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Spectral Efficiency Enhancement with Interference Cancellation for Wireless Relay Network

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Abstract— **The introduction of relaying into wireless communication system for coverage enhancement can cause severe decrease of spectral efficiency due to the requirement on extra radio resource. In this paper, we propose a method to increase spectral efficiency in such a wireless relay network by employing an interference cancellation technique. We focus on a typical scenario of relaying in a cellular system, where a mobile station (MS) requires the help of a relay station (RS) to communicate with the base station (BS). In such a case, interference cancellation can be used to achieve a small reuse distance of identical radio resource. We analyze a simple scenario with BS, single RS, and 2 MSs, and show that the proposed method has significant potential to enhance spectral efficiency in wireless relay networks.**

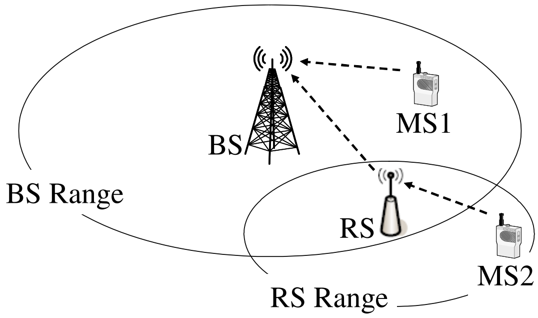

Fig. 1. Considered Scenario with 1 BS, 1 RS, and 2 MSs.

I. INTRODUCTION

The deployment of relay stations (RSs) in wireless communication systems (especially cellular systems) has been widely discussed in order to increase the system coverage [1][2]. Fig. 1 shows a typical up–link (from mobile station (MS) to base station (BS)) scenario to use RS for supporting a MS in an outage region of a BS. As shown in the figure, MS2 is located outside the communication range of BS. In this case, RS deployed by a system operator can relay signal from MS2 to BS, which enables MS2 to be served by the corresponding BS. Although the service area of BS can be extended by using such a relaying, extra radio resource is required to serve MS2: the transmission from MS2 to BS via RS needs 2 hops, and we need to allocate orthogonal radio resource to 2 separate links (RS–BS and MS2–RS) in order to achieve the end-to-end transmission. This increases the required radio resource, which has been considered as one of major drawbacks to utilize relaying in cellular systems.

In order to keep the required radio resource as small as possible, efficient radio resource allocation for wireless relay networks has been proposed and investigated. There have been a lot of works on efficient resource management, such as channel assignment and power control, to reduce the interference among different links (i.e. co-channel interference) in cellular systems with relaying [3], [4]. In these approaches, identical radio resource is reused by different links if they do not interfere with each other. For example, in Fig. 1, MS1 tries to directly communicate with BS. If MS1 is located far from RS, the links MS1–BS and MS2–RS can use the same radio resource as each transmission does not cause interference at the corresponding receivers due to signal attenuation. By achieving such a small reuse distance, the spectral efficiency can be significantly improved. However, there can be large area within a cell where MS1's signal can reach RS. In this case, the conventional approach does not enable MS1 and MS2 to use the identical radio resource as the transmission from MS1 to BS interferes with MS2's signal at RS. Therefore, three orthogonal radio resources are required to cope with the situation shown in Fig. 1, i. e., orthogonal resources to MS1–BS, MS2–RS, and RS–BS links.

In this paper, we propose an approach which can further reduce the reuse distance by assigning identical radio resource to different users even if they interfere with each other, i.e., MS1–BS and MS2–RS links in the example of Fig. 1. The interference caused at RS is cancelled at the final destination (e.g. BS) in an efficient way with a priori information. This allows the use of identical radio resource even more densely, and reduces significantly the required radio resource to support the increased number of links in wireless relay networks. Such an approach to increase the spectral efficiency with interference cancellation has been investigated in several literatures. For instance, in [5][6][7], relaying techniques with interference cancellation for bi–directional traffic have been proposed and investigated. Another technique employing interference cancellation with two amplify–and–forward relays has been proposed in order to avoid a loss in spectral efficiency due to half–duplex nature of relaying for uni–directional traffic[8]. The proposed technique improves spectral efficiency for delivering signal from a source to a destination when there is no direct link between them. Our approach also focuses on uni–directional traffic, but tries to improve spectral efficiency by multiplexing signals from different users with single relay when there is possibility for one of users to connect directly to the corresponding destination.

The rest of the paper is organized as follows: In Sec. II, we present system model and basic idea of our proposed relaying with interference cancellation. In Sec. III, we theoretically analyze bit error probability (BEP) performance of the proposed method with a simple scenario and show numerical results, which exhibits the effectiveness of the proposed method in terms of spectral efficiency. Sec. IV concludes the paper with possible future work.

II. System Model and Basic Idea

A. System Model

In order to illustrate the basic idea of our proposed method, we consider a simple scenario with a BS, a RS, and 2 MSs as shown in Fig. 1. We assume a half-duplex RS, i. e., RS cannot transmit and receive signals simultaneously. We focus on up-link transmission where the increase in computational complexity at BS implied by the proposed technique can be well–tolerated. We assume that BS knows perfectly the channel state information (CSI) for all BS-MSs and RS-MSs links. If the system is based on time division duplexing (TDD) as considered in IEEE 802.16 [9], these CSI are obtained at MS by using the pilot signals transmitted by BS and RS during the down-link frame, and are fed back to BS directly or via RS. By assuming channel reciprocity for each link, we can consider that BS has the CSI for all BS–MSs and RS–MSs links. We also assume that BS has perfect knowledge about CSI for BS–RS links. The narrow-band channel (e. g., one sub–channel in orthogonal frequency division multiple access (OFDMA) system) is assigned to each link, and is assumed to follow flat fading. Furthermore, the block Rayleigh fading is assumed, where the amplitude of channel is constant during the allocated time slot, but varies slot-by-slot with Rayleigh distribution.

B. Basic Idea

For supporting relayed transmission from MS2 to BS, a 2–phase transmission is required: in the first phase, MS2 transmits its signal to RS, then in the second phase, RS forwards the signal to BS. Here, 2 types of forwarding methods can be considered, Amplify–and–Forward (AF) and Decode–and–Forward (DF). With AF, RS amplifies the signal received during the first phase, and then forwards it to BS in the second phase. With DF, RS decodes the signal received during the first phase, then encodes and forwards it to BS in the second phase. In any case, when we try to support direct transmission from MS1 to BS simultaneously, in the conventional approach, orthogonal resource is allocated to MS1 so that it does not interfere with the transmission from MS2 to RS or from RS to BS. That is, the conventional approach requires at least 3 units of orthogonal radio resource to support the transmission in Fig. 1.

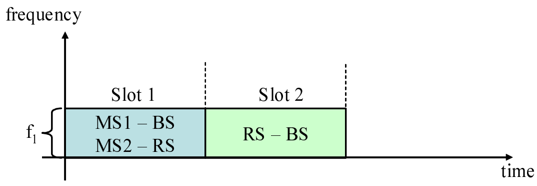

Fig. 2. An example of radio resource allocation with the proposed method to support the target scenario with 1 BS, 1 RS, and 2 MSs.

In order to reduce the required radio resource for relayed transmission, we propose a relaying method with interference cancellation (IC). In the proposed method, unlike the conventional transmission, we allow allocation of *identical* radio resource to MS1 → BS and MS2 → RS links in the first phase. An example of resource allocation is shown in Fig. 2[1]. Here, the first time slot is allocated to both MS1–BS and MS2–RS links. In the second time slot, RS forwards the received signal to BS. The received signals during the first phase at BS and RS can be respectively expressed as:

$$y_{BS}^{Ph1} = h_{1B}x_1 + h_{2B}x_2 + n_{BS}^{Ph1} \tag{1}$$

$$y_{RS}^{Ph1} = h_{1R}x_1 + h_{2R}x_2 + n_{RS} \tag{2}$$

where x_1 and x_2 are the transmitted symbols by MS1 and MS2, respectively, and n_{BS}^{Ph1} and n_{RS} are respectively the Gaussian noise at BS and RS with mean 0 and variance σ^2. We assume that the average energy per transmitted symbol is always normalized to 1. The instantaneous channel coefficients are defined as h_{1B}, h_{2B}, h_{1R}, and h_{2R} for MS1 → BS, MS2 → BS, MS1 → RS, and MS2 → RS links, respectively. In the end of the first phase, BS decodes x_1 from y_{BS}^{Ph1}. *A key observation here is that MS2 is far enough from BS to be considered as an outage user, therefore the term $h_{2B}x_2$ in eq. (1) is small enough not to cause severe interference for decoding the signal from MS1.* Therefore, BS has high probability to correctly decode x_1 after the first phase. In the second phase, RS amplifies and forwards the signal expressed in eq. (2) with the amplification factor β_{IC}. β_{IC} is calculated so that the transmit energy per symbol time of RS is 1, i.e.,

$$\beta_{IC} = \sqrt{\frac{1}{|h_{1R}|^2 + |h_{2R}|^2 + \sigma^2}}. \tag{3}$$

This signal is received at BS as:

$$\begin{aligned} y_{BS}^{Ph2} &= \beta_{IC}h_{RB}y_{RS}^{Ph1} + n_{BS}^{Ph2} \\ &= \beta_{IC}h_{RB}h_{1R}x_1 + \beta_{IC}h_{RB}h_{2R}x_2 \\ &\quad + \beta_{IC}h_{RB}n_{RS} + n_{BS}^{Ph2} \end{aligned} \tag{4}$$

[1]For simplicity, we ignore guard intervals and consider a simple time division frame with single frequency channel in this example. Practically, radio resource allocation algorithms need to be designed for the proposed scheme to be applied to multiple channel system such as orthogonal frequency division multiple access (OFDMA).

where h_{RB} is the instantaneous channel coefficient for RS → BS link and n_{BS}^{Ph2} is a Gaussian noise with mean 0 and variance σ^2. In eq. (4), signals transmitted by MS1 and MS2 interfere with each other as a consequence of allocation of identical radio resource during the first phase. However, as stated above, *BS can have x_1 as a priori information with high probability as a result of decoding in the end of the first phase.* Therefore, if x_1 has been correctly decoded, BS subtracts the contribution of x_1 from y_{BS}^{Ph2} and obtains the following signal:

$$y_{BS}^{Ph2'} = \beta_{IC} h_{RB} h_{2R} x_2 + \beta_{IC} h_{RB} n_{RS} + n_{BS}^{Ph2} \quad (5)$$

which is equivalent to an interference free channel for receiving x_2.

The proposed method described above only requires 2 separate radio resource for BS to obtain the signals from MS1 and MS2. If these signals can be decoded with the required reliability, the proposed scheme can significantly reduce the radio resource required to support the MS in outage.

III. Performance Evaluation

A. Bit Error Probability Analysis

In this section, we analyze the BEP performance of the proposed method, taking account of error propagation through successive IC. For simplicity, we assume that MSs employ uncoded binary phase shift keying (BPSK) as their modulation method.

With the proposed scheme, in the end of the first phase, BS observes the signal given by eq. (1). The BEP for decoding the signal from MS1 can be expressed as:

$$\begin{aligned} P_e^{IC1} &= \frac{1}{2} Q\left(\sqrt{\frac{|h_{1B}|^2}{\sigma^2}}\left(1 + \frac{h_{2B}}{h_{1B}}\right)\right) \\ &\quad + \frac{1}{2} Q\left(\sqrt{\frac{|h_{1B}|^2}{\sigma^2}}\left(1 - \frac{h_{2B}}{h_{1B}}\right)\right) \end{aligned} \quad (6)$$

where the Q function is defined as $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-t^2/2} dt$ [10]. The first term in eq. (6) corresponds to BEP when the bit transmitted by MS2 (i. e., x_2) is 1 while the second term corresponds to $x_2 = -1$. The BEP for decoding the signal of MS2 in the end of the second phase depends on the decoding result of MS1's signal as well as the bit transmitted by MS1, and we have the following 3 cases.

1) x_1 is correctly decoded (with probability $1 - P_e^{IC1}$). After subtraction of the contribution of x_1, BS observes the signal given by eq. (5).
2) x_1 is not correctly decoded and the transmitted bit by MS1 is 1 (with probability $\frac{1}{2} P_e^{IC1}$).
In this case, BS obtains the following signal:

$$\begin{aligned} y_{BS}^{Ph2'} &= \beta_{IC} h_{RB} h_{2R} x_2 + 2\beta_{IC} h_{RB} h_{1R} \\ &\quad + \beta_{IC} h_{RB} n_{RS} + n_{BS}^{Ph2} \end{aligned} \quad (7)$$

3) x_1 is not correctly decoded and the transmitted bit by MS1 is -1 (with probability $\frac{1}{2} P_e^{IC1}$).

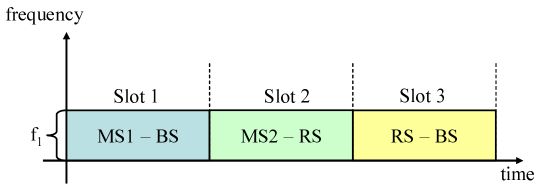

Fig. 3. An example of radio resource allocation with AF scheme to support the target scenario with 1 BS, 1 RS, and 2 MSs.

In this case, BS obtains the following signal:

$$\begin{aligned} y_{BS}^{Ph2'} &= \beta_{IC} h_{RB} h_{2R} x_2 - 2\beta_{IC} h_{RB} h_{1R} \\ &\quad + \beta_{IC} h_{RB} n_{RS} + n_{BS}^{Ph2} \end{aligned} \quad (8)$$

By obtaining BEP for the above 3 cases, the probability of bit error for MS2 can be obtained as follows:

$$\begin{aligned} P_e^{IC2} &= \left(1 - P_e^{IC1}\right) Q\left(\sqrt{A}\right) \\ &\quad + \frac{P_e^{IC1}}{2} Q\left(\sqrt{A}\left(1 + 2\frac{h_{1R}}{h_{2R}}\right)\right) \\ &\quad + \frac{P_e^{IC1}}{2} Q\left(\sqrt{A}\left(1 - 2\frac{h_{1R}}{h_{2R}}\right)\right) \end{aligned} \quad (9)$$

where A is defined as

$$A = \frac{\beta_{IC}^2 |h_{RB}|^2 |h_{2R}|^2}{\sigma^2 + \beta_{IC}^2 |h_{RB}|^2 \sigma^2}. \quad (10)$$

We compare the proposed scheme with the ordinary AF scheme without IC as well as the direct transmission without relaying. For AF relay without IC, in the first phase, MS2 transmits its signal to RS by using different radio resource from the direct transmission of MS1 to BS. RS amplifies and forwards the received signal from MS2 to BS in the second phase. An example of resource allocation with AF scheme is shown in Fig. 3. In this case, the BEP at BS during the first phase for MS1 is expressed as

$$P_e^{AF1} = Q(\sqrt{|h_{1B}|^2/\sigma^2}). \quad (11)$$

For MS2, with the amplification factor

$$\beta_{AF} = \sqrt{\frac{1}{|h_{2R}|^2 + \sigma^2}}, \quad (12)$$

BEP at BS can be obtained as:

$$P_e^{AF2} = Q\left(\sqrt{\frac{\beta_{AF}^2 |h_{RB}|^2 |h_{2R}|^2}{\beta_{AF}^2 |h_{RB}|^2 \sigma^2 + \sigma^2}}\right) \quad (13)$$

For the direct transmission without the use of relay, MS1 and MS2 transmit signals directly to BS by using orthogonal radio resource as shown in Fig. 4. BEP for decoding signals from MS1 is the same as AF case. Similarly, BEP for MS2 is expressed as

$$P_e^{Direct2} = Q(\sqrt{|h_{2B}|^2/\sigma^2}). \quad (14)$$

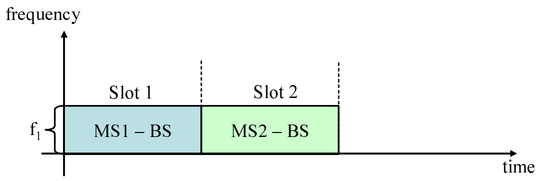

Fig. 4. An example of radio resource allocation with the direct transmissions to support the target scenario with 1 BS, 1 RS, and 2 MSs.

B. Numerical Results

We evaluate the average bit error rate (BER) based on the equations derived above, assuming independent Rayleigh fading for each link. We make 100000 iterations with different channel realizations for a given set of average signal to noise ratio (SNR), and obtain the average BER as the average of the probability of error over these iterations.

Figs. 5 and 6 show BER of the relaying with IC, AF relaying without IC, and direct transmission against the average SNR at MS2–BS link ($\overline{\gamma}_{2B}$) when the average SNR at MS1–BS link is set to 35 [dB] and 40 [dB], respectively. For all the cases, we set the average SNR at MSs–RS link to 40 [dB], and RS–BS link, 50 [dB]. Looking at the performance for relaying with the proposed IC in Fig. 5, we can see that BER degrades as $\overline{\gamma}_{2B}$ becomes higher. This is because the signal transmitted by MS2 can result in higher interference for MS1 as the link condition between MS2 and BS becomes better. The decoding error of MS1 can adversely affect the decoding of MS2 signal in the second phase of the relaying with IC, therefore, BER for MS2 is also degraded as $\overline{\gamma}_{2B}$ becomes higher.

Let us now analyze the results in Fig. 5 assuming that the minimum required BER of the system is 10^{-2}. The direct transmission cannot offer BER less than 10^{-2} for MS2 in this region of average SNR, therefore, the system has to employ relaying scheme in order to satisfy the required reliability. When $\overline{\gamma}_{2B}$ is larger than around 2 [dB], AF relaying without IC should be used as this is the only scheme which can offer the BER of 10^{-2} for both MSs. On the other hand, when $\overline{\gamma}_{2B}$ is less than around 2 [dB], the relaying with IC can offer the target BER. Furthermore, it requires less radio resource than the AF relaying (just 2/3 of radio resource), therefore, for this region, the relaying with the proposed IC should be used. Fig. 6 shows the same tendency as Fig. 5. However, we can notice that, as the average link condition at MS1–BS link becomes better, we have more region where the spectral efficiency can be improved by the relaying with the proposed IC. For example, from Fig. 6, we can see that the relaying with the proposed IC should be always utilized for $\overline{\gamma}_{2B}$ less than around 9 [dB] when the target BER of the system is 10^{-2}.

Next, we evaluate overall spectral efficiency of the above three schemes, which are respectively defined as

$$SE_{IC} = (R \cdot (1 - BER1_{IC}) + R \cdot (1 - BER2_{IC}))\,/2$$

$$SE_{AF} = (R \cdot (1 - BER1_{AF}) + R \cdot (1 - BER2_{AF}))\,/3$$

$$SE_{DR} = (R \cdot (1 - BER1_{DR}) + R \cdot (1 - BER2_{DR}))\,/2$$

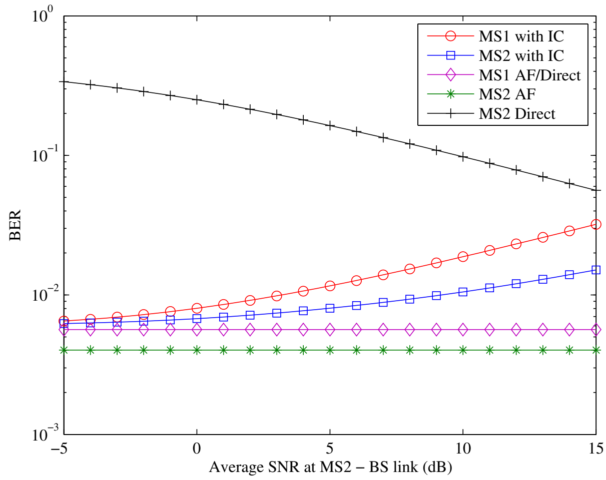

Fig. 5. BER against average SNR at MS2-BS link when average SNR at MS1-BS link is set to 35 [dB], MSs-RS links to 40 [dB], and RS-BS link to 50 [dB].

where $R = 1$ [bit/sec/Hz] is the spectral efficiency of BPSK transmission, $BER1$ and $BER2$ represent the average BER of MS1 and MS2, respectively. In the above equations, the spectral efficiency for the proposed scheme and direct transmission is divided by 2 as they require 2 units of orthogonal resource while it is divided by 3 for AF as 3 units of resource is required for supporting MS1 and MS2.

Fig. 7 shows the performance of overall spectral efficiency. From this figure, we can see that the AF relaying has much lower spectral efficiency than the other 2 schemes due to the higher amount of required radio resource. On the other hand, by employing our proposed IC, we can drastically improve the spectral efficiency even if the relaying is introduced into the system. When $\overline{\gamma}_{2B}$ becomes worse, the system without relay suffers from degraded spectral efficiency due to high BER at MS2–BS link. Our proposed relaying scheme can support such a user in outage without the cost of radio resource, which can lead to higher spectral efficiency as shown in this figure.

IV. Conclusions

In this paper, we have proposed a method of relaying with IC, which can overcome a problem on the degradation of spectral efficiency due to the extra radio resource required to support relayed links. We have investigated a typical scenario of relaying in a cellular system, where a MS requires the help of a RS to communicate with the BS. We have shown that the proposed interference cancellation can be used to achieve a small reuse distance of identical radio resource to support the MS in the outage region. With numerical results, we have shown that the proposed method is especially effective when one of MSs connected to BS directly has better channel condition. The proposed scheme has significant potential to improve spectral efficiency of cellular system employing relay transmission. Our future work includes the design of practical radio resource allocation algorithm for the

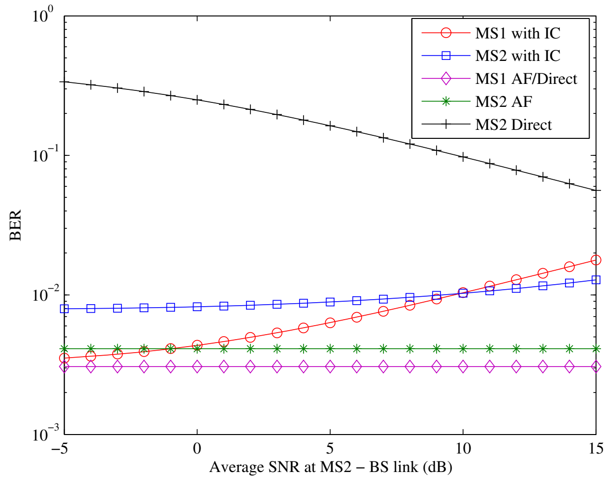

Fig. 6. BER against average SNR at MS2 - BS link when average SNR at MS1 - BS link is set to 40 [dB], MSs-RS links to 40 [dB], and RS-BS link to 50 [dB].

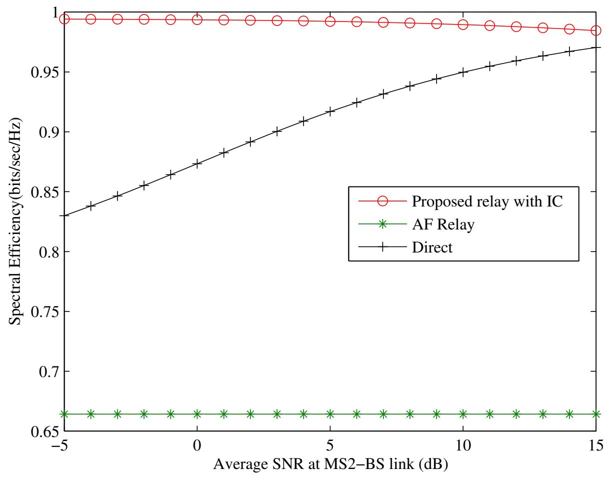

Fig. 7. Spectral Efficiency against average SNR at MS2 - BS link when average SNR at MS1 - BS link is set to 40 [dB], MSs-RS links to 40 [dB], and RS-BS link to 50 [dB].

proposed scheme to be applied to IEEE 802.16 system, the analysis with imperfect CSI, and system-level evaluation when adaptive modulation and coding (AMC) is considered. The other interesting work is to apply multiple input and multiple output (MIMO) processing to serve MSs within a cell at any location with user–pairing strategies.

Acknowledgement

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