—	100m	—	70m	100m
Relay R	300m	100m	100m	100m	—

The remaining two schemes calculate the rate of all users. In this paper, the conventional schemes calculate the achievable rate under two scenarios (scene A and scene B), and the proposed scheme only calculates the achievable rate of scene A. Scene A refers to the three-tier HetNet supposed in the system model. For the conventional schemes, they cannot solve the interference brought by the relay (the interference from relay to UE[0,1], UE[0,2], UE[1,1] and UE[2,1]), so they regard these interference as noise in the calculation of the sum rate. Scene B refers to the traditional two-tier HetNet where MBS and PBSs coexist, i.e., the system model in scene B is the same as scene A except there is no relay. In this scenario, the UE[2,1] is directly served by the MBS and other users keep the same with Scene A. Therefore, both conventional schemes can eliminate all interference through IA in Scene B. Note that the existence of scene B is to calculate the achievable rate of each user after eliminating all interference in the two-tier HetNet, so that it can be used to test whether the proposed scheme can eliminate all interference.

In the simulation process, all the experimental results are averaged over 1000 calculations under different channel conditions. In particular, we assume that the amplification factor is variable to maintain the maximum transmission power of the relay. The simulation configurations are described in detail in Section IV-A, and the simulation results and analysis are described in Section IV-B.

A. SIMULATION CONFIGURATIONS

Table. 1 is the parameter settings of the BS's transmission power, path loss coefficient and so on.

Table. 2 is the distance between the BSs and the users.

The unset values in Table. 2 indicate that there is no direct link between the corresponding BS and user. Similarly, in our system model, there is no direct link between the MBS0 and UE[0,2]. However, there is no relay in the scene B and UE[0,2] is served by MBS0 directly. So, we set a value for the link between MBS0 and UE[0,2] in Table. 2, which is used in the comparison schemes in scene B.

B. SIMULATION RESULTS

Fig. 3(a) and Fig. 3(b) show the achievable sum rates of CCSIA, Two stage IA and Min-WLI schemes as the SNR changes, where the conventional schemes are implemented in scene A and scene B respectively. We can see from the Fig. 3(a) that as the SNR increases, the sum rates of all the schemes increase, and the sum rate of CCSIA is much higher than that of Two stage IA and Min-WLI. The reason is that as the SNR increases, the transmit power of BSs increases, resulting in an increase in the sum rate. For CCSIA, the signals from the relay contain the desired signal and the

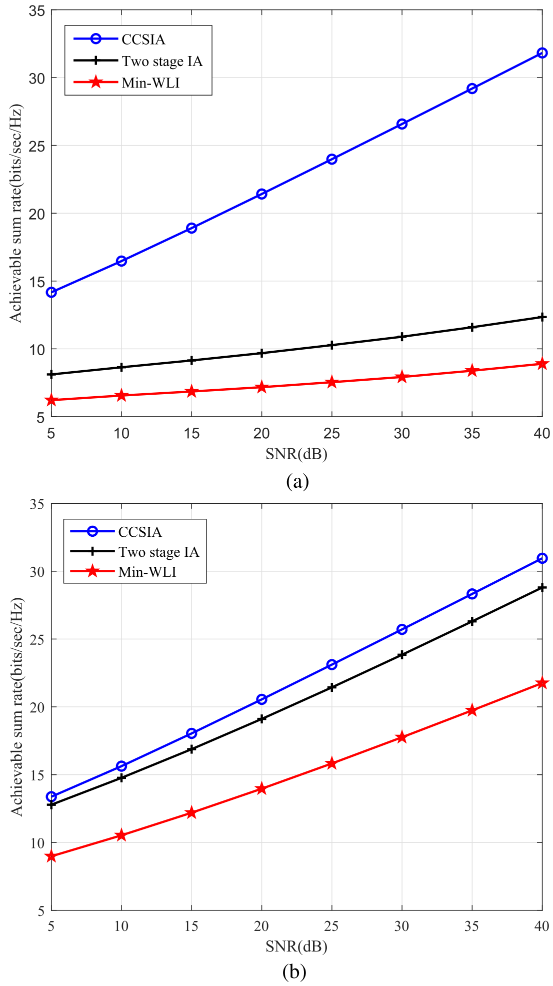

FIGURE 3. Achievable sum rate comparison of different schemes vs. SNR.

interference which can be eliminated. As the SNR increases, the scheme performance will be greatly improved. However, for the comparison schemes, the signals from the relay are treated as noise. The increase in SNR will cause aggravation of interference from relay to users. Therefore, the gap between the above two curves become larger with the increase of SNR. Thus, the interference brought by the relay would seriously affect the communication performance of the scene A while the traditional IA schemes cannot solve the interference. So it is necessary and effective for us to propose a new IA scheme. As shown in the Fig. 3(b), under the premise that other schemes do not consider the interference caused by the relay, the sum rate of CCSIA is highest, indicating that CCSIA can not only solve the original interference problem in scene B, but also solve the new interference problem caused by the relay. Another phenomenon we can observe from both Fig. 3(a) and Fig. 3(b) is that, the achievable rates of CCSIA and Two stage IA are higher than that of Min-WLI. Therefore, considering partial connectivity can increase achievable sum rate. It is reasonable to consider partial connectivity in our scheme.

The numbers of antennas required by different schemes to achieve IA are shown in Table. 3. Two Stage IA and Min-WLI

TABLE 3. Number of antennas for all BSs, all users and relay in different schemes.

Scheme	BSs	UEs	Relay
CCSIA	8	8	2
Two Stage IA	8	8	—
Min-WLI	8	8	—

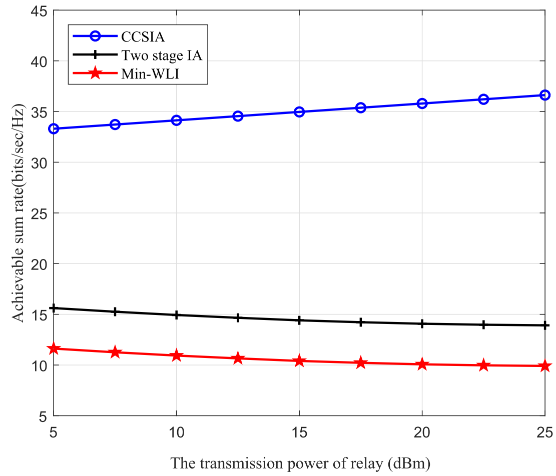

FIGURE 4. Achievable sum rate comparison of different schemes vs. relay transmit power in scene A.

cannot eliminate the interference caused by the relay, so the values in the table refer to the number of antennas needed to achieve IA in the scene B. We can see from the table that in terms of the number of antennas of all BSs and all users, CCSIA is equivalent to other schemes. In the total number of antennas, CCSIA only need two more antennas at the relay than other schemes. Therefore, the proposed scheme solves the three kinds of coexisting interference with a smaller number of antennas (two more antennas than the traditional schemes), thereby saving antenna resources and making the scheme more applicable.

Fig. 4 shows the sum rate of different schemes as the relay transmission power increases, all schemes are performed in scene A. As shown in this figure, as the relay transmission power increases, the sum rate of CCSIA remains the highest and increases steadily, on the contrary, the sum rates of Two stage IA and Min-WLI show a downward trend. This is because CCSIA can eliminate the cross time slot interference caused by the relay. Therefore, increasing the relay transmission power can increase the rate of the EMU, thereby increasing the sum rate. In Two stage IA and Min-WLI, the cross time slot interference caused by the relay is regarded as noise. As the relay transmission power increases, the interference at each user also increases, resulting in a decrease in the sum rate.

Fig. 5 shows the EMU's rates of different schemes as the distance between EMU and MBS increases when SNR=25dB. We can see from the figure that the average rate of CCSIA is higher than that of Two stage IA at all distances, indicating that CCSIA can not only solve the original interference problem in scene B, but also solve the new interference problem caused by the relay. For the Two stage IA in scene A, the EMU's rate is the lowest, because

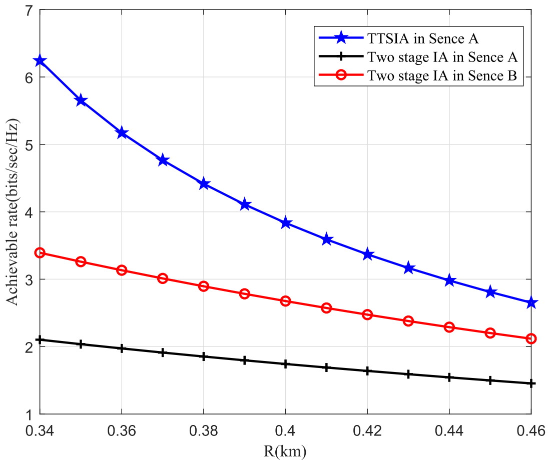

FIGURE 5. Average rate of EMU vs. the distance from MBS to EMU (R) when SNR=25dB.

this scheme cannot eliminate all interference in this scenario, so the relay would also amplify the interference signals while amplify the desired signal. As the distance increases, the rate of CCSIA decreases faster than the rate of Two stage IA. The reason is that when increasing the same distance, the value of the path loss of the relay is larger than the MBS, resulting in a faster decrease of the rate.

V. CONCLUSION

For the three-tier downlink MIMO HetNet, the CCSIA scheme, which achieves IA in the case of limited antennas by rationally designing the order and method of eliminating interference, is proposed in this paper. First, we align the interference from other BSs into the interference space generated by PBS to reduce the interference dimension of the relay, and then solve the interference between BSs and users by null space and concatenated precoding scheme. Furthermore, the feasibility condition of antenna configuration is analyzed. The simulation results show that the proposed scheme is superior to the traditional IA scheme in sum rate, and as the relay transmission power increases, the performance of the proposed scheme is further improved. In future work, we will consider increasing the number of PBSs in the system and extend the proposed scheme to more complex scenarios.

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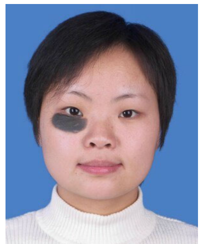

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