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Bidirectional Cooperative Relaying

Prabhat Kumar Upadhyay and Shankar Prakriya
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1. Introduction

Modern radio communication systems aim to enhance throughput and reliability in wireless networks with limited resources. Wireless mobile communication over a radio channel is limited by multipath, fading, path loss, shadowing, and interference. Spatial diversity techniques are widely adopted to combat fading and other channel impairments. Cooperative communications have been recently developed to harness spatial diversity even with single-antenna terminals. The distributed terminals cooperate by relaying each other's message in order to realize a virtual antenna array and achieve cooperative diversity. Cooperative relaying has become a promising technique for enhancing coverage, reliability and throughput of wireless networks with stringent spectrum and power constraints. They have found applications in wireless cellular, ad hoc/sensor networks, WiFi/WiMAX, etc.

Dual-hop three-terminal channels wherein a relay terminal assists in the communication between source and destination terminals through some cooperation protocol are of particular interest. Relaying can be performed in either full-duplex or half-duplex mode. Full-duplex relaying allows the radios to receive and transmit simultaneously using the same frequency channel and hence achieves higher spectral efficiency. However, the large difference in power levels of the transmit and receive signals (typically 100-150 dB) makes its implementation practically difficult. In half-duplex mode, the reception and transmission at the radios are performed in time/frequency/code division orthogonal channels. Half-duplex systems are therefore practically feasible. The major drawback of half-duplex relaying is a substantial loss in spectral efficiency. This is because half of the channel resources are allocated to the relay for cooperation, which reduces the overall data rate.

While much research has focused on exploiting cooperative diversity, little effort has been directed towards improving spectral efficiency under half-duplex constraints. The authors in (Rankov & Wittneben, 2007) propose a new two-phase two-way relaying protocol where a bidirectional connection between two terminals is established with one half-duplex relay. Under this scheme, two connections are realized in the same physical channel, thereby improving the spectral efficiency. Referred to as the Two-Way Relay Channel (TWRC) in literature, this pragmatic approach has become a focus of extensive recent research. An example of a TWRC is the downlink and uplink in wireless mobile networks whereby both the base station and the mobile station need to communicate via an assisting relay station due to the lack of a reliable direct link. This is advantageous in the case when the mobile is highly shadowed or near the cell edge. It is important to note that even when a direct link of sufficient quality is available, it cannot be utilized in two-phase TWRC because otherwise both terminals need to transmit and receive simultaneously in the same phase.

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In a separate remarkable development, the emergence of network coding (Ahlswede et al., 2000) has changed the way communication networks are designed. Network coding allows the intermediate nodes to combine and code the data from multiple sources in order to enhance the overall network throughput. Originally proposed for wired communication networks, there has recently been much interest in applying network coding to wireless relay networks (Hao et al., 2007). In view of the spectral efficiency loss due to half-duplex mode, a coded bidirectional relaying scheme with three transmission phases has been proposed independently in (Wu et al., 2005) and (Larsson et al., 2006). The authors in (Kim et al., 2008) compared and analyzed the performance of various half-duplex bidirectional relaying protocols. The idea of network coding has been further exploited for the bidirectional cooperation in (Hausl & Hagenauer, 2006); (Baik & Chung, 2008); (Cui et al., 2008a); (Cui et al., 2008b). It has been shown in (Katti et al., 2007b) that wireless two-way relaying coupled with network coding achieves higher data rates.

Two-way or bidirectional relaying is flexible to allow various physical-layer transmission techniques. A lot of research is in progress on topics like TWRC capacity region or achievable rate region (Oechtering et al., 2008), channel estimation (Zhao et al., 2008); (Gao et al., 2008), multi-hop relaying (Vaze & Heath Jr., 2008), resource allocation (Agustin et al., 2008), distributed space-time coding (Cui et al., 2008c), distributed relay selection (Ding et al., 2009) and the like, using various physical layer signalling techniques, OFDM for example (Ho et al., 2008); (Jit-vanichphaibool et al., 2008). Also, the bidirectional relaying scheme has been extended to the multi-user scenario (Chen & Yener, 2008); (Esli & Wittneben, 2008). Multiple-Input Multiple-Output (MIMO) bidirectional relaying (Unger & Klein, 2007); (Gunduz et al., 2008) is a hot research area and is often envisioned to further improve the link reliability and bidirectional throughput of wireless systems.

The aim of this chapter is to present, in a unified fashion, the state-of-the-art in this new area of bidirectional cooperative communication, to elaborate on the recent analytical findings and their significance, to support them with various simulation results, and to discuss future areas of research.

2. Cooperative Communications

Cooperative communication systems seek to enhance the link capacity and transmission reliability through cooperation between distributed radios. They exploit the broadcasting nature of the wireless medium and allow single-antenna terminals to cooperate through relaying. The conventional form of cooperation is multi-hopping, where a source communicates with a destination via a series of dedicated relays. It is mainly used to combat signal attenuation in long-range communication and it does not provide any diversity advantages. The key issue in cooperative communications is resource sharing among network nodes. A three-terminal network acts as a fundamental unit in cooperative communication and has been widely studied in the literature.

The three-terminal relay channel model, introduced in (Meulen, 1971), comprises a source T_1, a destination T_2, and a dedicated relay R (as shown in Figure 1). The relay aids in communicating information from source to destination without actually being an information source or sink. It was assumed that all nodes operate in the full-duplex mode, so the system can be viewed as a Broadcast Channel (BC) at the source, and a Multiple Access Channel (MAC) at the destination. The upper and lower bounds on the capacity of the non-faded relay channel, derived in (Meulen, 1971), were improved significantly in (Cover & Gamal, 1979). Later, models with multiple relays have been investigated in cooperation literature. However, the
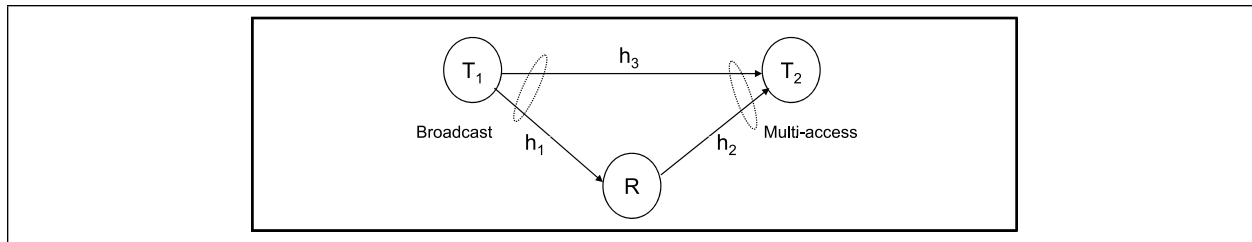
Fig. 1. The wireless relay channel.

recent developments are motivated by the user cooperation (Sendonaris et al., 2003) and co-operative diversity (Laneman et al., 2004) in a fading channel. The authors in (Sendonaris et al., 2003) introduced user cooperation by allowing the relay to transmit its own independent information. Cooperative diversity introduced in (Laneman et al., 2004) is realized by relaying and user cooperation. They proposed different cooperative diversity protocols and analyzed their performance in terms of outage probability. The terms Amplify-&-Forward (AF) and Decode-&-Forward (DF) were introduced in their work.

2.1 Cooperative Relaying Protocols

Consider a three-terminal wireless network as shown in Figure 1 in which terminal T_1 wants to transmit data to terminal T_2 with the help of a relay terminal R. In view of cellular network, T_1 and R might be mobile stations and T_2 might be a base station. Under cooperative relaying strategy, T_1 and a suitable R can share their resources, such as power and bandwidth, to transmit the information of T_1. This cooperation might provide diversity because, even if the direct link between T_1 and T_2 is severely faded, the information might be successfully transmitted via R. It is assumed that the relay node operates in half-duplex mode and has no
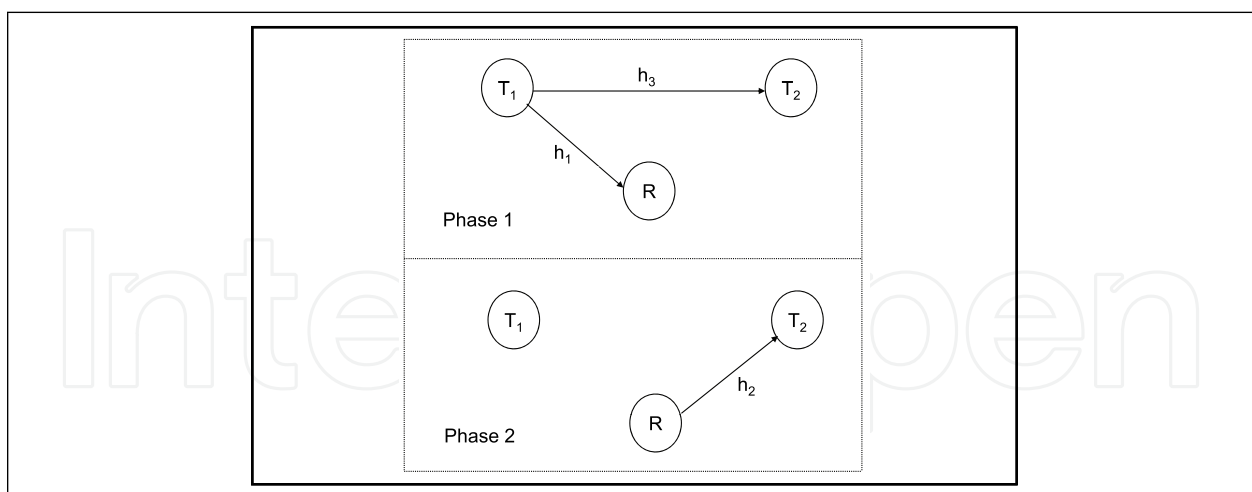
Fig. 2. Orthogonal relay transmission.

message of its own to transmit. Figure 2 illustrates the channel allocation for time-division approach with two orthogonal phases to ensure half-duplex operation. In phase 1, T_1 sends information to its destination T_2 and the information is also received by the relay R at the same time. In phase 2, the relay R can help the source T_1 by forwarding or retransmitting the information to the destination. However, there is 50% loss in spectral efficiency because of transmission in two phases.

The source and relay nodes can share their resources on the basis of some cooperation strategies to achieve the highest throughput possible for any given coding scheme. Based on different signal processing schemes employed at the relays, the cooperative relaying methods are classified into fixed relaying and adaptive relaying (Laneman et al., 2004). For fixed relaying, the relay can amplify its received signal subject to its power constraint, or decode, re-encode, and then retransmit the messages, referred to (respectively) as Amlify-&-Forward (AF) or Decode-&-Forward (DF). This scheme has the advantage of easy implementation, but the disadvantage of low spectral efficiency. This is because half of the channel resources are allocated to the relay for transmission. Adaptive relaying schemes build upon fixed relaying and adapt based upon Channel State Information (CSI) between cooperating terminals (selective relaying) or upon limited feedback from the destination (incremental relaying). Selective relaying allows transmitting terminals to select a suitable cooperative or non-cooperative action based on the measured SNR between them. If the received SNR at the relay exceeds a certain threshold, the relay performs DF operation on the message. Otherwise, if the channel between T_1 and R has severe fading such that SNR falls below the threshold, the relay idles. Incremental relaying improves upon the spectral efficiency of both fixed and selective relaying by exploiting limited feedback from the destination and relaying only when direct link from source to destination has an SNR below a threshold.

2.2 Outage Analysis and Diversity Gain

When the channel is time-varying, the channel capacity has different notions depending on the different fading states. Ergodic (Shannon) capacity is an appropriate capacity metric for channels that vary quickly, or where the channel is ergodic over the time period of interest. It can be evaluated by averaging the mutual information over all possible channel realizations. An alternate outage capacity notion is suitable for applications where the data rate cannot depend on channel variations (except in outage states, where no data are transmitted). It is a measure of data rate that can be supported by a system with a certain error probability. To investigate the diversity gain, the performance of relaying protocols is characterised in terms of outage probability. Assume frequency flat slow fading channel with CSI knowledge at the receivers only. Perfect synchronization among the terminals is also assumed. Considering a baseband-equivalent discrete-time channel model, the transmissions in time slot k can be expressed as

$$y_r[k] = h_1[k]x_1[k] + n_1[k] \tag{1}$$

$$y_2[k] = h_3[k]x_1[k] + n_3[k] \tag{2}$$

where $x_1[k]$ is the transmitted signal from T_1, $y_r[k]$ and $y_2[k]$ are the received signals at the relay and T_2 respectively, h_i captures the effects of path-loss, shadowing and frequency nonselective fading, $n_i \sim \mathcal{CN}(0, \sigma^2)$ is the Additive White Gaussian Noise (AWGN) which captures the effects of receiver noise and other forms of interference in the system, where $i \in \{1, 2, 3\}$. Throughout the chapter, we use $h_i[k]$ and h_i interchangeably for brevity. The relay processes $y_r[k]$ and relays the information by transmitting $x_r[k]$. The signal received at T_2 in time slot $k+1$

$$y_2[k+1] = h_2[k+1]x_r[k] + n_2[k+1]. \tag{3}$$

As a function of the fading coefficients h_i (modeled as zero-mean, independent, circularly symmetric complex Gaussian random variables with variances σ_{hi}^2), the mutual information

for a protocol is a random variable I. For a target rate $\mathcal{R}$, $I < \mathcal{R}$ denotes the outage event and $\Pr[I < \mathcal{R}]$ denotes the outage probability (Laneman et al., 2004). The maximum average mutual information between input and output in direct transmission, achieved by independent identically distributed (i.i.d.) zero-mean, circularly symmetric complex Gaussian inputs, is given by

$$I_D = \log\left(1 + \gamma|h_3|^2\right) \tag{4}$$

where $\gamma = P_1/\sigma^2$ is defined as SNR without fading and P_1 is the average transmit power of terminal T_1. For Rayleigh fading, $|h_3|^2$ is exponentially distributed with parameter $1/\sigma_{h3}^2$, the outage probability derived in (Laneman et al., 2004) is given as

$$\Pr[I_D < \mathcal{R}] = 1 - \exp\left(-\frac{2^{\mathcal{R}} - 1}{\gamma\sigma_{h3}^2}\right) \sim \frac{1}{\sigma_{h3}^2}\frac{2^{\mathcal{R}} - 1}{\gamma}. \tag{5}$$

The direct transmission does not achieve any diversity gain as is obvious from γ^{-1} dependence of outage probability in Equation (5).

2.3 AF Relaying

In this protocol, the relay amplifies the received signal in the first time slot according to its available average transmit power and forwards a scaled signal in the second time slot to the destination terminal. To remain within its power constraint, an amplifying relay must use gain

$$g[k] \leq \sqrt{\frac{P_r}{P_1|h_1|^2 + \sigma^2}} \tag{6}$$

which is inversely proportional to the received power. Thus the relay transmits the signal $x_r[k+1] = g[k]y_r[k]$ with the power P_r in the second time slot. This scheme can be viewed as repetitive coding from two distributed transmitters T_1 and R, except that the relay R amplifies the noise in its received signal. The destination T_2 can decode its received signal y_2 by suitably combining the signals from the two time slots. This protocol produces an equivalent one-input two-output complex Gaussian noise channel with different noise levels in the outputs. The SNR received at the destination is the sum of the SNRs from T_1 and R links. The maximum average mutual information between the input and the two outputs, achieved by i.i.d. complex Gaussian inputs, is given by

$$I_{AF} = \frac{1}{2}\log\left[1 + \gamma|h_3|^2 + \frac{\gamma|h_2gh_1|^2}{(1 + |h_2g|^2)}\right]. \tag{7}$$

Note that g is a function of h_1. Notations $g[k]$ and g are used interchangeably throughout for brevity. The outage probability can be approximated at high SNR (Laneman et al., 2004) as

$$\Pr[I_{AF} < \mathcal{R}] \sim \left(\frac{\sigma_{h1}^2 + \sigma_{h2}^2}{2\sigma_{h3}^2\left(\sigma_{h1}^2\sigma_{h2}^2\right)}\right)\left(\frac{2^{2\mathcal{R}} - 1}{\gamma}\right)^2. \tag{8}$$

The pre-log factor $1/2$ in Equation (7) is due to half-duplex relaying which needs two channel uses to transmit the information from source to destination. The outage behavior decays as γ^{-2}, which indicates that fixed AF protocol offers diversity gain of 2.

2.4 DF Relaying

In this scheme the relay processes its received signal $y_r[k]$ in the first time slot to obtain an estimate $\hat{x}_1[k]$ of the source transmitted signal. Under a repetition-coded scheme, the relay transmits the signal $x_r[k+1] = \hat{x}_1[k]$ in the second time slot. Although fixed DF relaying has the advantage over AF relaying in reducing the effects of additive noise at the relay, it entails the possibility of forwarding erroneously detected symbols to the destination. Therefore it is required that both the relay and destination decode the entire codeword without error. This leads to the expression of maximum average mutual information I_{DF} between T_1 and T_2 as the minimum of the two maximum rates, one at which the relay R can reliably decode the source message, and the other at which the destination T_2 can reliably decode the source message given repeated transmissions from the source and relay. This implies that

$$I_{DF} = \frac{1}{2}\min\left\{\log\left(1 + \gamma|h_1|^2\right), \log\left(1 + \gamma|h_3|^2 + \gamma|h_2|^2\right)\right\}. \tag{9}$$

Here it is obvious that the performance of this system is limited by the worst link among the T_1-T_2 and T_1-R. The outage probability can be obtained for high SNR (Laneman et al., 2004) as

$$\Pr[I_{DF} < \mathcal{R}] \sim \frac{1}{\sigma_{h1}^2}\frac{2^{2\mathcal{R}} - 1}{\gamma}. \tag{10}$$

The γ^{-1} behavior in Equation (10) indicates that fixed DF protocol does not provide diversity gain for large SNR.

2.5 Numerical Results

We compare the outage analysis results of AF and DF relaying protocols with direct transmission. We consider the case of statistically symmetric networks in which the Rayleigh fading channel variances are identical i.e., $\sigma_{hi}^2 = 1$. The noise variance σ^2 is assumed to be unity. We realized 10000 random channels using Monte Carlo simulation. Figure 3 shows the outage probabilities versus SNR in dB for low spectral efficiency (roughly 2 bps/Hz). The diversity order of 2 achieved by AF protocol is clear from the steeper curve slope in Figure 3. Also the fixed DF relaying curve indicates no diversity gain and hence does not have any advantage
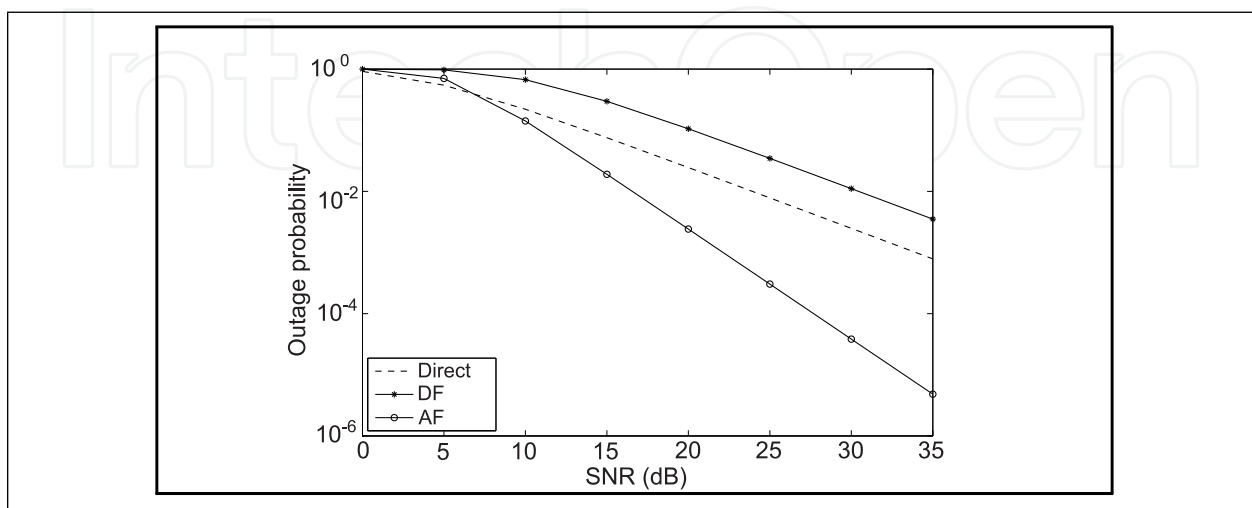
Fig. 3. Outage probabilities versus SNR in the low spectral efficiency regime.
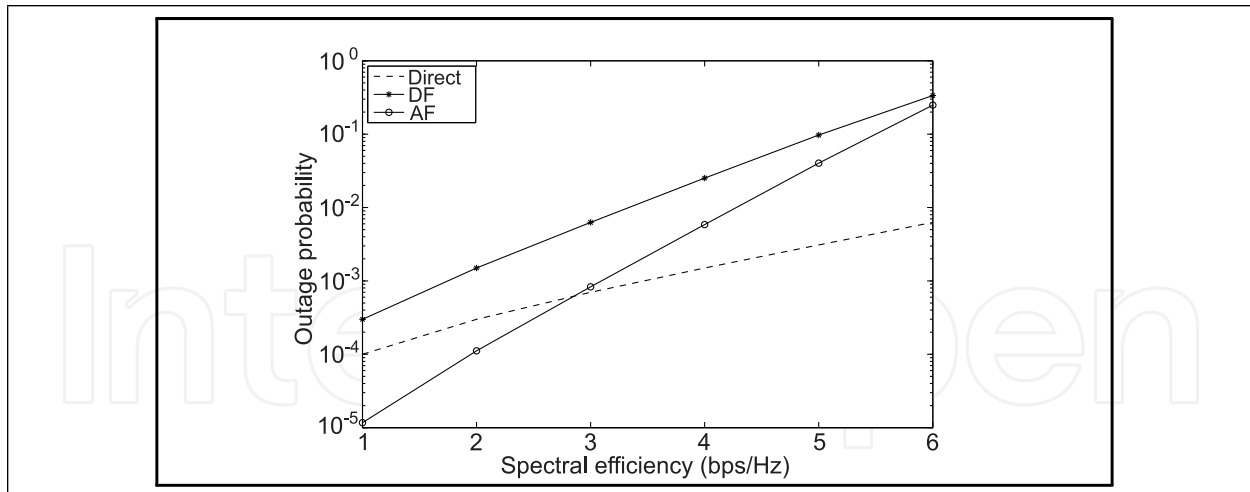
Fig. 4. Outage probabilities versus spectral efficiency for high SNR.

over direct transmission. In Figure 4, the outage probabilities are depicted as functions of spectral efficiency $\mathcal{R}$ for a fixed SNR of 35 dB. It is clear from Figure 4 that the performance of fixed AF and DF protocols generally degrade with increasing rate $\mathcal{R}$. It degrades faster for AF scheme because of the inherent loss in spectral efficiency. Again, fixed DF protocol does not have any diversity advantage over direct transmission. At sufficiently high rate $\mathcal{R}$, direct transmission becomes more efficient than cooperative relay communication. So we can conclude that half-duplex operation requires double channel resources compared to direct transmission for a given rate and hence leads to larger effective SNR losses for increasing rate. However the performance enhancements in low spectral efficiency regime can be translated into decreased transmit power for the same reliability.

3. Bidirectional Relaying

Although unidirectional or one-way communication has been extensively considered in the literature, there is a lot of interest in recent years on bidirectional or two-way communication. In two-way communication, two terminals simultaneously transmit their messages to each other and the messages interfere with each other. The Two-Way Communication Channel (TWC) was first studied by Shannon, who derived inner and outer bounds on the capacity region (Shannon, 1961). He used a restricted two-way channel in which the encoders of both terminals do not cooperate, and the transmitted symbols at one terminal only depend on the message to be transmitted at that terminal (and not on the previously received symbols). He showed that the inner bound coincides with the capacity region of the restricted two-way channel. Later, the two-way communication problem was investigated for the full-duplex relay channel, and the achievable rate regions were derived in (Rankov & Wittneben, 2006), (Avestimehr et al., 2008), (Nam et al., 2008) and references therein. Further TWC has been exploited in (Rankov & Wittneben, 2007), as TWRC, in order to mitigate the spectral efficiency loss of cooperative protocols under half-duplex relaying. Recall that cooperative protocols can provide higher outage capacity but not ergodic capacity because of use of orthogonal time slots for relaying. Our goal here is to analyze spectrally efficient (measured in bits per channel use) transmission schemes for the half-duplex bidirectional relay channel. Presently the TWRC protocol has drawn much interest from both academic and industrial communities owing to its potential application in wireless networks.

3.1 One-Way Relay Channel (OWRC)

Consider a wireless channel in which two nodes T_1 and T_2 wish to exchange independent messages with the help of a relay node R. Once again, we assume that all terminals operate in half-duplex fashion. Therefore the relay terminal cannot receive and transmit simultaneously on the same channel resource; it receives a signal on a first hop, applies signal processing and retransmits the signal on a second hop. More importantly, there is no reliable direct link between T_1 and T_2 due to shadowing, large separation between them, or use of low power signaling. This is feasible in practice when the users are geographically separated, and the signals received from each other are very weak. This is the case when two distant land stations communicate with a satellite, or two mobile users located on opposite sides of a building communicate with the same base station on top of the building. When there is no direct connection between the two wireless terminals, relays are essential to enable communication.
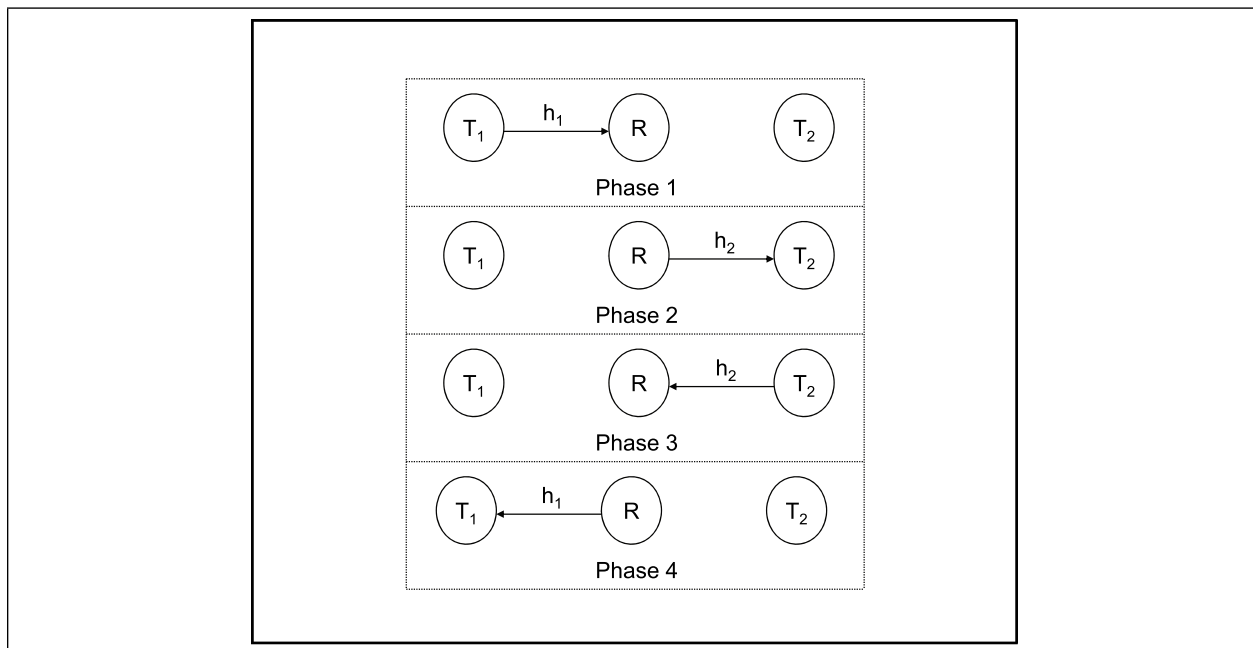
Fig. 5. Four-phase one-way relaying for bidirectional cooperation.

For a one-way relaying approach, two resources are required for the transmission from T_1 to T_2 via R and two resources are required for the transmission from T_2 to T_1 via R, leading to an overall requirement of four resources. This is a four phase protocol (Kim et al., 2008) whereby transmissions $T_1 \rightarrow R$, $R \rightarrow T_2$, $T_2 \rightarrow R$, and $R \rightarrow T_1$ occur in four consecutive phases, as illustrated in Figure 5.

3.1.1 AF-OWRC

The source terminal T_1 transmits in the first time slot an information symbol to the relay terminal R. The relay amplifies the received symbol (including noise) according to its available average transmit power and forwards a scaled signal in the second time slot to the destination terminal T_2 (Rankov & Wittneben, 2007). In time slot k, the relay receives

$$y_r[k] = h_1[k]x_1[k] + n_r[k] \tag{11}$$

where h_1 is the complex channel gain between source and relay (first hop), $x_1 \sim \mathcal{CN}(0, P_1)$ is the transmit symbol of the source, and $n_r \sim \mathcal{CN}(0, \sigma_r^2)$ is the AWGN at the relay. The relay scales $y_r[k]$ by

$$g[k] = \sqrt{\frac{P_r}{P_1|h_1[k]|^2 + \sigma_r^2}} \tag{12}$$

where P_r is the average transmit power of the relay. Depending on the amount of channel knowledge at the relay, different choices for the relay gain are possible. In time slot $k+1$, the destination receives

$$y_2[k+1] = h_2[k+1]g[k]h_1[k]x_1[k] + h_2[k+1]g[k]n_r[k] + n_2[k+1] \tag{13}$$

where h_2 is the complex channel gain between relay and destination (second hop) and $n_2 \sim \mathcal{CN}(0, \sigma_2^2)$ is the AWGN at the destination. The information rate of this scheme for i.i.d. fading channels $h_1[k]$ and $h_2[k]$ is given by (Rankov & Wittneben, 2007)

$$I_{AF} = \frac{1}{2}E\left\{\log\left(1 + \frac{P_1|h_2gh_1|^2}{\sigma_2^2 + \sigma_r^2|h_2g|^2}\right)\right\} \tag{14}$$

where $E\{\cdot\}$ denotes the expectation with respect to the channels h_1 and h_2. The pre-log factor $1/2$ follows because of the two channel uses needed to transmit the information from T_1 to T_2.

3.1.2 DF-OWRC
In this scheme, the relay decodes the message sent by the source, re-encodes it (by using the same or a different codebook), and forwards the message to the destination. In time slot k, the relay receives

$$y_r[k] = h_1[k]x_1[k] + n_r[k]. \tag{15}$$

After decoding and retransmission, the destination receives in time slot $k+1$

$$y_2[k+1] = h_2[k+1]x_r[k+1] + n_2[k+1] \tag{16}$$

where $x_r \sim \mathcal{CN}(0, P_r)$ is the transmit symbol of the relay. The information rate of this scheme for i.i.d. fading channels $h_1[k]$ and $h_2[k]$ is given by (Rankov & Wittneben, 2007)

$$I_{DF} = \frac{1}{2}\min\left[E\left\{\log\left(1 + \frac{P_1|h_1|^2}{\sigma_r^2}\right)\right\}, E\left\{\log\left(1 + \frac{P_r|h_2|^2}{\sigma_2^2}\right)\right\}\right]. \tag{17}$$

This rate is exactly the ergodic capacity of the conventional half-duplex cooperative relay channel with no direct connection. Compared to a bidirectional communication between T_1 and T_2 without two-hop relaying, the number of required resources is doubled. Therefore this protocol is spectrally inefficient and does not take full advantage of the broadcast nature of the wireless channel.

3.2 Two-Way Relay Channel (TWRC)
The two-way relaying protocol (Rankov & Wittneben, 2007) is an effective means to increase the spectral efficiency of a half-duplex relay network. As illustrated in Figure 6, messages of nodes T_1 and T_2 are delivered to nodes T_2 and T_1 respectively in two phases, named the Multiple Access Channel (MAC) and Broadcast Channel (BC) phase. In the first (MAC) phase,

T_1 and T_2 transmit their signals to the relay node at the same time. After receiving the signals, the relay node performs appropriate signal processing and broadcasts the resulting signal to both nodes T_1 and T_2 in the second (BC) phase. At each node, its symbols contribute self interference but can clearly be canceled (because they are known). The channels in the forward direction are assumed to be the same as in the backward direction i.e., channel reciprocity is assumed.
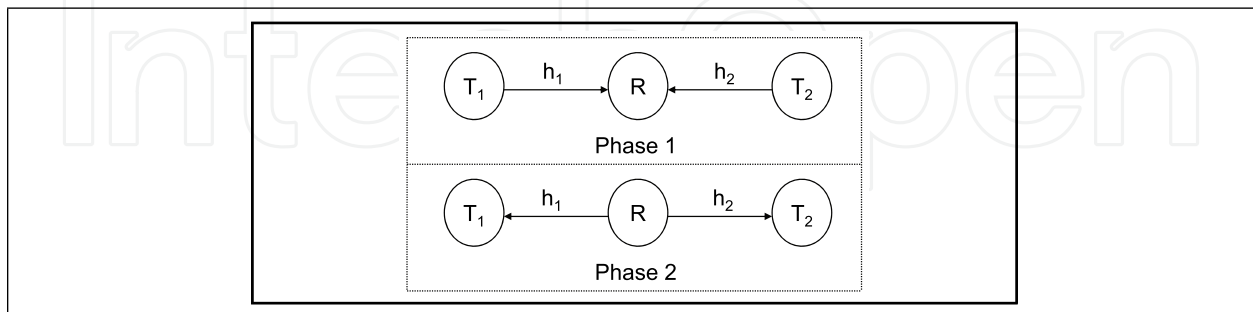

Fig. 6. Two-phase two-way relaying for bidirectional cooperation.

3.2.1 AF-TWRC
In this scheme, both terminals T_1 and T_2 transmit their symbols to relay R in the same time slot k using the same bandwidth. The relay then receives

$$y_r[k] = h_1[k]x_1[k] + h_2[k]x_2[k] + n_r[k] \qquad (18)$$

where the symbols $x_1[k] \sim \mathcal{CN}(0, P_1)$ and $x_2[k] \sim \mathcal{CN}(0, P_2)$ are the i.i.d. transmit symbols of terminals T_1 and T_2 respectively. The relay scales the received signal by

$$g[k] = \sqrt{\frac{P_r}{P_1|h_1[k]|^2 + P_2|h_2[k]|^2 + \sigma_r^2}} \qquad (19)$$

in order to meet its average transmit power constraint. It then broadcasts the signal in the next time slot to both terminals T_1 and T_2. The signals received at terminals T_1 and T_2 are

$$y_2[k+1] = h_2[k+1]g[k]h_1[k]x_1[k] + h_2[k+1]g[k]h_2[k]x_2[k] + h_2[k+1]g[k]n_r[k] + n_2[k+1] \qquad (20)$$

$$y_1[k+1] = h_1[k+1]g[k]h_2[k]x_2[k] + h_1[k+1]g[k]h_1[k]x_1[k] + h_1[k+1]g[k]n_r[k] + n_1[k+1]. \qquad (21)$$

Assuming channel reciprocity for h_1 and h_2. Unless mentioned otherwise, we assume that h_i remains static at least over two time slots. Since nodes T_1 and T_2 know their own transmitted symbols, they can subtract the back-propagating self-interference prior to decoding, assuming perfect knowledge of the corresponding channel coefficients. The sum-rate is given by (Rankov & Wittneben, 2007)

$$I_{AF(sum)} = \frac{1}{2}E\left\{\log\left(1 + \frac{P_1|h_2gh_1|^2}{\sigma_2^2 + \sigma_r^2|h_2g|^2}\right)\right\} + \frac{1}{2}E\left\{\log\left(1 + \frac{P_2|h_2gh_1|^2}{\sigma_1^2 + \sigma_r^2|h_1g|^2}\right)\right\}. \qquad (22)$$

The transmission in each direction suffers still from the pre-log factor $1/2$. However, the half-duplex constraint can here be exploited to establish a bidirectional connection between two terminals and to increase the sum rate of the network.

3.2.2 DF-TWRC

Consider now a two-way communication between terminals T_1 and T_2 via a half-duplex DF relay R. In time slot k both terminals T_1 and T_2 transmit their symbols to relay R. In this MAC phase, the relay receives

$$y_r[k] = h_1[k]x_1[k] + h_2[k]x_2[k] + n_r[k], \tag{23}$$

decodes the symbols $x_1[k]$ and $x_2[k]$ and transmits $x_r[k+1] = \sqrt{\beta}x_1[k] + \sqrt{1-\beta}x_2[k]$ in the next time slot (BC phase). The received signals at T_2 and T_1 are

$$y_2[k+1] = h_2[k+1]x_r[k+1] + n_2[k+1] \tag{24}$$

$$y_1[k+1] = h_1[k+1]x_r[k+1] + n_1[k+1]. \tag{25}$$

The relay uses an average transmit power of βP_r for the forward direction and $(1-\beta)P_r$ for the backward direction. Since T_1 knows $x_1[k]$ and T_2 knows $x_2[k]$, these symbols (back-propagating self-interference) can be subtracted at the respective terminals prior to decoding of the symbol transmitted by the partner terminal. We assume that the relay decodes $x_1[k]$ and $x_2[k]$ without errors. The sum-rate is given (Rankov & Wittneben, 2007) by

$$I_{DF(sum)} = \max_{\beta} \ \min(I_{MA}, I_1(\beta) + I_2(1-\beta)) \tag{26}$$

$$\text{where} \quad I_{MA} = \frac{1}{2}C\left(\frac{P_1|h_1|^2 + P_2|h_2|^2}{\sigma_r^2}\right)$$

$$I_1(\beta) = \frac{1}{2}\min\left\{C\left(\frac{P_1|h_1|^2}{\sigma_r^2}\right), C\left(\frac{\beta P_r|h_2|^2}{\sigma_2^2}\right)\right\}$$

$$I_2(1-\beta) = \frac{1}{2}\min\left\{C\left(\frac{P_2|h_2|^2}{\sigma_r^2}\right), C\left(\frac{(1-\beta)P_r|h_1|^2}{\sigma_1^2}\right)\right\}$$

$$\text{where} \quad C(x) = E\{\log(1+x)\}.$$

In the absence of CSI knowledge in the BC phase, $\beta = \frac{1}{2}$ is used by the relay. Note that in fast fading channels, the channel coefficients change from phase to phase, and reliable CSI may not be available. In other case β may be optimally chosen to maximize the sum rate. The choice of β will depend on the amount of channel knowledge available (CSI or its statistics), and applicable path losses in the links.

3.3 Simulation Results

We compute the achievable rates of the one-way and two-way relaying schemes by Monte Carlo simulations. We consider a fixed symmetric network in which the relay is equidistant from the two terminals. The Rayleigh fading channel gains are modeled as $h_i \sim \mathcal{CN}(0, 1)$. The AWGN variances are chosen as $\sigma_1^2 = \sigma_2^2 = \sigma_r^2 = \sigma^2$ and the transmit powers $P_1 = P_2 = P/2$ and $P_r = P$ such that the network consumes in each time slot an average power of P. The SNR

is defined as the ratio P/σ^2. Over 10000 random channels were used to average the rates in Figures 7 and 8.
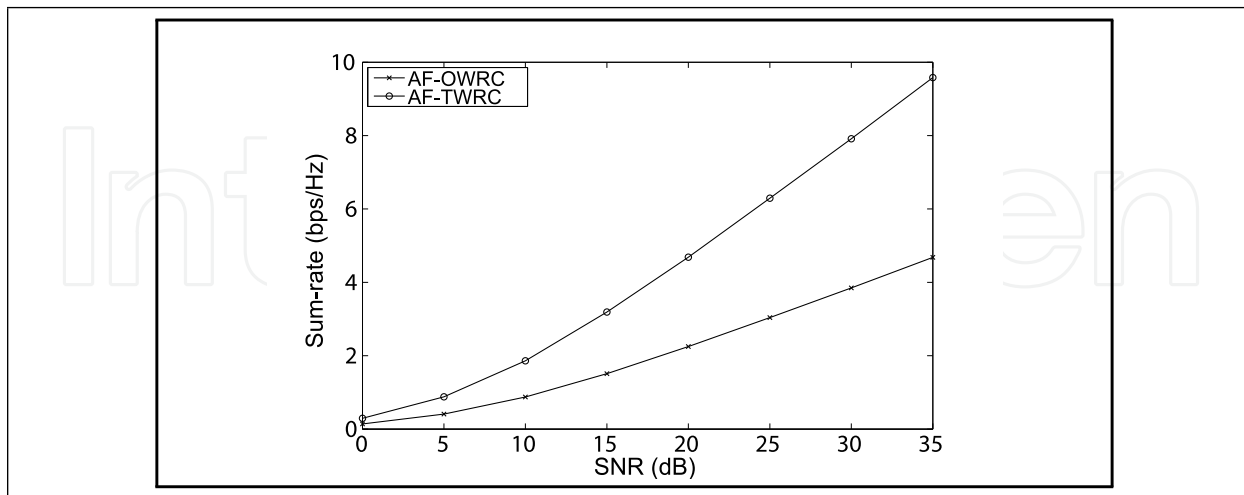

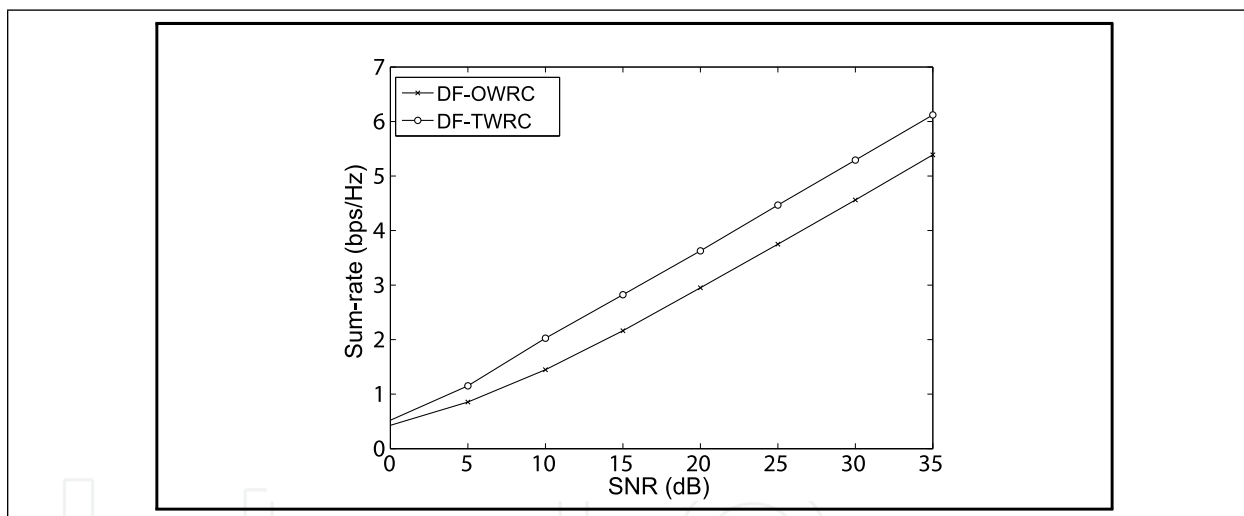Fig. 7. Sum rate for two-way half-duplex AF relaying protocol.

Fig. 8. Sum rate for two-way half-duplex DF relaying protocol.

We compare the sum rate of the two-way AF and two-way DF protocols with their one-way counterparts in Figures 7 and 8 respectively. We observe that both two-way protocols, AF and DF, achieve sum-rates that are larger than the rates of their one-way counterparts. Moreover, AF scheme has more pronounced improvement compared with DF. For the two-way symmetric case considered here, the DF protocol is worse than AF protocol because the sum rate is dominated by the multiple-access sum rate. Intuitively we can say that for an asymmetric channel scenario, when the relay is in the vicinity of one terminal T_1 or T_2 (and thereby experiences a stronger channel gain than the other terminal), the DF scheme achieves the maximum sum rate which can be further improved by optimal choice of β.

4. Resource Allocation

The performance of wireless relay networks can be significantly improved by efficient management of available radio resources. Mostly, resource management via power allocation is employed. We have discussed bidirectional relaying in the previous section, static resource allocation was assumed where all transmission phases are of same duration and all terminals have individual power constraints with balanced rates. Dynamic resource allocation has been investigated in (Agustin et al., 2008) in terms of phase durations, individual and sum-average power, and data rate. The system model employs a DF relay that applies superposition coding and takes into account the traffic asymmetry. It is assumed that the transmission is performed in frames of length v with N channel uses and normalized bandwidth of unity. The duration of the two phases (MAC and BC) are denoted by v_1 and v_2 respectively. The two power constraints considered are maximum power and sum-average power (both denoted by P). The first constraint assumes that all terminals transmit with power P, whereas in second case the total average power used by the three terminals is considered to be P. The mutual information of different links assuming equal noise power at all terminals is given by

$$I_{1r}(P_1) = N \log \left(1 + \frac{P_1 |h_1|^2}{\sigma^2} \right) \tag{27}$$

$$I_{2r}(P_2) = N \log \left(1 + \frac{P_2 |h_2|^2}{\sigma^2} \right) \tag{28}$$

$$I_{MAC}(P_1, P_2) = N \log \left(1 + \frac{P_1 |h_1|^2}{\sigma^2} + \frac{P_2 |h_2|^2}{\sigma^2} \right) \tag{29}$$

where I_{1r} and I_{2r} represent mutual information of $T_1 - R$ and $T_2 - R$ links respectively, and I_{MAC} is the mutual information at the relay when both terminals transmit simultaneously in the MAC phase. The signal received by the relay in MAC phase is given by

$$y_r[k] = \begin{cases} h_1[k]x_1[k] + h_2[k]x_2[k] + n_r[k] & \text{for} \quad 0 \le k \le v_1 N \\ 0 & \text{for} \quad v_1 N \le k \le N. \end{cases} \tag{30}$$

Under superposition coding, the DF relay forwards one signal $x_r[k]$ intended to each destination by distributing the total power between them as

$$x_r = \sqrt{\frac{\beta_1 P_r}{P_1}} x_1 + \sqrt{\frac{\beta_2 P_r}{P_2}} x_2 \tag{31}$$

where β_1 and β_2 indicate the fraction of power allocated to each signal. The signal received by each destination in second phase is given by

$$y_1[k] = \begin{cases} 0 & \text{for} \quad 0 \le k \le v_1 N \\ h_1[k]x_r[k] + n_1[k] & \text{for} \quad v_1 N \le k \le N \end{cases} \tag{32}$$

$$y_2[k] = \begin{cases} 0 & \text{for} \quad 0 \le k \le v_1 N \\ h_2[k]x_r[k] + n_2[k] & \text{for} \quad v_1 N \le k \le N. \end{cases} \tag{33}$$

The optimal selection of phase duration, data rate of each terminal are found as the maximization of the following problem (Agustin et al., 2008):

$$arg \max_{v, R_1, R_2, P_1, P_2, P_r} \vartheta_1 R_1 + \vartheta_2 R_2 \quad \text{s.t.} \begin{cases} (R_1, R_2) \in \rho(v) & \text{for} \quad 0 \le \ell(v) \le 1 \\ \varphi(P_1, P_2, P_r) \le P & \text{for} \quad \zeta(R_1, R_2) = \kappa \end{cases} \tag{34}$$

where R_1, R_2 represents the rate transmitted by terminal T_1, T_2 respectively, v is a vector that contains the duration of different phases, function $\ell(v)$ defines the linear connection between duration of phases, $\rho(v)$ denotes the achievable rate region for a given v, function $\varphi(P_1, P_2, P_r)$ represents a combination of the transmitted power by the terminals considering the power constraints, function $\zeta(R_1, R_2)$ indicates a linear dependence between data rates R_1 and R_2. The achievable rate region boundary can be attained with optimum phase and rate selection (by adjusting the parameters ϑ_1 and ϑ_2).

The achievable rate region $\rho(v)$ for the two-way DF protocol, described under MAC (Cover & Thomas, 1991), is given by

$$\rho(v_1, v_2) = \begin{cases} R_1 \leq \min\{v_1 I_{1r}(P_1), v_2 I_{2r}(\beta_1 P_r)\} \\ R_2 \leq \min\{v_1 I_{2r}(P_2), v_2 I_{1r}(\beta_2 P_r)\} \\ R_1 + R_2 \leq v_1 I_{MAC}(P_1, P_2) \end{cases} \tag{35}$$

with $\ell(v_1, v_2) = v_1 + v_2$. For terminals transmitting with their maximum power P, the maximum power constraint can be expressed as

$$\varphi_{max}(P_1, P_2, P_r) = \{P_1 = P, P_2 = P, P_r = P\}. \tag{36}$$

The power distribution at the relay satisfies $0 \leq \beta_1 + \beta_2 \leq 1$. Hence the power allocation can be optimized at the relay only. For sum-average power constraint, each terminal uses a fraction of total power P which is controlled by variables δ and β as follows

$$\varphi_{avg}(P_1, P_2, P_r) = \left\{P_1 = \frac{\delta_1 P}{v_1}, P_2 = \frac{\delta_2 P}{v_1}, P_r = \frac{P}{v_2}\right\}. \tag{37}$$

It has been shown in (Agustin et al., 2008) that the sum-average power constraint must satisfy

$$P_1 v_1 + P_2 v_1 + \varsigma P_r v_2 = P \tag{38}$$

where $\varsigma = \beta_1 + \beta_2$ so that $\delta_1 + \delta_2 + \beta_1 + \beta_2 = 1$. The data rates achieved on each link are connected through

$$\zeta(R_1, R_2) = R_1 - \kappa R_2 \leq 0 \tag{39}$$

where κ is a positive real number accounts for the traffic asymmetry.

Under the sum-average power constraint the optimization problem for resource allocation is convex and has a unique solution. However for maximum power constraint, the problem has to be transformed into a convex one by introducing some auxiliary variables [see (Agustin et al., 2008) and references therein].

5. Coded Bidirectional Relaying

So far we have discussed the TWRC from cooperative communication perspectives with a major objective being compensation to make up for for the half-duplex loss. In a separate but significant development, the authors in (Ahlswede et al., 2000) have proposed the concept of network coding in which intermediate network nodes are allowed not only to route but also to mix and code the incoming data from multiple links. This reduces the amount of data transmissions in the network (thus improving the overall network throughput). Originally, the network coding concept was proposed for wired communication networks. Later it was applied to wireless communication networks by exploiting the broadcasting nature of wireless medium [it was used for relay networks for the first time in (Hao et al., 2007)]. Network

coding has been proven to be a very effective solution to overcome the interuser interference in wireless networks because of its ability to combining the different signals instead of separating them from a traditional viewpoint.

Traditionally simultaneous transmission from T_1 and T_2 was avoided in order to simplify the medium access control, and to avoid the interference at the relay R. Thereby four phases were required to perform one round of information exchange between T_1 and T_2 through R. However, by applying the idea of network coding, the authors in (Wu et al., 2005) proposed a scheme to reduce the number of required phases from four to three as illustrated in Figure 9. In this scheme, T_1 first transmits during first phase the message x_1 to R consisting of bits $b_1(1), ..., b_1(N)$ with N denoting the message length in bits, which are decoded. During the second phase, T_2 transmits to R the message x_2 consisting of bits $b_2(1), ..., b_2(N)$, which R decodes. In the third phase, R broadcasts to T_1 and T_2 a new message x_r consisting of bits $b_r(n)$'s, $n = 1, ..., N$, obtained by bit-wise exclusive-or (XOR) operation over $b_1(n)$'s and $b_2(n)$'s i.e., $b_r(n) = b_1(n) \oplus b_2(n), \forall\, n$. Since T_1 knows $b_1(n)$'s, T_1 can recover its desired message x_2 by first decoding $b_r(n)$ and then obtaining $b_2(n)$'s of x_2 as $b_1(n) \oplus b_r(n), \forall n$. Similarly, T_2 can recover x_1. The same type of three-phase coded bidirectional relaying scheme was proposed independently in (Larsson et al., 2006). The resulting pre-log factor with respect to the sum-rate of this three-phase coded scheme is thus 2/3 compared to 1/2 for conventional half-duplex scheme. In this protocol, if a reliable direct link is possible, then the scheme may gain in additional diversity and often better coverage as discussed in (Kim et al., 2008).
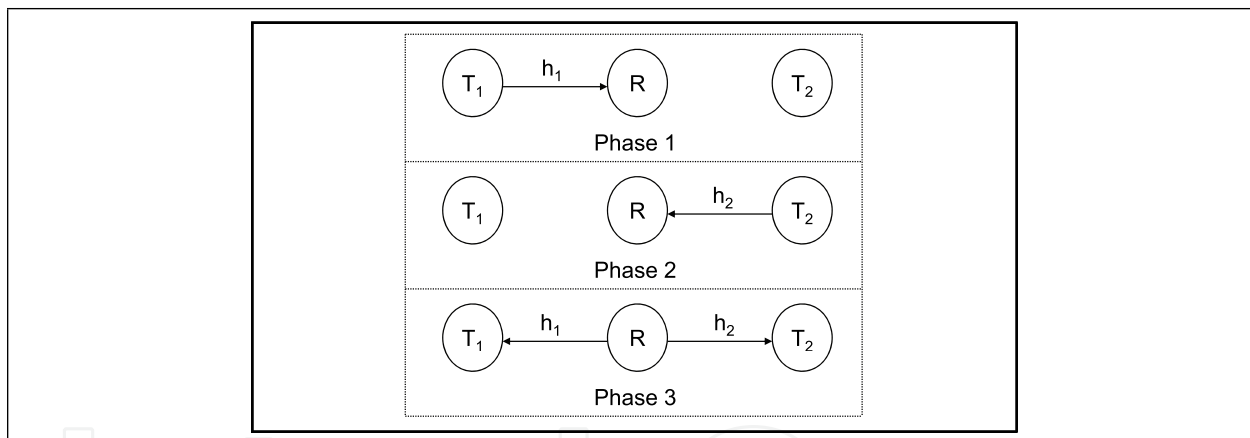

Fig. 9. Three-phase two-way relaying.

In (Popovski & Yomo, 2006); (Popovski & Yomo, 2007a); (Popovski & Yomo, 2007b), the authors reduce the number of required phases from three to two by allowing T_1 and T_2 to transmit simultaneously to R during the first phase, thereby eliminating the need for the second phase. This corresponds to the MAC phase of DF-TWRC (Rankov & Wittneben, 2007). The scheme proposed in (Katti et al., 2007a) is named as Analog Network Coding (ANC), while that in (Zhang et al., 2006) is referred to as Physical-layer Network Coding (PNC). These schemes differ in their relay operations, which are Amplify-and-Forward (AF) and Estimate-and-Forward (EF), respectively. In ANC, R simply amplifies the mixed signal received simultaneously from T_1 and T_2 and then broadcasts it to both. By subtracting the back-propagating self-interference, both T_1 and T_2 are able to receive their intended messages. Thus ANC scheme is similar to the AF-TWRC (Rankov & Wittneben, 2007). Compared to ANC, PNC (Zhang et al., 2006) performs more sophisticated operations than AF at R. Instead of decoding

messages x_1 from T_1 and x_2 from T_2 separately in two different phases like in (Wu et al., 2005), the EF method estimates at R the bitwise XORs between $b_1(n)$'s and $b_2(n)$'s from the mixed signal received, and re-encodes the decoded bits into a new broadcasting message x_r. Each of T_1 and T_2 then recovers the otherŠs message by the same decoding method discussed in (Wu et al., 2005).

Although the schemes proposed in these works are similar to AF- and DF-TWRC, they are inspired by network coding. The principle of network coding has been further investigated for the TWRC in (Hausl & Hagenauer, 2006); (Baik & Chung, 2008); (Cui et al., 2008a); (Cui et al., 2008b). It has been shown in (Katti et al., 2007b) that joint relaying and network coding achieves higher data rates as compared to routing at the relay. In (Kim et al., 2008), the authors compared the different half-duplex bidirectional DF relaying protocols and derived their performance bounds. Note that two-phase TWRC does not exploit spatial diversity advantage like conventional approach. Including the direct link would provide diversity gain but at the cost of spectral efficiency. Even more recently, the authors in (Li et al., 2009) analyze the outage performance of two-phase AF- and DF-TWRC under half-duplex constraint. They derived the exact closed-form expressions for the outage probabilities by considering network coding at the relay for DF case. Furthermore, they propose an adaptive bidirectional relaying protocol which switches between AF and DF to minimize the outage probability of the system. TWRC coupled with network coding is thus developing as a promising technology to combat interference and to improve throughput in wireless networks.

6. MIMO Bidirectional Relaying

It is well known that Multiple-Input Multiple-Output (MIMO) communication systems have the ability to enhance the channel capacity and link reliability without requiring an increase in power or bandwidth. In (Unger & Klein, 2007) it is proposed to extend two-way relaying to terminals with multiple antennas (leading to MIMO-TWRC). They investigate the average performance of MIMO-TWRC by using multiple antennas at the ralay terminal only. The proposed scheme exploits the fact that the relay R is a receiver as well as a transmitter in the dual-hop case, and hence assumes CSI at the R is not unreasonable. Like in a Time Division Duplex (TDD) system, CSI for receive and transmit processing can be obtained by directly estimating the channel from T_1 to the R and from T_2 to the R in the first phase, and then exploiting channel reciprocity in the second phase. Thereafter, the relay can perform spatial filtering to its receive and transmit signal. In (Han et al., 2008) the average sum rate improvement of two-way relaying is analyzed by deriving an upper and a lower bound for average sum rate of two-way relaying which was not derived in (Rankov & Wittneben, 2007). They also extend the work to the case when the source terminal and the destination terminal have two antennas each and the relay has only one antenna (in order to implement Alamouti's scheme). The proposed scheme achieves higher average sum rate compared to the single antenna case, and furthermore both the source and destination terminals achieve diversity of order two. The authors in (Zhang et al., 2009) analyze the capacity region for of the ANC/AF-based TWRC with linear processing (beamforming) at the relay with multiple antennas. They have also shown that the ANC/AF-based TWRC have a capacity gain over the DF-based TWRC for sufficiently large channel correlations and equal MAC and BC phase-durations.

In (Hammerstrom et al., 2007) the authors further extend the two-way relaying scheme of (Rankov & Wittneben, 2007) to the case when multiple antennas are used at all terminals (assuming the knowledge of transmit CSI at the DF relay). Figure 10 shows a set up for MIMO two-way relaying where all the terminals are equipped with $M > 1$ antennas. It is assumed
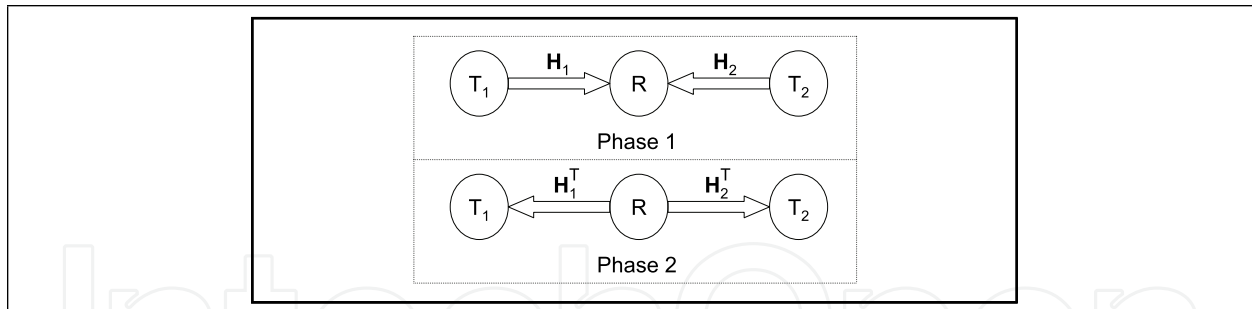
Fig. 10. MIMO two-way relay channel.

that both T_1 and T_2 perfectly know ($\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_1^T$ and $\mathbf{H}_2^T$) in the receiving mode, but not in the transmit mode. The relay R on the other hand has knowledge of both receive and transmit CSI. This is a reasonable assumption since the relay has to estimate the channels ($\mathbf{H}_1$ and $\mathbf{H}_2$) for decoding in the first phase and exploting channel reciprocity in the second phase (like in TDD system). Terminal T_1 transmits vector $\mathbf{x}_1$ to T_2 whereas T_2 transmits vector $\mathbf{x}_2$ to T_1 respectively in two phases. Frequency flat slow fading and perfect synchronization is assumed between all terminals. The signal received at the relay in the first phase is given by

$$\mathbf{y}_r = \mathbf{H}_1\mathbf{x}_1 + \mathbf{H}_2\mathbf{x}_2 + \mathbf{n}_r \tag{40}$$

where $\mathbf{H}_1$ and $\mathbf{H}_2$ are the $M \times M$ channel matrices (with each element being i.i.d. complex Gaussian with zero mean and unit variance) that remain constant during the block transmission, $\mathbf{x}_1$ and $\mathbf{x}_2$ are $M \times 1$ symbol vectors with power P_1 and P_2 respectively, and $\mathbf{n}_r \sim \mathcal{CN}(0, \sigma_r^2\mathbf{I}_M)$ is the $M \times 1$ complex AWGN vector.

During first phase, the relay decodes the messages from both terminals T_1 and T_2. Using a Gaussian codebook, the achievable rates of both terminals are theoretically described by the MIMO-MAC (Cover & Thomas, 1991), which imposes constraints on the individual first-phase rates $R_{1,I}$ and $R_{2,I}$, as well as the first-phase sum rate $R_{1,I} + R_{2,I}$ for successful decoding at the destination terminal:

$$R_{1,I} \leq I_{1,I} = \log\left|\mathbf{I} + \frac{P_1}{M\sigma_r^2}\mathbf{H}_1\mathbf{H}_1^H\right| \tag{41}$$

$$R_{2,I} \leq I_{2,I} = \log\left|\mathbf{I} + \frac{P_2}{M\sigma_r^2}\mathbf{H}_2\mathbf{H}_2^H\right| \tag{42}$$

$$R_{1,I} + R_{2,I} \leq I_I = \log\left|\mathbf{I} + \frac{\frac{P_1}{M}\mathbf{H}_1\mathbf{H}_1^H + \frac{P_2}{M}\mathbf{H}_2\mathbf{H}_2^H}{\sigma_r^2}\right|. \tag{43}$$

In the second phase, the relay applies bit-level XOR precoding on decoded messages. The relay therefore broadcasts the vector $\mathbf{x}_r$ with power P_r. The received signals at T_1 and T_2 are given by

$$\mathbf{y}_1 = \mathbf{H}_1^T\mathbf{x}_r + \mathbf{n}_1 \tag{44}$$

$$\mathbf{y}_2 = \mathbf{H}_2^T\mathbf{x}_r + \mathbf{n}_2 \tag{45}$$

where $\mathbf{n}_1 \sim \mathcal{CN}(0, \sigma_1^2 \mathbf{I}_M)$ and $\mathbf{n}_r \sim \mathcal{CN}(0, \sigma_2^2 \mathbf{I}_M)$ are the complex AWGN $M \times 1$ vectors at T_1 and T_2 respectively. Since both destinations have to be able to decode $\mathbf{x}_r$, the maximum data rate in the second phase is given by

$$I_{II} = \min\{I_{1,II}, I_{2,II}\} \tag{46}$$

where

$$I_{1,II} = \log \left| \mathbf{I} + \frac{1}{\sigma_1^2} \mathbf{H}_1^T \boldsymbol{\Lambda}_r \mathbf{H}_1^* \right| \tag{47}$$

$$I_{2,II} = \log \left| \mathbf{I} + \frac{1}{\sigma_2^2} \mathbf{H}_2^T \boldsymbol{\Lambda}_r \mathbf{H}_2^* \right| \tag{48}$$

where $\boldsymbol{\Lambda}_r = \mathrm{E}\left\{ \mathbf{x}_r \mathbf{x}_r^H \right\}$ and $\mathrm{trace}\left(\boldsymbol{\Lambda}_r\right) = P_r$. The maximum sum-rate of this MIMO two-way relaying scheme is given by (Hammerstrom et al., 2007)

$$R_{sum} = \frac{1}{2} \min\left\{ I_I, \min\{I_{1,I}, I_{2,II}\} + \min\{I_{2,I}, I_{1,II}\} \right\}. \tag{49}$$

The above rate expression can be optimized by exploiting CSI knowledge at the relay subject to the relay transmit power constraint. This is achieved by maximizing the data rate in the second phase as follows

$$I_{II,opt} = \max_{\boldsymbol{\Lambda}_r} \min\{I_{1,II}, I_{2,II}\} \tag{50}$$
$$\text{s.t.} \quad \mathrm{trace}\left(\boldsymbol{\Lambda}_r\right) = P_r.$$

This optimization problem is independent of first phase data rates and can be solved by semidefinite programming method by assuming $\boldsymbol{\Lambda}_r$ to be positive semidefinite [see (Hammerstrom et al., 2007) and references therein].
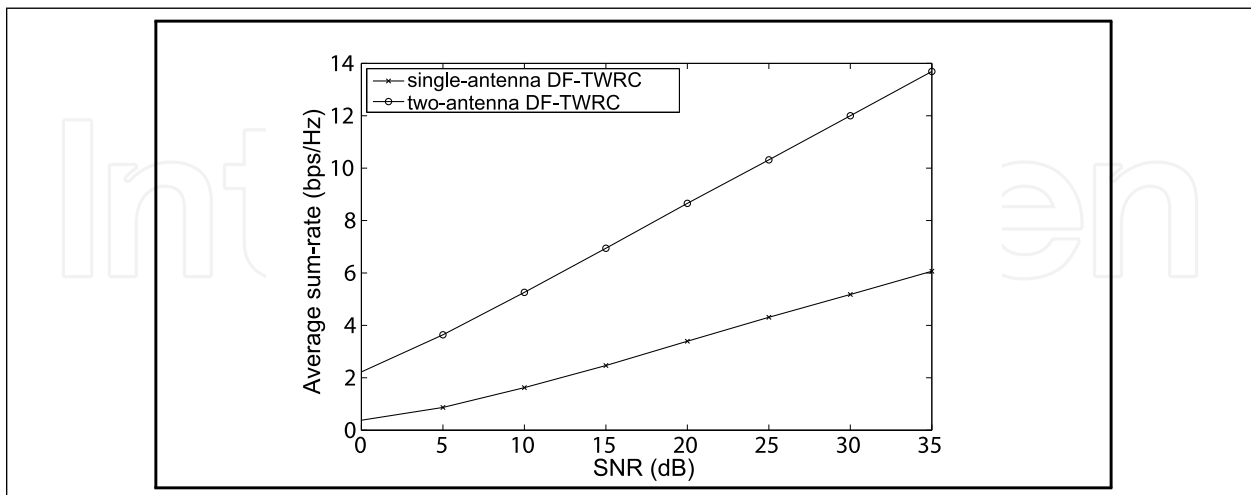

Fig. 11. Average sum-rate of two-antenna DF-TWRC with XOR precoding compared to one-antenna case.

Figure 11 compares the average sum-rate obtained (assuming Gaussian codebook) for DF-TWRC using XOR precoding with one and two antennas at the terminals T_1 and T_2. Rayleigh

fading is assumed, and the elements of the channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ are zero mean and unit variance complex Gaussian random variables. All nodes use the same transmit power $P_1 = P_2 = P_r = P$ and are assumed to have the same noise variance $\sigma_1^2 = \sigma_2^2 = \sigma_r^2 = \sigma^2$. The SNR is defined as P/σ^2. We simulated 10000 random channels for each value in Figure 11. We observe that there is considerable improvement in sum-rate by using two antennas at each node compared to the single antenna case.

Further, the authors in (Hammerstrom et al., 2007) compared two approaches of combining the messages in the second phase at the relay (the superposition coding and the XOR precoding) and showed that MIMO-TWRC achieves substantial improvement in spectral efficiency compared to conventional relaying with or without transmit CSI at the relay. They also showed that the difference in sum-rate compared to the case where no CSIT is used increases with increasing ratio between number of relay antennas and number of node antennas. Also XOR precoding always achieves higher minimum user rates than superposition coding if CSIT is used. In (Oechtering & Boche, 2007) the authors propose transmit strategies in a MIMO two-way DF relaying scenario with individual power constraints. The optimal relay transmit strategy is given by two point-to-point water-filling solutions which are coupled by the relay power distribution. The diversity-multiplexing trade-off analysis for the MIMO-TWRC is dealt in (Gunduz et al., 2008). In (Yang & Chun, 2008), the transmission rate is improved by using the generalized Schur decomposition-based MIMO-TWRC.

7. Bidirectional Relaying with Multiple Relays

This section extends the theory of single-relay two-way communication to one level up in the network hierarchy by employing multiple relays. In two-way multiple relay channel two terminals T_1 and T_2 exchange information with the help of M relay terminals in two phases. Dedicated multiple relays can be utilized to relay copies of the transmitted information to the destination such that each copy experiences independent channel fading, hence providing diversity gain to the system. Such communication strategy is best suited for applications in wireless ad-hoc networks, cellular scenarios, and wireless backhaul interconnections.

7.1 Distributed Space-Time Coding

The idea of space-time coding devised for MIMO systems can be applied to a wireless relay network [see (Jing & Hassibi, 2006)] by having the relays that cooperate distributively. The concept of distributed space-time coding (Jing & Hassibi, 2006) is investigated for two-way multiple relay channel in (Cui et al., 2008c). The authors in (Cui et al., 2008c) propose a new type of relaying scheme called *partial* DF for distributed TWRC where each relay removes part of the noise before relaying information in the broadcast phase. They suggest two-way relaying protocols using Linear Dispersion (LD) codes that operate over two time slots. In this scheme, two terminals T_1 and T_2 communicate through multiple relays R_i, $i = 1, ..., M$. Each half-duplex terminal is equipped with a single antenna. Terminal T_j, $j \in [1, 2]$, transmits the signal vector $\mathbf{s}_j = [s_{j1}, ..., s_{jT}]^T$ where $s_{jt} \in \mathcal{A}_m, t = 1, ..., T$, $\mathcal{A}_m$ is a finite constellation with average power of unity, and T is the length of each time slot. Hence, $E\left\{\mathbf{s}_j^H \mathbf{s}_j\right\} = T$. The average power of terminal T_j is P_j and each relay has the equal power P_r/M so that the total power of all the relays is P_r. The noise variance is assumed to be unity at every node. During the first phase, both terminals T_1 and T_2 transmit their message to the relays. The signal received by the ith relay is given by

$$\mathbf{y}_{ri} = \sqrt{2P_1}h_{1i}\mathbf{s}_1 + \sqrt{2P_2}h_{2i}\mathbf{s}_2 + \mathbf{n}_{ri} \tag{51}$$

where $h_{ji} \sim \mathcal{CN}(0,1)$ represents the channel gain between terminal T_j and relay R_i, $\mathbf{n}_{ri}$ is the $T \times 1$ vector representing the AWGN at the ith relay. The source transmit power is assumed to be $\sqrt{2P_j}$ because each source terminal transmits every two time slots. During second time slot, the ith relay processes $\mathbf{y}_{ri}$ and transmits $\mathbf{s}_{ri}$ scaled by g to maintain average power P_r. The signal received by jth terminal is given as

$$\mathbf{y}_j = \sum_{i=1}^{M} gh_{ji}\mathbf{s}_{ri} + \mathbf{n}_j, \quad j = 1, 2, \tag{52}$$

where $\mathbf{n}_j$ is the AWGN vector at the jth terminal.

7.1.1 2-AF

In this scheme $\mathbf{s}_{ri}$ is obtained by precoding $\mathbf{y}_{ri}$ with a unitary matrix $\mathbf{W}_{ri}$ and then scaled by $g = \sqrt{\frac{2P_r}{M(2P_1 + 2P_2 + 1)}}$. The signal received at terminal T_2 is given by

$$\mathbf{y}_2 = g\left(\sqrt{2P_1}\mathbf{S}_1\mathbf{h}_1^- + \sqrt{2P_2}\mathbf{S}_2\mathbf{h}_2^-\right) + \mathbf{z}_2 = g\left(\sqrt{2P_1}\mathbf{H}_1\mathbf{s}_1 + \sqrt{2P_2}\mathbf{H}_2\mathbf{s}_2\right) + \mathbf{z}_2 \tag{53}$$

where $\mathbf{S}_j = [\mathbf{W}_{ri}\mathbf{s}_j, ..., \mathbf{W}_{rM}\mathbf{s}_j]$, $\mathbf{h}_1' = [h_{11}h_{21}, ..., h_{1M}h_{2M}]^T$, $\mathbf{h}_2' = [h_{21}^2, ..., h_{2M}^2]^T$, $\mathbf{z}_2 = g\sum_{i=1}^{M}h_{2i}\mathbf{W}_{ri}\mathbf{n}_{ri} + \mathbf{n}_2$, $\mathbf{H}_1 = g\sum_{i=1}^{M}h_{1i}h_{2i}\mathbf{W}_{ri}$, $\mathbf{H}_2 = g\sum_{i=1}^{M}h_{2i}^2\mathbf{W}_{ri}$.

Since terminal T_2 knows the back propagating signal $\mathbf{s}_2$, the maximum-likelihood (ML) decoding of $\mathbf{s}_1$ is obtained as (Cui et al., 2008c)

$$\hat{\mathbf{s}}_1 = arg \min_{\tilde{\mathbf{s}}_1 \in \mathcal{A}_1^M} \left\| \mathbf{y}_2 - g\left(\sqrt{2P_1}\mathbf{H}_1\tilde{\mathbf{s}}_1 + \sqrt{2P_2}\mathbf{H}_2\mathbf{s}_2\right) \right\|^2. \tag{54}$$

Similarly, ML decoding of $\mathbf{s}_2$ is performed at terminal T_1. The disadvantage of this scheme is that it amplifies the relay noise.

7.1.2 Partial DF I

This protocol overcomes the drawback of 2-AF scheme (Cui et al., 2008c) by allowing each relay R_i to first decode $\mathbf{s}_1$ and $\mathbf{s}_2$ via the ML decoder

$$\{\hat{\mathbf{s}}_{1i}, \hat{\mathbf{s}}_{2i}\} = arg \min_{\tilde{\mathbf{s}}_1 \in \mathcal{A}_1^M, \tilde{\mathbf{s}}_2 \in \mathcal{A}_2^M} \left\| \mathbf{y}_{ri} - \sqrt{2P_1}h_{1i}\mathbf{W}_{ri}\tilde{\mathbf{s}}_1 - \sqrt{2P_2}h_{2i}\mathbf{W}_{ri}\tilde{\mathbf{s}}_2 \right\|^2. \tag{55}$$

The number of unknowns in the above equation is twice the number of equations, this making the error probability high. For this reason it has been suggested in (Cui et al., 2008c) that instead of sending $\hat{\mathbf{s}}_{1i}$ and $\hat{\mathbf{s}}_{2i}$ directly, each relay transmits

$$\mathbf{s}_{ri} = \mathbf{W}_{ri}\left(\sqrt{2P_1}h_{1i}\hat{\mathbf{s}}_{1i} + \sqrt{2P_2}h_{2i}\hat{\mathbf{s}}_{2i}\right) \tag{56}$$

scaled by $g = \sqrt{\frac{P_r}{M(P_1 + P_2)}}$. Thus the relays remove noise from the received signal without dealing with the channel effects. If $Pr(\Delta\mathbf{s}_{1i}, \Delta\mathbf{s}_{2i})$ represents the pairwise error probability at the ith relay, where $\Delta\mathbf{s}_{1i} = \mathbf{s}_1 - \hat{\mathbf{s}}_{1i}$ and $\Delta\mathbf{s}_{2i} = \mathbf{s}_2 - \hat{\mathbf{s}}_{2i}$, then the ML decoding at T_2 is given as (Cui et al., 2008c)

$$\hat{\mathbf{s}}_1 = arg \max_{\tilde{\mathbf{s}}_1 \in \mathcal{A}_1^M} \sum_{\Delta \mathbf{s}_{1i}, \Delta \mathbf{s}_{2i}} \prod_{i=1}^{M} Pr(\Delta \mathbf{s}_{1i}, \Delta \mathbf{s}_{2i}) \exp\left\{ - \left\| \mathbf{y}_2 + \mathbf{y}' - \mathbf{y}'' \right\|^2 \right\} \tag{57}$$

where $\mathbf{y}' = g \sum_{i=1}^{M} \mathbf{W}_{ri} \left(\sqrt{2P_1} h_{1i} \Delta \mathbf{s}_{1i} + \sqrt{2P_2} h_{2i} \Delta \mathbf{s}_{2i} \right)$ and $\mathbf{y}'' = g \left(\sqrt{2P_1} \mathbf{H}_1 \tilde{\mathbf{s}}_1 + \sqrt{2P_2} \mathbf{H}_2 \mathbf{s}_2 \right)$.

It is difficult to implement the above decoder directly when either number M or constellation size is large. At high SNR, $\prod_{i=1}^{M} Pr(\Delta \mathbf{s}_{1i}, \Delta \mathbf{s}_{2i})$ is dominated by $\Delta \mathbf{s}_{1i} = \mathbf{0}$, $\Delta \mathbf{s}_{2i} = \mathbf{0}$. Therefore the ML decoding at terminal T_2 can be approximated as follows

$$\hat{\mathbf{s}}_1 = arg \min_{\tilde{\mathbf{s}}_1 \in \mathcal{A}_1^M} \left\| \mathbf{y}_2 - g \left(\sqrt{2P_1} \mathbf{H}_1 \tilde{\mathbf{s}}_1 + \sqrt{2P_2} \mathbf{H}_2 \mathbf{s}_2 \right) \right\|^2. \tag{58}$$

Similarly, ML decoding at terminal T_1 can be approximated (Cui et al., 2008c).

7.1.3 Partial DF II

In both AF and *partial* DF I schemes, a weighted sum of symbols is transmitted from two terminals. This causes wastage of power since each destination knows the back-propagating signal. In *partial* DF II (Cui et al., 2008c), components are superimposed via modular arithmetic. Let the size of constellation $\mathcal{A}_j$ be Z_j with $\mathcal{A}_j(q)$ representing the qth element of $\mathcal{A}_j$, where $j = 1, 2$ and $q = 0, ..., Z_j - 1$. Consider $\mathbf{u}_1$ and $\mathbf{u}_2$ such that $\mathcal{A}_1(\mathbf{u}_1) = \mathbf{s}_1$ and $\mathcal{A}_2(\mathbf{u}_2) = \mathbf{s}_2$. With the setting $Z = \max\{Z_1, Z_2\}$, it can be assume that $Z_1 \geq Z_2$ without loss of generality. Under this protocol, each relay obtains $\hat{\mathbf{s}}_{1i}, \hat{\mathbf{s}}_{2i}$ from Equation (55) as in *partial* DF I. If $\mathcal{A}_1(\hat{\mathbf{u}}_{1i}) = \hat{\mathbf{s}}_{1i}$ and $\mathcal{A}_2(\hat{\mathbf{u}}_{2i}) = \hat{\mathbf{s}}_{2i}$ then each relay transmits

$$\mathbf{s}_{ri} = \mathbf{W}_{ri} \mathcal{A}_1 \left(mod \left(\hat{\mathbf{u}}_{1i} + \hat{\mathbf{u}}_{2i}, Z \right) \right) \tag{59}$$

where "*mod*" stand for the componentwise modular operation and $g = g_i = \sqrt{\frac{2P_r}{M}}$. Since fading channels are considered, the probability that there exists a pair of vectors $\{\mathbf{u}_1, \mathbf{u}_2\}$ and $\{\hat{\mathbf{u}}_1, \hat{\mathbf{u}}_2\}$ such that $\sqrt{2P_1} h_{1i} \mathcal{A}_1(\mathbf{u}_1) + \sqrt{2P_2} h_{2i} \mathcal{A}_2(\mathbf{u}_2) = \sqrt{2P_1} h_{1i} \mathcal{A}_1(\hat{\mathbf{u}}_1) + \sqrt{2P_2} h_{2i} \mathcal{A}_2(\hat{\mathbf{u}}_2)$ is very small. It has been shown in (Cui et al., 2008) that the AF protocol achieves the diversity order $min\{M, T\} \left(1 - \frac{\log\log P}{\log P}\right)$, where P is the total power of the network whereas the *partial* DF II protocol achieves a diversity order M when $T \geq M$.

7.2 Distributed Relay Selection Scheme

A distributed relay selection strategy is proposed in (Ding et al., 2009) that selects the best suited relay for realizing PNC in a dense relays network. In this transmission scheme, both T_1 and T_2 broadcast their information to all M relays simultaneously during first phase. The signal received at the ith relay R_i is given by

$$y_{ri} = \sqrt{P} h_{1i} s_1 + \sqrt{P} h_{2i} s_2 + n_{ri} \tag{60}$$

where P is the source transmission power, s_j represents the unit-power signal transmitted by the jth source, and h_{ji} represents the channel gain between the jth source and the ith relay. The channel model for frequency flat Rayleigh fading is considered as

$$h_{ji} = \frac{\hbar_{ji}}{\sqrt{d_{ji}^\alpha}} \tag{61}$$

where $\hbar_{ji}$ accounts for the channel fading characteristics due to the rich scattering environment, d_{ji} represents the distance between the jth source and the ith relay, and α is the path loss exponent. It is reasonable to assume that each relay terminal has its local channel information under channel reciprocity condition. This local channel information can be exploited in realizing a distributed strategy of relay selection to improve the system performance. For instance, consider that the relay R_b has been chosen as the best relay with corresponding channels h_{1b} and h_{2b}. In the second phase the best relay R_b performs AF operation and transmits the mixed signal given by

$$s_{rb} = \frac{\sqrt{P}h_{1b}s_1 + \sqrt{P}h_{2b}s_2 + n_{rb}}{\sqrt{P|h_{1b}|^2 + P|h_{2b}|^2 + \sigma^2}}\sqrt{P} \tag{62}$$

to the two destinations. After removing the back-propagating self interference, the signal received at jth terminal is given by

$$y_j = \frac{\sqrt{P}h_{jb}}{\sqrt{P|h_{1b}|^2 + P|h_{2b}|^2 + \sigma^2}}\left(\sqrt{P}h_{lb}s_l + n_{rb}\right) + n_j. \tag{63}$$

Therefore the mutual information between the lth source and jth destination is given by

$$I_{jl} = \log\left(1 + \frac{\gamma^2|h_{1b}|^2|h_{2b}|^2}{2\gamma|h_{jb}|^2 + \gamma|h_{lb}|^2 + 1}\right), \forall \quad j \neq l \quad \& \quad j,l \in [1,2], \tag{64}$$

where $\gamma = P/\sigma^2$ represents the SNR. Relay selection (Ding et al., 2009) is performed in medium access layer. It has been claimed that the two destinations have different preferences but they do not tend to contradict each other. The relay with channels yielding large I_{12} also has channels that give a large value for I_{21}, if not exactly the maximum. The best relay is selected based on the following criterion

$$\frac{|h_{1b}|^2|h_{2b}|^2}{2\gamma|h_{1b}|^2 + \gamma|h_{2b}|^2 + 1} \tag{65}$$

that maximizes the value of I_{12}. Then for this selected relay, the mutual information for second source, I_{21} is determined. The relay selected in such a way is suboptimal for the second source and hence some performance loss for the second source can be expected. The outage probability for this scheme (Ding et al., 2009) at high SNR is

$$Pr[I_{jl} < \mathcal{R}] = \frac{[(d_{jb}^\alpha + 2d_{lb}^\alpha)(2^\mathcal{R} - 1)]^M}{\gamma^M}. \tag{66}$$

It is clear from Equation (66) that the proposed transmission scheme in (Ding et al., 2009) has the advantage of diversity of order M. While the authors in (Ding et al., 2009) dealt with the relay selection scheme for the specific case of PNC-based TWRC, the problem is relevent in all TWRC based links.

8. Summary and Future Directions

Cooperative relaying has evolved in recent years as a powerful tool to enhance the reliability and throughput of wireless radio networks. The basic research challenge is to design spectrally efficient relaying schemes for better utilization of the available resources like power

and spectrum. In this chapter, we discussed several half-duplex cooperative relaying protocols and their performances. Among these, two-way relaying is envisioned as a promising protocol to save radio resources in wireless networks, whereby both up- and down-link are transmitted on the same channel resources.

There are still many open issues related to the channels investigated so far. Mostly the slow frequency flat fading scenarios has been considered in the literature, performance analysis for fast as well as frequency selective fading two-way relay channels need to be addressed. The theoretical capacity limits or achievable rate regions of TWRC still needs to be developed for clustered and distributed scenarios. The reported protocols still suffer performance loss as compared to the theoretical bounds. So better code designs with acceptable complexity need to be urgently evolved to meet the above challenge. MIMO bidirectional relaying strategies has already gained some momentum, but schemes like beamforming, distributed coding, and relay selection still need to be explored. Perfect synchronization among multiple radios is perhaps the most difficult task to perform for bidirectional traffic in a cooperative network.

Cooperative relaying techniques can be expected to be adopted in future wireless systems, as it has been introduced in the IEEE 802.16j (WiMAX) standard. However, substantial research efforts are needed to construct practical systems based on bidirectional cooperation for larger wireless networks. Immense research interest is currently being focused to assess whether the cooperation technology enables the implementation of cognitive radio.

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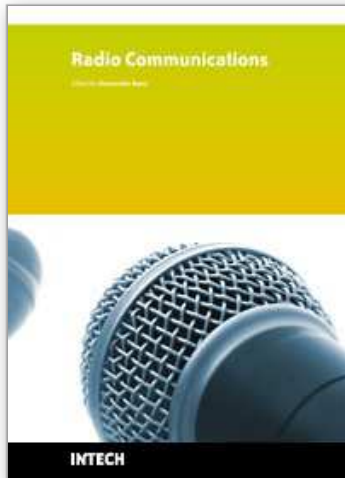
Radio Communications

Edited by Alessandro Bazzi

In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.

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