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Published in:
I E E E Communications Letters

DOI (link to publication from Publisher):
10.1109/LCOMM.2013.051313.130288

Publication date:
2013

Document Version
Early version, also known as pre-print

Cell-Edge Multi-User Relaying with Overhearing

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***Abstract*—Carefully designed protocols can turn overheard interference into useful side information to allow simultaneous transmission of multiple communication flows and increase the spectral efficiency in interference-limited regime. We propose a novel scheme in a typical cell-edge scenario. By exploiting the overhearing link through proper relay precoding and adaptive receiver processing, rate performance can be significantly improved compared to the conventional transmission which does not utilize overhearing.**

I. Introduction

Wireless cellular networks serve multiple data flows simultaneously, where the term flow stands for the data packets emerging from a specific source and intended for a specific destination. Joint processing and transmission of multiple independent data flows can improve the spectral efficiency of a cellular network. This is achieved by turning inter-flow interference into an advantage and using it as side information in the decoding, rather than treating it as detrimental noise to be avoided. Such an approach is an essence of, for example, the techniques based on physical-layer network coding [1], [2].

In this letter, we focus on the design of the transmission protocol which intentionally introduces inter-flow interference in a way that the receiver can overhear the interference and exploit it as side information to improve the overall spectral efficiency of the network. In [3], the authors propose a protocol for multi-user relaying under the assumption that one user equipment (UE) overhears the data from the other UE perfectly. However, such assumption is difficult to ensure in practice, since the overhearing link between the UEs tends to be noisy. More realistic overhearing-based relaying schemes have been proposed in [4], [5], which assume the setup with two UEs: one UE has a good direct link to the base station (BS) and the other UE has no direct link to the BS. Different approaches have been considered to exploit the overheard interference: [4] is based on a non-linear receiver where the interference is decoded and canceled first, while [5] uses a linear receiver for interference suppression. The overhearing-based relaying system with linear receiver [4] is further applied to a cooperative cognitive radio network in [6]. Meanwhile, [7] focuses on a scenario with multiple cell-edge UEs. Some UEs require huge uplink traffic and have no direct connections to the BS. The other UEs demand huge downlink traffic and have weak direct links to the BS. The optimal degree of freedom is identified through *interference neutralization* at the relay in [7], which cancels the overheard interference by using a different copy of the interference propagated through the two-hop relaying. While such interference neutralization is optimal in terms of securing the degree of freedom in the network, its performance in practice under finite SNR regime can be further improved by relay precoding and receiver processing.

This work was supported in part by the Danish Research Council for Technology and Production Grant 09-065920, and by NSF Grant CCF-1256548. Part of this work has been performed in the framework of the EU FP7 project ICT-317669 METIS. The authors would like to acknowledge the contributions of their colleagues in METIS, although the views expressed are those of the authors and do not necessarily represent the project.

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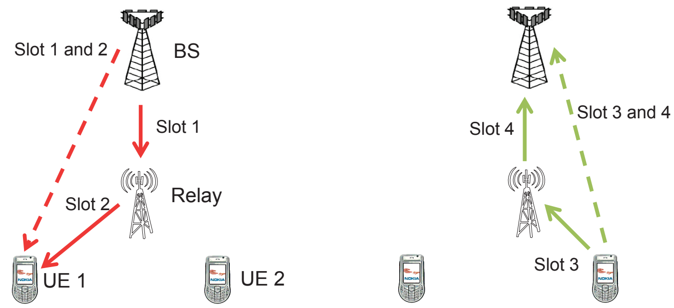
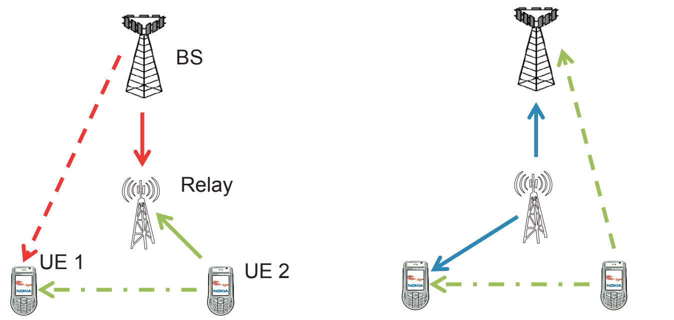


(a) Time Slot 1 and 2 (b) Time Slot 3 and 4

Fig. 1. System model (benchmark): direct link (dashed), relay link (solid).



(a) Time Slot 1 (b) Time Slot 2

Fig. 2. System model (proposed): direct link (dashed), relay link (solid), overhearing link (dashed dot).

To illustrate how to efficiently use the overhearing link, we focus on a scenario with two cell-edge UEs having asymmetric traffic requirements, where one UE requires uplink traffic, e.g. sharing HD video with friends while the other UE demands downlink traffic, e.g. watching movies on Youtube. In particular, the links between the BS and UEs are assumed to be weaker compared to the links between the relay and the other nodes. But the weak direct links are not neglected, which is more general compared to [4]–[6]. The transmission mainly relies on the links through the relay amplify-and-forward (AF) operation [8]. In the conventional scheme shown in Fig. 1, the two flows will require two orthogonal uplink and downlink phases, where each phase takes two time slots.

In the proposed scheme shown in Fig. 2, we have three key contributions in the 2nd time slot: we intentionally allow the uplink UE to interfere the downlink UE via signal retransmission for better receptions of both traffic; the downlink UE overhears the interference and uses it as side information to recover its desired signal by performing appropriate receiver processing based on different interference levels; the relay plays a central role in balancing the two flows via relay precoding. By optimizing the relay precoding and selecting the receiver processing, the overheard information is demonstrated to be beneficial to the spectral efficiency increase by allowing to accomplish the overall transmission in only two time slots instead of the four time slots in the conventional method. The value of this scenario is to extend the wireless network coding principle, introduced in the two-way relaying [9], to a scenario which has asymmetric traffic requirements for two cell-edge UEs.

The downlink traffic is inherently more susceptible to the inter-flow interference than the uplink traffic, as the uplink enjoys interference-free reception after the self-interference cancellation. Therefore, the relay precoding and the receiver processing are chosen in order to maximize the minimum weighted SNR/SINR of the two flows, which reflects different types of user fairness. We stay with the single-antenna setup for all the nodes to highlight the principle of overhearing in this work.

II. System Model and Four-slot Transmission

We assume two information flows in a perfectly synchronized network: the BS transmits x_1 to UE 1 and UE 2 delivers x_2 to the BS. All links are assumed to be static within the duration of the schemes considered in the paper. We assume that the noise power is normalized to unity. We denote the (narrowband) channel between nodes A and B as h_{AB}. The channel coefficients also embed the transmit power, so that the average SNR corresponding to the link between A and B is defined as $\gamma_{AB} = \mathbb{E}(|h_{AB}|^2)$. Equivalently, the maximum transmit power of each node is set to 1. In this paper, we consider the cell-edge scenario where the direct transmissions between the BS and the UEs significantly suffer from the poor link quality. Therefore, the use of the relay is crucial to support both flows. The BS and UE 2 transmit at full power; the relay can adjust its transmit power as well as apply a phase change to the transmit signal. For simplicity, we use 1, 2, *B*, *R* as the indices in the formulas to denote UE 1, UE 2, BS and the relay, respectively. We assume that the relay has a perfect knowledge of all channels. The BS and UEs need only a subset of all channels, as will be clear in the description of the post-processing at each node.

The reference scheme does not employ overhearing and consists of four slots as shown in Fig. 1. The transmission of each flow takes two slots. We apply the non-orthogonal AF (NAF) [10] for both flows, where in the 2nd time slot the BS retransmits the same signal as in the 1st slot simultaneously with the relay transmission. The complex relay gains in slot 2 and slot 4 are chosen to optimize the rate of individual flow.

III. Proposed Two-slot Transmission

The use of four time slots makes the previously described scheme very inefficient. We can reduce the transmission duration from four slots to two slots using side information: the overheard signals at UE 1 and the self-interference cancellation at BS. We illustrate the proposed transmission in Fig. 2. In the 1st slot, UE 2 transmits x_2 to the relay while x_1 is delivered from the BS to UE 1 and the relay. Meanwhile, UE 1 overhears the interfering signal from UE 2 while the relay receives the combined signal. Then the relay forwards the received signal to both the BS and UE 1 in the 2nd slot. Meanwhile, UE 2 retransmits x_2 to the BS and UE 1 will again overhear this information.

Remark 1: Although UE 2 should remain inactive not to create any interference in the 2nd slot, it retransmits the signal already transmitted for better receptions of both flows: improved reception for uplink via the direct link h_{B2}; better interference distinguishability at UE 1 which helps to facilitate the processing at UE 1. We consider the full transmission power is used in both slots at BS and UE 2 as used in the benchmark.[1]

A. Transmission Scheme

The received signals at the relay and UE 1 in the 1st slot are

$$\begin{aligned} y_R(1) &= h_{RB}x_1 + h_{R2}x_2 + n_R \\ y_1(1) &= h_{1B}x_1 + h_{12}x_2 + n_1(1) \end{aligned} \quad (1)$$

where the noise variables at the relay and UE 1, denoted by n_R and $n_1(1)$, are zero mean circularly symmetric complex Gaussian (ZMCSCG) random variables with unit variance. The received signals at BS and UE 1 in the 2nd slot are

$$\begin{aligned} y_B(2) &= h_{BR}x_R + h_{B2}x_2 + n_B \\ y_1(2) &= h_{1R}x_R + h_{12}x_2 + n_1(2) \end{aligned} \quad (2)$$

where the signal transmitted from the relay is of the form $x_R = w\, y_R(1)$ with w being the complex relay gain. The complex relay gain is broadcasted to the two reception nodes through control signaling. n_B and $n_1(2)$ are ZMCSCG noise variables with unit variance at the BS and UE 2. The complex relay gain is our key design parameter and is constrained as $\mathbb{E}[|x_R|^2] = |w|^2 \left(|h_{RB}|^2 + |h_{R2}|^2 + 1\right) \leq 1$.

With the knowledge of the channel gains and the relay gain w, the BS can remove the self interference x_1 in the received signal completely. Therefore, there is no interference when the BS decodes x_2. After interference cancellation, we have $\hat{y}_B(2) = (h_{B2} + h_{BR}wh_{R2})\, x_2 + h_{BR}wn_R + n_B$. Then the SNR at BS is expressed as $\mathrm{SNR_B} = \frac{|h_{B2}+wh_{BR}h_{R2}|^2}{|w|^2|h_{BR}|^2+1}$.

Meanwhile, UE 1 uses $y_1(1)$ and $y_1(2)$ from the two slots to form a virtual 2-antenna received signal vector

$$\mathbf{y}_1 = \begin{bmatrix} h_{1B} \\ h_{1R}wh_{RB} \end{bmatrix} x_1 + \begin{bmatrix} h_{12} \\ h_{12} + h_{1R}wh_{R2} \end{bmatrix} x_2 + \begin{bmatrix} n_1(1) \\ h_{1R}wn_R + n_1(2) \end{bmatrix} = \mathbf{h}_1 x_1 + \mathbf{h}_2 x_2 + \mathbf{n}_1.$$

UE 1 wants to decode the desired signal x_1 while x_2 is the interference. The interference x_2 is received from two slots. In the following section, we will cover the adaptive principle in details via two decoding options at UE 1.

B. Decoding Options

The receiver takes different decoding strategies depending on the relative interference level. Weak interference is suppressed by a linear receiver and strong interference is decoded and mitigated via successive interference cancellation (SIC) processing.

1) Linear decoding: After applying individual linear MMSE receivers for x_1 and x_2, we will obtain $\mathrm{SINR}_1 = \mathbf{h}_1^{\mathrm{H}} \left\{\mathbb{E}\left[(\mathbf{h}_2x_2 + \mathbf{n}_1)(\mathbf{h}_2x_2 + \mathbf{n}_1)^{\mathrm{H}}\right]\right\}^{-1} \mathbf{h}_1$ and $\mathrm{SINR}_2 = \mathbf{h}_2^{\mathrm{H}} \left\{\mathbb{E}\left[(\mathbf{h}_1x_1 + \mathbf{n}_1)(\mathbf{h}_1x_1 + \mathbf{n}_1)^{\mathrm{H}}\right]\right\}^{-1} \mathbf{h}_2$ with final expressions shown in (3) and (4), respectively. If $\mathrm{SINR}_1 \geq \mathrm{SINR}_2$,

$$|h_{12} + h_{1R}wh_{R2}|^2 \leq \left(1 + |w|^2 |h_{1R}|^2\right)\left(|h_{1B}|^2 - |h_{12}|^2\right) + |w|^2 |h_{1R}|^2 |h_{RB}|^2 . \quad (5)$$

In this situation, a linear MMSE receiver is applied at UE 1 to suppress interference first. Then we directly decode x_1 while treating x_2 as interference.

[1] Varying power at BS and UE 2 may offer better performance at the expense of more complicated optimization. However, it is out of scope of this letter.

$$\mathrm{SINR}_1 = \frac{\left(1+|w|^2|h_{1R}|^2\right)|h_{1B}|^2 + |w|^2|h_{1R}|^2|h_{RB}|^2 + |h_{1B}h_{12} + w\left(h_{1B}h_{1R}h_{R2} - h_{12}h_{1R}h_{RB}\right)|^2}{\left(1+|w|^2|h_{1R}|^2\right)\left(|h_{12}|^2+1\right) + |h_{12}+wh_{1R}h_{R2}|^2} \quad (3)$$

$$\mathrm{SINR}_2 = \frac{\left(1+|w|^2|h_{1R}|^2\right)|h_{12}|^2 + |h_{12}+wh_{1R}h_{R2}|^2 + |h_{1B}h_{12} + w\left(h_{1B}h_{1R}h_{R2} - h_{12}h_{1R}h_{RB}\right)|^2}{\left(1+|w|^2|h_{1R}|^2\right)\left(|h_{1B}|^2+1\right) + |w|^2|h_{1R}|^2|h_{RB}|^2} \quad (4)$$

2) Non-linear decoding: Here we apply the MMSE-SIC processing. Observing that UE 1 receives both x_1 and x_2, if the interference related to x_2 is stronger compared to the signal level, we resort to decode x_2 and then subtract it via the interference cancellation process. If $\mathrm{SINR}_1 \leq \mathrm{SINR}_2$, which means

$$|h_{12}+h_{1R}wh_{R2}|^2 \geq \left(1+|w|^2|h_{1R}|^2\right)\left(|h_{1B}|^2 - |h_{12}|^2\right) + |w|^2|h_{1R}|^2|h_{RB}|^2, \quad (6)$$

we will decode x_2 first. We assume x_2 is successfully decoded and the contribution of $\mathbf{h}_2x_2$ can be mitigated in $\mathbf{y}_2$ to form

$$\hat{\mathbf{y}}_1 = \begin{bmatrix} h_{1B} \\ h_{1R}wh_{RB} \end{bmatrix} x_1 + \begin{bmatrix} n_1(1) \\ h_{1R}wn_R + n_1(2) \end{bmatrix}.$$

Therefore, we will not have interference when decoding x_1. We thus obtain $\mathrm{SNR}_1 = |h_{1B}|^2 + \frac{|w|^2|h_{1R}|^2|h_{RB}|^2}{|w|^2|h_{1R}|^2+1}$.

C. Optimization Formulation and Adaptive Algorithm

In order to balance the two flows with fairness, we optimize the relay precoding and choose the receiver processing to maximize the minimum weighted SNR/SINR. We denote $\beta_\mathrm{B}, \beta_1 > 0$ to be the priority factors associated with the two flows. In our problem, the amount of interference is intermingled with the relay precoding. Thus, we cannot determine which decoding option to use beforehand. Our approach is to solve two different problems addressing different decoding options and choose the one with higher minimum weighted SNR/SINR.

Problem 1 (P1). Maximizing the minimum weighted S-NR/SINR with linear decoding:

$$\begin{aligned} \underset{w}{\text{maximize}} \quad & \min\left(\beta_\mathrm{B}\mathrm{SNR}_\mathrm{B},\ \beta_1\mathrm{SINR}_1\right) \\ \text{subject to} \quad & |w|^2\left(|h_{RB}|^2+|h_{R2}|^2+1\right) \leq 1 \\ & \mathrm{SINR}_1 \geq \mathrm{SINR}_2 \text{ in } (5). \end{aligned} \quad (7)$$

Problem 2 (P2). Maximizing the minimum weighted S-NR/SINR with SIC:

$$\begin{aligned} \underset{w}{\text{maximize}} \quad & \min\left[\beta_\mathrm{B}\min\left(\mathrm{SNR}_\mathrm{B},\ \mathrm{SINR}_2\right),\ \beta_1\mathrm{SNR}_1\right] \\ \text{subject to} \quad & |w|^2\left(|h_{RB}|^2+|h_{R2}|^2+1\right) \leq 1 \\ & \mathrm{SINR}_1 \leq \mathrm{SINR}_2 \text{ in } (6). \end{aligned} \quad (8)$$

where $\min\left(\mathrm{SNR}_\mathrm{B}, \mathrm{SINR}_2\right)$ comes from the rate requirement for x_2 in order to be decodable both at the BS and at UE 1.

1) Adaptive Algorithm: To maximize the minimum weighted SNR/SINR, we compare the results from P1 and P2 and choose the optimal solution. Both P1 and P2 are non-convex problems, where the global optimal solutions can be obtained via extensive numerical search over the complex field. This search is difficult to accomplish within reasonable computation time. Here, we resort to the structured solutions based on the bisection principle and the relevant feasibility problem similar to [9].

The detailed process is shown in Algorithm 1. First, we form two feasibility problems associated with P1 and P2, (9) and (10) to check whether the given r_0 and r_{0_SIC} (corresponding to the rate) can be satisfied, respectively. These feasibility problems are used in the one-dimensional bisection search to obtain the optimal values for P1 and P2, respectively. ϵ_r is the bisection threshold. The convergence proof for Part I or Part II of the algorithm can be easily constructed by contradiction and letting $\epsilon_r \to 0$, similar to *Appendix D* in [9].

Algorithm 1 Minimum weighted SNR/SINR maximization

Part I: solution for P1 (linear decoding at UE 1)
initialize r_min and r_max
repeat until $r_\mathrm{max} - r_\mathrm{min} \leq \epsilon_r$
I. set $r_0 = \frac{1}{2}(r_\mathrm{min} + r_\mathrm{max})$
II. solve the feasibility problem (9)
if (9) is feasible, $r_\mathrm{min} = r_0$
else $r_\mathrm{max} = r_0$

Part II: solution for P2 (non-linear SIC at UE 1)
initialize $r_{\mathrm{min}_\mathrm{SIC}}$ and $r_{\mathrm{max}_\mathrm{SIC}}$
repeat until $r_{\mathrm{max}_\mathrm{SIC}} - r_{\mathrm{min}_\mathrm{SIC}} \leq \epsilon_r$
I. set $r_{0_\mathrm{SIC}} = \frac{1}{2}(r_{\mathrm{min}_\mathrm{SIC}} + r_{\mathrm{max}_\mathrm{SIC}})$
II. solve the feasibility problem (10)
if (10) is feasible, $r_{\mathrm{min}_\mathrm{SIC}} = r_{0_\mathrm{SIC}}$
else $r_{\mathrm{max}_\mathrm{SIC}} = r_{0_\mathrm{SIC}}$

Minimum weighted SNR/SINR: $\max\left(r_0,\ r_{0_\mathrm{SIC}}\right)$

$$\begin{aligned} \text{find} \quad & w \\ \text{subject to} \quad & |w|^2\left(|h_{RB}|^2+|h_{R2}|^2+1\right) \leq 1,\ \beta_\mathrm{B}\mathrm{SNR}_\mathrm{B} \geq r_0 \\ & \beta_1\mathrm{SINR}_1 \geq r_0,\ \mathrm{SINR}_1 \geq \mathrm{SINR}_2 \text{ in } (5). \end{aligned} \quad (9)$$

$$\begin{aligned} \text{find} \quad & w \\ \text{subject to} \quad & |w|^2\left(|h_{RB}|^2+|h_{R2}|^2+1\right) \leq 1 \\ & \beta_\mathrm{B}\mathrm{SNR}_\mathrm{B} \geq r_{0_\mathrm{SIC}},\ \beta_\mathrm{B}\mathrm{SINR}_2 \geq r_{0_\mathrm{SIC}} \\ & \beta_1\mathrm{SNR}_1 \geq r_{0_\mathrm{SIC}},\ \mathrm{SINR}_1 \leq \mathrm{SINR}_2 \text{ in } (6). \end{aligned} \quad (10)$$

D. Optimal Solutions

Both (9) and (10) are with non-convex quadratic constraints. We apply the widely-used semidefinite relaxation (SDR) [11].

1) Notations: In order to homogenize (9) and (10) following [11], we use $\mathbf{b} = [w\ 1]^\mathrm{T}$. The power constraint at the relay is $\mathbf{b}^\mathrm{H}\mathbf{A}\mathbf{b} = \mathbf{b}^\mathrm{H}\left[|h_{RB}|^2+|h_{R2}|^2+1\quad 0; 0\quad 0\right]\mathbf{b} \leq 1$. We also have $\mathrm{SNR}_\mathrm{B} = \frac{\mathbf{b}^\mathrm{H}\mathbf{c}\mathbf{c}^\mathrm{H}\mathbf{b}}{\mathbf{b}^\mathrm{H}\mathbf{D}\mathbf{b}}$, $\mathrm{SINR}_1 = \frac{\mathbf{b}^\mathrm{H}\left(\mathbf{e}\mathbf{e}^\mathrm{H}+\mathbf{F}\right)\mathbf{b}}{\mathbf{b}^\mathrm{H}\left(\mathbf{g}\mathbf{g}^\mathrm{H}+\mathbf{J}+\mathbf{K}\right)\mathbf{b}}$, $\mathrm{SINR}_2 = \frac{\mathbf{b}^\mathrm{H}\left(\mathbf{e}\mathbf{e}^\mathrm{H}+\mathbf{g}\mathbf{g}^\mathrm{H}+\mathbf{J}\right)\mathbf{b}}{\mathbf{b}^\mathrm{H}\left(\mathbf{F}+\mathbf{K}\right)\mathbf{b}}$, $\mathrm{SNR}_1 = |h_{1B}|^2 + \frac{\mathbf{b}^\mathrm{H}\mathbf{L}\mathbf{b}}{\mathbf{b}^\mathrm{H}\mathbf{K}\mathbf{b}}$ where $\mathbf{c}^\mathrm{H} = [h_{BR}h_{R2}\ \ h_{B2}]$, $\mathbf{e}^\mathrm{H} = [\left(h_{1B}h_{R2} - h_{12}h_{RB}\right)h_{1R}\ \ h_{1B}h_{12}]$,

$$\mathbf{D} = \begin{bmatrix} |h_{BR}|^2 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{K} = \begin{bmatrix} |h_{1R}|^2 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{g}^\mathrm{H} = [h_{1R}h_{R2}\ h_{12}]$$

$$\mathbf{F} = \begin{bmatrix} \left(|h_{RB}|^2+|h_{1B}|^2\right)|h_{1R}|^2 & 0 \\ 0 & |h_{1B}|^2 \end{bmatrix},$$

$$\mathbf{J} = \begin{bmatrix} |h_{12}|^2 |h_{1R}|^2 & 0 \\ 0 & |h_{12}|^2 \end{bmatrix}, \mathbf{L} = \begin{bmatrix} |h_{RB}|^2 |h_{1R}|^2 & 0 \\ 0 & 0 \end{bmatrix}.$$

$\mathrm{SINR}_1 \geq \mathrm{SINR}_2$ is written as $\mathbf{b}^{\mathrm{H}} \left(\mathbf{g}\mathbf{g}^{\mathrm{H}} + \mathbf{J} - \mathbf{F}\right) \mathbf{b} \geq 0$.

2) SDR framework: By introducing $\mathbf{X} = \mathbf{b}\mathbf{b}^{\mathrm{H}}$, we can solve (9) and (10) via resorting to the SDR and discarding the non-convex constraint $\mathrm{Rank}(\mathbf{X}) = 1$ [11]:

$$\begin{aligned} &\text{find} && \mathbf{X} && (11)\\ &\text{subject to} && \mathrm{Tr}\left(\mathbf{A}\mathbf{X}\right) \leq 1,\ \mathrm{Tr}\left[\left(\mathbf{c}\mathbf{c}^{\mathrm{H}} - r_0\mathbf{D}\right)\mathbf{X}\right] \geq 0 \\ &&& \mathrm{Tr}\left[\left(\mathbf{e}\mathbf{e}^{\mathrm{H}} + \mathbf{F} - r_0\mathbf{g}\mathbf{g}^{\mathrm{H}} - r_0\mathbf{J} - r_0\mathbf{K}\right)\mathbf{X}\right] \geq 0 \\ &&& \mathrm{Tr}\left[\left(\mathbf{g}\mathbf{g}^{\mathrm{H}} + \mathbf{J} - \mathbf{F}\right)\mathbf{X}\right] \geq 0,\ \mathbf{X} \succeq 0,\ \mathbf{X}(2,2) = 1. \end{aligned}$$

$$\begin{aligned} &\text{find} && \mathbf{X} && (12)\\ &\text{subject to} && \mathrm{Tr}\left(\mathbf{A}\mathbf{X}\right) \leq 1,\ \mathrm{Tr}\left[\left(\mathbf{c}\mathbf{c}^{\mathrm{H}} - r_{0_{\mathrm{SIC}}}\mathbf{D}\right)\mathbf{X}\right] \geq 0 \\ &&& \mathrm{Tr}\left[\left(\mathbf{e}\mathbf{e}^{\mathrm{H}} + \mathbf{g}\mathbf{g}^{\mathrm{H}} + \mathbf{J} - r_{0_{\mathrm{SIC}}}\mathbf{F} - r_{0_{\mathrm{SIC}}}\mathbf{K}\right)\mathbf{X}\right] \geq 0 \\ &&& \mathrm{Tr}\left[\mathbf{L}\mathbf{X} + \left(|h_{1B}|^2 - r_{0_{\mathrm{SIC}}}\right)\mathbf{K}\mathbf{X}\right] \geq 0, \\ &&& \mathrm{Tr}\left[\left(\mathbf{F} - \mathbf{g}\mathbf{g}^{\mathrm{H}} - \mathbf{J}\right)\mathbf{X}\right] \geq 0,\ \mathbf{X} \succeq 0,\ \mathbf{X}(2,2) = 1. \end{aligned}$$

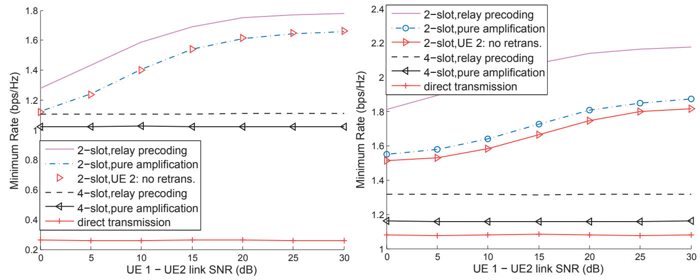
where $\mathbf{X} \succeq 0$ means that $\mathbf{X}$ is positive semidefinite and $\mathbf{X}(2,2) = 1$ comes from $\mathbf{b} = [w\ 1]^{\mathrm{T}}$. Notice that the optimal $\mathbf{X}$ could have $\mathrm{Rank}(\mathbf{X}) > 1$, where the randomization technique [11] can be applied for near global optimal solution.

3) Initial Range: A rough choice for $r_{\max}$ and $r_{\max_{\mathrm{SIC}}}$ is derived from $\mathrm{SNR_B}$ maximization, where the phase of w is easily determined and $|w|$ is derived based on [10]. Then $r_{\min} = r_{\min_{\mathrm{SIC}}} = 0$, $r_{\max} = r_{\max_{\mathrm{SIC}}} = \beta_{\mathrm{B}}\mathrm{SNR}_{\mathrm{B,max}}$.

IV. Numerical Results

We present the results for the minimum rate of the two flows, with $\beta_{\mathrm{B}} = \beta_1 = 1$ and $\epsilon_r = 0.01$. As the weak direct links h_{B2} and h_{1B} are active, we include the benchmark relying on transmissions using the direct links. We also include the trivial pure amplification relaying where $w = \sqrt{\frac{1}{|h_{RB}|^2 + |h_{R2}|^2 + 1}}$ and the 2-slot benchmark where UE 2 does not retransmit in the 2nd slot. We consider the realistic average SNR conditions for different links, $\gamma_{BR} = 20\,\mathrm{dB}$, $\gamma_{1R} = \gamma_{R2} = 20\,\mathrm{dB}$, $\gamma_{1B} = \gamma_{B2} = 0\,\mathrm{dB}$ or $10\,\mathrm{dB}$, as the average SNR of the links between UEs to the BS is weak in this cell-edge setup. To evaluate the impact of the overhearing link, we vary the average SNR of the overhearing link (γ_{12}). The channels are assumed to be independently Rayleigh-faded.

From Fig. 3, we observe that the proposed transmission scheme improves the rate dramatically compared to the 4-slot scheme and the direct transmission. When $\gamma_{1B} = 0\,\mathrm{dB}$, the rate improvements are 18%-63% compared to the 4-slot scheme. When $\gamma_{1B} = 10\,\mathrm{dB}$, the gains are 38%-69%. The corresponding spectral efficiency gains are at similar levels. In addition, the gain from optimal relay precoding compared to pure amplification is obvious, and larger γ_{1B} leads to larger rate increase. The rate loss from the 2-slot benchmark without retransmission at UE 2 coincides with *Remark 1*. The 2-slot one without retransmission performs nearly the same as the pure amplification when $\gamma_{1B} = 0\,\mathrm{dB}$; it is worse than the amplification when γ_{1B} becomes larger. As γ_{12} becomes better, the rate for the overhearing-based scheme increases no matter whether relay is performing precoding or not. It is worth mentioning that the 4-slot scheme and the direct transmission are not dependent on the overhearing link.



(a) $\gamma_{1B} = 0\,\mathrm{dB}$ (b) $\gamma_{1B} = 10\,\mathrm{dB}$

Fig. 3. Minimum rate performance.

V. Conclusion

We propose a novel overhearing-based scheme in a cell-edge scenario, where interference is intentionally allowed and used as side information at the receiver. Combined with the joint relay precoding and receiver processing, the proposed overhearing-based scheme is shown to improve the minimum rate of the multiple flows significantly.

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