Inter-cell Interference Cancelation Schemes Using Alternate Relay Transmission

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***Abstract*—For multicell environment, relays introduce additional interferences at the cell edge. To overcome such inter-cell interferences, we propose the alternate relay transmission schemes. We quantify the ergodic rate performance of the proposed schemes over Nakagami-m fading channel. Numerical results show that the proposed schemes can effectively cancel the inter-cell interference and improve the sum rate performance for cell edge users.**

***Index Terms*—Relay, ergodic rate, Nakagami-m fading**

I. Introduction

In cellular wireless communication systems, cell edge users usually suffer from low signal to interference plus noise ratio (SINR) because of weak signal power from the serving base station (BS) and strong inter-cell interference from the neighbor BSs. To overcome such inter-cell interference, a co-operative BS transmission scheme, also known as coordinated multi-point (CoMP) transmission in 3GPP LTE-Advanced, has emerged as a promising solution [1], [2]. With this scheme, BSs transmit signals to the mobile stations (MSs) not only in their own cells but also in neighbor cells, assuming that BSs share all the data and channel information [3]. Limitations in coverage, especially at the cell edge, can be overcome by transmission over the relay station (RS). While conventional cellular networks are assumed to have cells of diameter 2km$\sim$ 5km, the RS will only be expected to cover a region of diameter 200m$\sim$ 500m [4]. This means that the transmit power requirements for RS are significantly reduced compared to those for BS. However, employing the multiple RSs suffers from capacity loss caused by inefficient time-slot allocation [5], [6]. Recently, the cooperation between RSs has been studied to enhance multiuser transmission in the downlink of a cellular system. In order to manage the mutual interference, linear joint precoding schemes across BS and RS(s) were proposed in [7], [8]. These previous works were focused on the single BS transmission. That is, RS sends a signal to MSs in its coverage without any regard to MS in the neighbor cell, which results in additional interferences to MSs. To overcome such interferences, the related studies on multicell shared RS scheme have been presented in [9]–[11]. The previous works on multicell shared RS scheme in [9], [10] consider that a single shared relay with multiple antennas behaves as a combination of three relays with single antenna. However, these solutions come with the price of a sophisticated RS.

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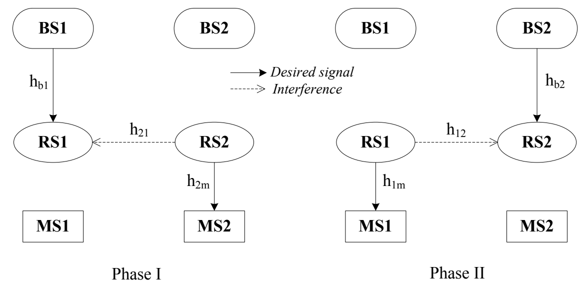

Fig. 1. Two phase alternate relay transmission (ART).

In this paper, we propose two alternate relay transmission (ART) schemes in the downlink of the cellular system, where each RS is served by each BS, to cancel the inter-cell interferences. In the nature of alternately processing with the adjacent cell, we limit the relay enhanced cellular system to the two-cell coordinated model. Especially, this simplified model makes it possible to analyze more tractably. The proposed ART scheme may incur inter-relay interference (IRI) due to simultaneous transmission from BS and RS. In order to eliminate this IRI, RS can perform successive interference cancelation (SIC). However, this can be only useful in the scenario having the very strong inter-relay channel, since RS first decodes the strongest IRI signal and removes the IRI from the aggregated received signal. Furthermore, the use of SIC requires the heavy processing burden at RS. For passing this processing burden to BS, we propose the precoding scheme associated with our proposed ART scheme at BSs. We develop the precoding vectors to eliminate IRI at RSs and carry out statistical analysis on the ergodic information rate of the precoding scheme. To verify the performance of the ART with precoding scheme, we derive the exact expressions of the ergodic rate for the relay enhanced cellular system over Nakagami-m fading channels. We show from our numerical examples that the analytical results exactly match to the numerical results and the proposed ART schemes can effectively cancel the interference and improve the sum rate for cell edge users.

II. System Description

In this paper, the relay enhanced cellular system consists of two cells where MS1 is served by BS1 while MS2 by BS2 and RS is located between BS and MS at each cell edge, and all nodes are equipped with a single antenna. We do not consider the direct path between BSs and MSs, making the analysis simple and realistic for the case when MS is highly shadowed near the cell edge [7], [12]. We assume that RS employs the decode-and-forward (DF) protocol in a half-duplex operation, and its transmit power is much smaller than BS. For alternate transmission from BSs, we assume either full or limited coordination between BSs. Under full coordination, BSs share all the data and full channel state information (CSI) of MS1 and MS2. Under limited coordination, the transmission scheduling information between BSs is shared, not sharing the user data and CSI. We adopt Nakagami-m fading channel model to characterize the diverse fading environment [13]. We assume that the channels are flat block fading.

A. ART Scheme

Generally, relaying operates in two-phase mode due to the half-duplex constraint. That is, in the first phase the source transmits the signal to the relay and in the second phase the signal is forwarded to the destination. Our proposed ART scheme utilizes the two-phase operation of relaying. Fig. 1 shows the operation of the ART scheme. We assume limited coordination between BSs for the ART scheme. Note that the transmission powers at BS1, BS2, RS1 and RS2 are constrained as P_{BS1}, P_{BS2}, P_{RS1} and P_{RS2}. Initially, BS1 or BS2 transmits its own symbol data to both RS1 and RS2. In time slot k (phase I), BS1 transmits its data to RS1, and at the same time, RS2 transmits the decoded data to both RS1 and MS2. Then, the received signals at RS1 and MS2 in time slot k are given by

$$y_{RS1}[k]=h_{b1}\sqrt{P_{BS1}}s_1[k]+h_{21}\sqrt{P_{RS2}}s_2[k-1]+n_{RS1}[k], \quad (1)$$

$$y_{MS2}[k]=h_{2m}\sqrt{P_{RS2}}s_2[k-1]+n_{MS2}[k], \quad (2)$$

where h_{b1}, h_{2m} and h_{21} are the channel gains of BS1-RS1, RS2-MS2 and RS2-RS1 links, respectively, and s_1 and s_2 are the unit-power transmitted data for MS1 and MS2, and n_{RS1}, n_{RS2}, n_{MS1} and n_{MS2} are additive White Gaussian noises (AWGN) with a variance with N_0. In time slot $k+1$ (phase II), BS2 transmits data to RS2 and RS1 relays data both RS2 and MS1. The received signals at RS2 and MS1 in time slot $k+1$ are given by

$$y_{RS2}[k+1]=h_{b2}\sqrt{P_{BS2}}s_2[k+1]+h_{12}\sqrt{P_{RS1}}s_1[k]+n_{RS2}[k+1], \quad (3)$$

$$y_{MS1}[k+1]=h_{1m}\sqrt{P_{RS1}}s_1[k]+n_{MS1}[k+1], \quad (4)$$

where h_{b2}, h_{1m} and h_{12} are the channel gains of BS2-RS2, RS1-MS1 and RS1-RS2 links, respectively. We assume that the channels are symmetric such as equal variances of the channel gains of BS1-RS1 and BS2-RS2 links, and equal variances of RS1-MS1 and RS2-MS2 links, and the reciprocity for the inter-relay channel. In (1) and (3), RS1 and RS2 can decode $s_1[k]$ and $s_2[k+1]$ treating the IRI components, $h_{12}\sqrt{P_{RS2}}s_2[k-1]$ and $h_{12}\sqrt{P_{RS1}}s_1[k]$, as noise respectively. Using that the achievable rate at MS1 is limited to the rate of the relay path of BS1-RS1 [14], the achievable rate of our proposed ART scheme for MS1, $\mathrm{C_{ART}}$, is given by

$$\min\left\{C\left(\frac{P_{BS1}|h_{b1}|^2}{N_0+P_{RS2}|h_{21}|^2}\right),C\left(\frac{P_{RS1}|h_{1m}|^2}{N_0}\right)\right\}, \quad (5)$$

where $C(x)=\frac{1}{2}\log_2(1+x)$. Hereafter, we focus on the performance of MS1, because the one of MS2 can be obtained in the same way. Since IRI can be treated as noise, this leads to performance degradation. To overcome such degradation, the SIC operation can be employed at RSs. That is, in (1), RS1 decodes first $s_2[k-1]$ treating $h_{b1}\sqrt{P_{BS1}}s_1[k]$ as noise, subtracts $h_{12}\sqrt{P_{RS2}}s_2[k-1]$ from the received signal $y_{RS1}[k]$, then decodes $s_1[k]$ interference-free. The achievable rate of the ART with SIC scheme for MS1, $\mathrm{C_{ART\_SIC}}$, is given by

$$\min\left\{C\left(\frac{P_{BS1}|h_{b1}|^2}{N_0}\right),C\left(\frac{P_{RS1}|h_{1m}|^2}{N_0}\right),C\left(\frac{P_{RS2}|h_{21}|^2}{N_0+P_{BS1}|h_{b1}|^2}\right)\right\}. \quad (6)$$

The third term in (6) is the maximum rate from RS2 to RS1 when the signal s_1 is treated as interference. This show that the ART with SIC scheme works well when the inter-relay channel is strong, since the rate in (6) is not limited by the third term [12].

B. ART with Precoding

As described in the previous section, the ART scheme suffers from IRI between RSs. To eliminate IRI between RSs, SIC can be employed at RS. However, the use of SIC requires the processing burden at RS, and this scheme will be useful only for the strong inter-relay channel. Therefore, we additionally propose the ART with precoding scheme at BSs, assuming full coordination between BSs. The received signal at RS1 in time slot k is given by

$$\begin{aligned}y_{RS1}[k] &= h_{b1}x_1[k]+h_{12}\sqrt{P_{RS2}}s_2[k-1]+n_{RS1}[k]\\ &=h_{b1}w_{11}s_1[k]+(h_{b1}w_{12}+h_{21}\sqrt{P_{RS2}})s_2[k-1]+n_{RS1}[k], \quad (7)\end{aligned}$$

where $x_1[k]$ is precoded data from BS1 such as $x_1[k]=w_{11}s_1[k]+w_{12}s_2[k-1]$, where $\mathbf{w}_1=[w_{11}\ \ w_{12}]^T$ is the precoding vector at BS1. The received signal at RS2 in time slot $k+1$ is given by

$$\begin{aligned}y_{RS2}[k+1] &= h_{b2}x_2[k+1]+h_{12}\sqrt{P_{RS1}}s_1[k]+n_{RS2}[k]\\ &=h_{b2}w_{22}s_2[k+1]+(h_{b2}w_{21}+h_{12}\sqrt{P_{RS1}})s_1[k]+n_{RS2}[k], \quad (8)\end{aligned}$$

where $x_2[k+1]$ is precoded data from BS2 such as $x_2[k+1]=w_{21}s_1[k]+w_{22}s_2[k+1]$, where $\mathbf{w}_2=[w_{21}\ \ w_{22}]^T$ is the precoding vector at BS2. The achievable rate of the ART with precoding scheme for MS1, $\mathrm{C_{ART\_Precoding}}$, is obtained by

$$\min\left\{C\left(\frac{|h_{b1}w_{11}|^2}{N_0+|h_{b1}w_{12}+h_{21}\sqrt{P_{RS2}}|^2}\right),C\left(\frac{P_{RS1}|h_{1m}|^2}{N_0}\right)\right\}. \quad (9)$$

We will derive the precoding vectors and develop the ergodic rate of the ART with precoding scheme in the following section.

III. The Proposed Precoding Scheme for ART

In this section, we present the design of the proposed multiuser precoding scheme for the ART and derive the ergodic rate for the performance analysis. In this paper, we limit ourselves to the linear precoding schemes. The main schemes for the linear precoding include the zero forcing (ZF) scheme and the minimum mean square error (MMSE) scheme.

Although the MMSE scheme is known to perform better than the ZF scheme, it comes at the expense of higher complexity. Furthermore, [15] shows that the performance gap between the inter-cell ZF scheme and the inter-cell MMSE scheme is very small. Therefore, we consider the ZF scheme for designing the precoding vectors.

A. Precoder Design

The objective of the proposed multiuser precoding scheme is to eliminate IRI at RSs. For this purpose, we design the precoding vectors $\mathbf{w}_1$ and $\mathbf{w}_2$. In phase I, the received signal at RS1 in (7) contains the interference s_2, which can be canceled through the following condition,

$$\begin{aligned} & h_{21}\sqrt{P_{RS2}} + h_{b1}w_{12} = 0 \\ & \text{s.t. } |w_{11}|^2 + |w_{12}|^2 \leq P_{BS1} \end{aligned} \tag{10}$$

Let us first design the precoding values w_{12} as a function of channel gains by employing the ZF scheme. We design w_{12} to cancel the interference s_2 at RS1 such as $w_{12} = \sqrt{\alpha P_{BS1}}e^{j\theta_{ZF1}}$. Under this assumption, the precoding vector $\mathbf{w}_1$ can be obtained by

$$\mathbf{w}_1 = [w_{11} \;\; w_{12}] = \left[\sqrt{(1-\alpha)P_{BS1}} \;\; \sqrt{\alpha P_{BS1}}e^{j\theta_{ZF1}}\right], \tag{11}$$

where the phase of w_{12}, θ_{ZF1}, can be aligned as $\pi + \theta_{21} - \theta_{b1}$, where θ_{12} and θ_{b1} are the phases of h_{b1} and h_{21}, respectively. In (11), the power portion, α $(0 \leq \alpha \leq 1)$, is determined by

$$\alpha = \begin{cases} \frac{|h_{21}|^2 P_{RS2}}{|h_{b1}|^2 P_{BS1}} & \text{, if } |h_{b1}|^2 P_{BS1} \geq |h_{21}|^2 P_{RS2} \\ 0 & \text{otherwise.} \end{cases} \tag{12}$$

In phase II, the received signal at RS2 in (8) contains the interference s_1, which can be canceled through the following condition,

$$\begin{aligned} & h_{12}\sqrt{P_{RS2}} + h_{b2}w_{21} = 0 \\ & \text{s.t. } |w_{21}|^2 + |w_{22}|^2 \leq P_{BS2} \end{aligned} \tag{13}$$

We design w_{21} to cancel the interference s_1 at RS2 such as $w_{21} = \sqrt{\beta P_{BS1}}e^{j\theta_{ZF2}}$. Under this assumption, the precoding vector $\mathbf{w}_2$ can be obtained by

$$\mathbf{w}_2 = [w_{21} \;\; w_{22}] = \left[\sqrt{\beta P_{BS2}}e^{j\theta_{ZF2}} \;\; \sqrt{(1-\beta)P_{BS2}}\right], \tag{14}$$

where the phase of w_{21}, θ_{ZF2}, can be aligned as $\pi + \theta_{12} - \theta_{b2}$, where θ_{b2} is the phase of h_{b2}, respectively. Similar to (12), the power portion, β $(0 \leq \beta \leq 1)$, in (14) is determined by

$$\beta = \begin{cases} \frac{|h_{12}|^2 P_{RS1}}{|h_{b2}|^2 P_{BS2}} & \text{, if } |h_{b2}|^2 P_{BS2} \geq |h_{12}|^2 P_{RS1} \\ 0 & \text{otherwise.} \end{cases} \tag{15}$$

B. Ergodic Rate Analysis

We now evaluate the ergodic rate with the proposed precoding scheme through statistical analysis. We assume $P_{BS1} = P_{BS2} = P$ and $P_{RS1} = P_{RS2} = \kappa P$, where κ is the power ratio between RS and BS $(0 < \kappa < 1)$. Due to the simplicity of expression, we denote $\gamma_{xy} = \frac{|h_{xy}|^2 P}{N_0}$, where γ_{xy} is a random variable (RV). We define SINR as the compound of each signal to noise ratio (SNR). Substituting (11) into (9), we can write the achievable rate at MS1 as

$$\begin{cases} \min\{C(\gamma_{b1} - \kappa\gamma_{1m}), C(\kappa\gamma_{1m})\} & \text{, if } \gamma_{b1} \geq \kappa\gamma_{12} \\ \min\left\{C\left(\frac{\gamma_{b1}}{\kappa\gamma_{12}+1}\right), C(\kappa\gamma_{1m})\right\} & \text{, if } \gamma_{b1} < \kappa\gamma_{12}. \end{cases} \tag{16}$$

The ergodic rate of MS1 can be obtained with the conditional probability density functions (PDFs) of all possible SINRs in (16). We derive the closed-form expressions of the conditional PDFs for Nakagami-m fading channels in the Appendix. Using the conditional PDFs of (21)-(22) and (25)-(26) in Appendix, we can show the ergodic rate for MS1 can be written as

$$\begin{aligned} E[R_{MS1}] = & E\left[\min\{C(\gamma_{b1} - \kappa\gamma_{12}), C(\kappa\gamma_{1m})\} \,\middle|\, \gamma_{b1} \geq \kappa\gamma_{12}\right]\mu_1 \\ & + E\left[\min\left\{C\left(\frac{\gamma_{b1}}{\kappa\gamma_{12}+1}\right), C(\kappa\gamma_{1m})\right\} \,\middle|\, \gamma_{b1} < \kappa\gamma_{12}\right]\mu_2, \end{aligned} \tag{17}$$

where $\Pr[\gamma_{b1} \geq \kappa\gamma_{12}] \equiv \mu_1$ and $\Pr[\gamma_{b1} < \kappa\gamma_{12}] \equiv \mu_2$. In (17), the conditional ergodic rate given by $\gamma_{b1} \geq \kappa\gamma_{12}$ is obtained by

$$\begin{aligned} & E\left[\min\{C(\gamma_{b1} - \kappa\gamma_{12}), C(\kappa\gamma_{1m})\} \,\middle|\, \gamma_{b1} \geq \kappa\gamma_{12}\right] \\ & = E\left[C(\gamma_{b1} - \kappa\gamma_{12}) \,\middle|\, \gamma_{b1} - \kappa\gamma_{12} < \kappa\gamma_{1m}, \gamma_{b1} \geq \kappa\gamma_{12}\right]\upsilon_1\mu_1 \\ & \quad + E\left[C(\kappa\gamma_{1m}) \,\middle|\, \gamma_{b1} - \kappa\gamma_{12} \geq \kappa\gamma_{1m}, \gamma_{b1} \geq \kappa\gamma_{12}\right]\upsilon_2\mu_1, \end{aligned} \tag{18}$$

where $\Pr[\gamma_{b1} - \kappa\gamma_{12} < \kappa\gamma_{1m}] \equiv \upsilon_1$ and $\Pr[\gamma_{b1} - \kappa\gamma_{12} \geq \kappa\gamma_{1m}] \equiv \upsilon_2$. Also, the conditional ergodic rate given by $\gamma_{b1} < \kappa\gamma_{12}$ is obtained by

$$\begin{aligned} & E\left[\min\left\{C\left(\frac{\gamma_{b1}}{\kappa\gamma_{12}+1}\right), C(\kappa\gamma_{1m})\right\} \,\middle|\, \gamma_{b1} < \kappa\gamma_{12}\right] \\ & = E\left[C\left(\frac{\gamma_{b1}}{\kappa\gamma_{12}+1}\right) \,\middle|\, \frac{\gamma_{b1}}{\kappa\gamma_{12}+1} < \kappa\gamma_{1m}, \gamma_{b1} < \kappa\gamma_{12}\right]\nu_1\mu_2 \\ & \quad + E\left[C(\kappa\gamma_{1m}) \,\middle|\, \frac{\gamma_{b1}}{\kappa\gamma_{12}+1} \geq \kappa\gamma_{1m}, \gamma_{b1} < \kappa\gamma_{12}\right]\nu_2\mu_2, \end{aligned} \tag{19}$$

where $\Pr\left[\frac{\gamma_{b1}}{\kappa\gamma_{12}+1} < \kappa\gamma_{1m}\right] \equiv \nu_1$ and $\Pr\left[\frac{\gamma_{b1}}{\kappa\gamma_{12}+1} \geq \kappa\gamma_{1m}\right] \equiv \nu_2$.

Similarly, we can find the ergodic rate for MS2, R_{MS2}, like the case of R_{MS1}. Finally, the overall ergodic rate of the proposed precoding scheme is given by

$$E[R] = E[R_{ms1}] + E[R_{ms2}]. \tag{20}$$

IV. Numerical Results

In this section, we present several numerical examples to illustrate the performance for the relay enhanced cellular system. For notational simplicity, we assume that equal channel variances from BSs to RSs and equal channel variances from RSs to MSs, respectively, i.e., $E[|h_{b1}|^2] = E[|h_{b2}|^2] = \sigma_{br}^2$, $E[|h_{1m}|^2] = E[|h_{2m}|^2] = \sigma_{rm}^2$, and the inter-relay channel is symmetric such that $E[|h_{12}|^2] = E[|h_{21}|^2] = \sigma_{12}^2$. To characterize the unbalance of channel strength between per-hop relay links, we set $\sigma_{br}^2 = 1$. Also, we set the power ratio for RS $\kappa = 0.1$ as an example. Typically, a cellular system consists of regular placement of BSs that transmit at high

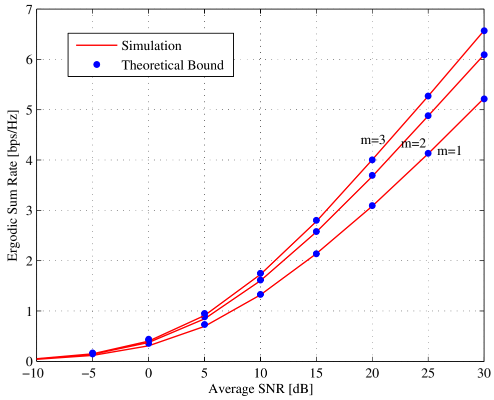

Fig. 2. Ergodic sum rates of the ART with precoding scheme over Nakagami-m channels ($m = 1 \sim 3$, $\sigma^2_{rm} = \sigma^2_{12} = 5$).

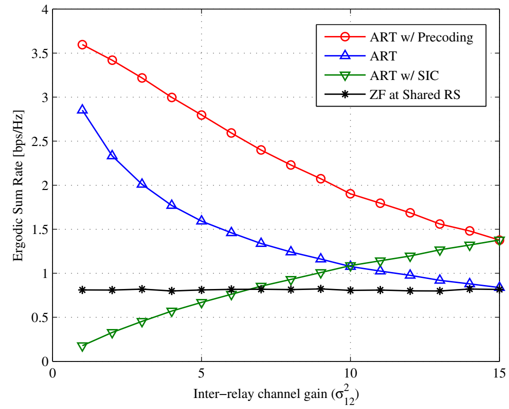

Fig. 4. Comparison of ergodic sum rates of the proposed ART schemes and the conventional scheme as inter-relay channel gain increases ($m = 3$, $\sigma^2_{rm} = 5$).

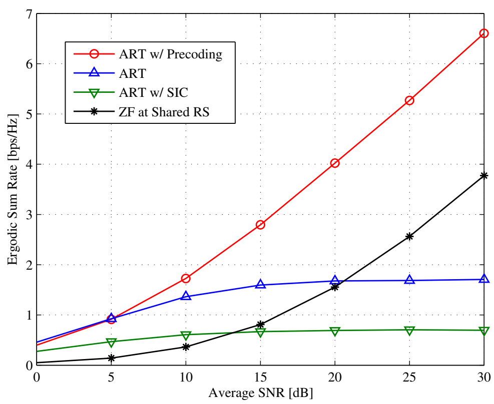

Fig. 3. Comparison of ergodic sum rates of the proposed ART schemes and the conventional scheme over Nakagami-m channels ($m = 3$, $\sigma^2_{rm} = \sigma^2_{12} = 5$).

power level (up to 40W) and RSs that transmit at substantially low power levels (up to 2W) [16], i.e., κ is less than one tenth.

In Fig. 2, we examine the accuracy of our analytical results for the ART with precoding vectors obtained in (11) and (14). We consider the Nakagami-m fading channels with various m values and set the channel variances $\sigma^2_{rm} = \sigma^2_{12} = 5$ to emulate the environment which RSs are deployed near cell boundary and MSs are located at cell edge. The average SNR is defined as $\frac{P}{N_0}$. We show the ergodic sum rates of the proposed scheme when the Nakagami-m parameter increases from 1 to 3. As shown in Fig. 2, the analytical result of the proposed scheme matches to the simulation result well. In addition, the performance of the proposed scheme improves considerably as the m parameter increases from 1 to 3, that is, the relay links have stronger LOS.

In Fig. 3, the ergodic sum rates of the proposed schemes, ART, ART with SIC and ART with precoding, are compared with the conventional scheme, ZF at shared RS. For comparison, we consider ZF at shared RS, where the shared RS equipped with two antennas, communicating with both BSs, decodes signals from BSs via ZF receiver and it transmits two interference-free signals by performing ZF precoding. We set the Nakagami parameter $m = 3$ and the channel variances $\sigma^2_{rm} = \sigma^2_{12} = 5$. In low and median SNR region, the ART scheme can achieve a performance gain over the conventional scheme, ZF at shared RS, where a shared relay network operates with less total interference than a tree architecture that each RS communicates with only one BS. Meanwhile, in high SNR region, the rate of the ART scheme is limited since the ART scheme suffers from IRI between RSs. To overcome the effect of IRI on the performance, we propose the ART with SIC and the ART with precoding schemes. As shown in Fig. 3, the ART with precoding scheme offers the superior capacity gain over the simple ART scheme, while the rate of the ART with SIC scheme is limited due to insufficient inter-relay channel gains for successful decoding at RS, i.e., the rate is limited by the third term in (6).

Fig. 4 shows the ergodic sum rates for different variances σ^2_{12} of the inter-relay channel gain and compares the impact of interference cancelation on the ART scheme. We set the Nakagami parameter $m = 3$, the channel variance $\sigma^2_{rm} = 5$ and the average SNR is 15dB as an example. When the inter-relay channel gain is not strong, the ART scheme performs very well as well as the ART with precoding scheme. However, for the inter-relay channel gains that are considerably stronger than other channel gains, the ART scheme and the ART with precoding scheme do not work well. In case of the ART with precoding scheme, BSs will limit their transmission of the desired symbol data to eliminate the IRI signal as the inter-relay channel is getting stronger. As shown in this figure, the ART with SIC scheme works well for the strong inter-relay channel, where this situation is equivalent to the multi-antenna shared RS scenario making the strong self-interference channel that loops back from the shared RS's transmit antenna to its receive antenna.

V. Conclusion

We introduced the inter-cell interference cancelation schemes for the relay enhanced cellular system: namely ART,

ART with SIC and ART with precoding. For the ART with precoding scheme, we proposed cooperative joint precoding method, and derived the precoding vectors as a function of the channel gains and phases. Numerical results showed that the proposed ART schemes can effectively cancel the inter-cell interference and improve the sum rate for the users at cell edge. We also verified that the analytical result of the ergodic rate for the ART with precoding scheme represents a very tight bound of the actual values through simulation. The ART with precoding scheme offers the considerable capacity gain over the ART scheme by eliminating the inter-relay interference at RSs, while the ART with SIC scheme works well for the strong inter-relay channel.

APPENDIX
THE CONDITIONAL PDFS FOR ART WITH PRECODING

In order to obtain the ergodic rates of MS1 in (17), we derive the conditional PDFs of SINRs defined in (18) and (19). We consider the case of Nakagami fading with common Nakagami parameter m, where m is an integer. To derive the conditional PDFs of SINRs given by the channel condition, we first derive the conditional cumulative distribution functions (CDFs) of SINRs, and then differentiate the conditional CDF with respect to SINR, which leads to the corresponding PDF. Especially, in (19), we make use of the upper bound for the analysis to be more tractable such as $\frac{\gamma_{b1}}{\kappa\gamma_{12}+1} \leq \frac{\gamma_{b1}}{\kappa\gamma_{12}}$. Fig. 2 confirms that the analytical result of the ergodic sum rate represents a very tight upper bound of the actual values obtained through simulation study. Note that we employ the finite-sum representation of the incomplete gamma function and carry out some necessary manipulation in order to obtain the closed-form expressions including the integration of the incomplete gamma function [17]. For simple notation, we denote that the mean of a RV $(\kappa)\gamma_{xy}$ is $\lambda_{xy} \equiv 1/(\kappa)\bar{\gamma}_{xy}$, and $\bar{\gamma} = E[\gamma]$ with $E[\cdot]$ denoting the statistical expectation.

In (18), the conditional PDFs can be derived by

$$\begin{aligned} &f_{\gamma_{b1}-\kappa\gamma_{12}|\gamma_{b1}-\kappa\gamma_{12}<\kappa\gamma_{1m},\gamma_{b1}\geq\kappa\gamma_{12}}(x)\cdot\upsilon_1\mu_1 \\ &= \frac{\Gamma(m, m\lambda_{1m}x)}{\Gamma(m)^2}(m\lambda_{12})^m e^{-m\lambda_{b1}x} \\ &\quad\times\sum_{i=1}^{m}\sum_{j=1}^{m} \mathrm{c}_{i,j}\mathrm{K}_{i,j}\left\{m\lambda_{b1}x^{i-1}-(i-1)x^{i-2}\right\}, \quad (21)\end{aligned}$$

$$\begin{aligned} &f_{\kappa\gamma_{1m}|\gamma_{b1}-\kappa\gamma_{12}\geq\kappa\gamma_{1m},\gamma_{b1}\geq\kappa\gamma_{12}}(x)\cdot\upsilon_2\mu_1 \\ &=\frac{(m^2\lambda_{12}\lambda_{1m})^m}{\Gamma(m)^2}e^{-m(\lambda_{1m}+\lambda_{b1})x}x^{m-1}\sum_{i=1}^{m}\sum_{j=1}^{m}\mathrm{c}_{i,j}\mathrm{K}_{i,j}x^{j-1}, \quad (22)\end{aligned}$$

where $\Gamma(\cdot,\cdot)$ is the upper incomplete gamma function, $\Gamma(\cdot)$ is the gamma function,

$$\mathrm{c}_{i,j} = \begin{cases} 1 & , i=j \text{ or } i=1 \\ \sum_{k=i-1}^{j-1}\mathrm{c}_{i-1,k} & , i\neq j\ (i\geq 2)\end{cases}, \quad (23)$$

and

$$\mathrm{K}_{i,j} = \frac{\Gamma(m+j-i)}{\Gamma(j)}\frac{(m\lambda_{b1})^{j-1}}{(m(\lambda_{12}+\lambda_{b1}))^{m+j-i}}. \quad (24)$$

In (19), the conditional PDFs can be derived by

$$\begin{aligned} &f_{\frac{\gamma_{b1}}{\kappa\gamma_{12}}|\frac{\gamma_{b1}}{\kappa\gamma_{12}}<\kappa\gamma_{1m},\gamma_{b1}<\kappa\gamma_{12}}(x)\cdot\nu_1\mu_2 \\ &\quad= \frac{\Gamma(m, m\lambda_{1m}x)}{\Gamma(m)^2}(m\lambda_{12})^m\sum_{k=1}^{m}\{\mathrm{A}_k(x)-\mathrm{B}_k(x)\}, \quad (25)\end{aligned}$$

$$\begin{aligned} &f_{\kappa\gamma_{1m}|\frac{\gamma_{b1}}{\kappa\gamma_{12}}\geq\kappa\gamma_{1m},\gamma_{b1}<\kappa\gamma_{12}}(x)\cdot\nu_2\mu_2 \\ &\quad= \frac{(m^2\lambda_{12}\lambda_{1m})^m}{\Gamma(m)^2}e^{-m\lambda_{1m}x}x^{m-1}\sum_{k=1}^{m}\{\mathrm{C}_k(x)-\mathrm{K}_{1,k}\}, \quad (26)\end{aligned}$$

where

$$\mathrm{A}_k(x) = \frac{\Gamma(m+k-1)}{\Gamma(k)}\frac{\lambda_{b1}^k\ x^{k-1}}{m^{m-1}(\lambda_{12}+\lambda_{b1}x)^{m+k}}, \quad (27)$$

$$\mathrm{B}_k(x) = \frac{\Gamma(m+k-1)}{\Gamma(k)}\frac{(k-1)\lambda_{12}\lambda_{b1}^{k-1}\ x^{k-2}}{m^m(\lambda_{12}+\lambda_{b1}x)^{m+k}}, \quad (28)$$

and

$$\mathrm{C}_k(x) = \frac{\Gamma(m+k-1)}{\Gamma(k)}\frac{\lambda_{b1}^{k-1}\ x^{k-1}}{m^m(\lambda_{12}+\lambda_{b1}x)^{m+k-1}}. \quad (29)$$

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