Chapter 2
Relay Protocols

This chapter introduces the input-output relations for the AF relay schemes considered in this brief.

2.1 General System Model

The system considered in this brief, shown in Fig. 2.1, consists of three single-antenna nodes: a relay node R, and two HD source nodes S_1 and S_2. The relay node R assists in the transmission between S_1 and S_2, and might operate in either HD or FD mode. In the FD mode, the residual self-interference is explicitly taken into account. The channel gain from S_1 to S_2 is denoted by h_0, whereas the gains from S_1 to R and S_2 to R are given respectively by h_1 and h_2. These channel gains are assumed to be reciprocal so that the gains from node A to node B and from B to A are the same, $A, B \in \{S_1, S_2, R\}$ $(A \neq B)$. For simplicity, we denote $h_l = \sqrt{\alpha_l} e^{j\theta_l}$, where α_l and θ_l are the magnitude squared and phase of h_l, $l \in \{0, 1, 2\}$. In this brief, we consider *frequency-flat Rayleigh fading* so that the channel gains are independent zero-mean circularly Gaussian distributed which is denoted as $h_l \sim \mathscr{CN}(0, \phi_l)$, i.e., with Rayleigh distributed magnitude. Furthermore, we adopt the *block fading* model such that the channel gains $\boldsymbol{h} = [h_0, h_1, h_2]$ remain constant for a coherence interval T_c (given in number of symbol periods) and change independently after. We consider both the static scenario (where transmitted codeword spans over a time-invariant $\boldsymbol{h}$) and the fast fading one (where it spans over multiple realizations of $\boldsymbol{h}$). We first introduce the HD protocols of interest before describing the FD ones.

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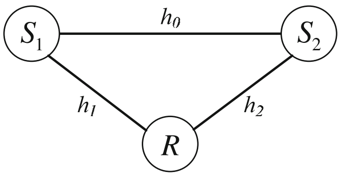
Fig. 2.1 Relay system



2.2 HD Protocols

The considered HD protocols are described in the following.

2.2.1 NAF Protocol

We first introduce the OW *non-orthogonal AF* (NAF) protocol, which is obtained by combining non-orthogonal transmission in Fig. 1.1 with the AF relaying scheme. Specifically, we consider the NAF scheme studied in [1, 3, 7], which has been shown to be optimal in terms of diversity-multiplexing tradeoff over the single-relay AF channel [1]. Without loss of generality, we assume S_1 is the source node S and S_2 the destination node D. In this protocol, transmission is carried in cooperative frames composed of two unit-time phases (where $T_c \geq 2$ is a multiple of two). In the first phase, denoted as the broadcasting phase, S sends the first signal x_1 to both R and D. The received signals at R and D can be written respectively as

$$y_{r,1} = \sqrt{P_s} h_1 x_1 + n_{r,1}, \quad \text{and} \quad y_1 = \sqrt{P_s} h_0 x_1 + n_{d,1},$$

where P_s is a constant related to the transmission power at S; and $n_{r,1}$ and $n_{d,1}$ are the independent noise samples with respective variance N_r and N_d, denoted as $n_{r,1} \sim \mathscr{CN}(0, N_r)$ and $n_{d,1} \sim \mathscr{CN}(0, N_d)$. In the second or cooperative phase, S sends the signal x_2 to D while R amplifies and forwards the symbol received during the first phase to D using an amplification coefficient b. The received signal at D in the second phase is expressed as

$$y_2 = \sqrt{P_s} h_0 x_2 + \sqrt{P_r} b h_2 y_{r,1} + n_{d,2} = \sqrt{P_s} h_0 x_2 + \sqrt{P_r} b h_2 (\sqrt{P_s} h_1 x_1 + n_{r,1}) + n_{d,2},$$

where P_r is a constant related to the transmission power at R and $n_{d,2} \sim \mathscr{CN}(0, N_d)$.

The signal received at D over these two phases, $\boldsymbol{y} = [y_1, y_2]^\top$, can be written in matrix form as in [3]:

$$y = \sqrt{P_s}\underbrace{(h_0 \boldsymbol{I}_2 + \sqrt{P_r} h_1 h_2 \boldsymbol{B})}_{\boldsymbol{H}_{\mathrm{NAF}}} \boldsymbol{x} + \underbrace{\sqrt{P_r} h_2 \boldsymbol{B} \boldsymbol{n}_r + \boldsymbol{n}_d}_{\boldsymbol{n}} = \sqrt{P_s} \boldsymbol{H}_{\mathrm{NAF}} \boldsymbol{x} + \boldsymbol{n}, \tag{2.1}$$

where $\boldsymbol{x} = [x_1, x_2]^\top$ is the input vector; $\boldsymbol{B} = \begin{pmatrix} 0 & 0 \\ b & 0 \end{pmatrix}$; $\boldsymbol{n}_r = [n_{r,1}, n_{r,2}]^\top \sim \mathscr{CN}(\boldsymbol{0}, N_r \boldsymbol{I}_2)$ is the noise vector at R; and $\boldsymbol{n}_d = [n_{d,1}, n_{d,2}]^\top \sim \mathscr{CN}(\boldsymbol{0}, N_d \boldsymbol{I}_2)$ is the noise vector at D. The equivalent 2×2 channel matrix in (2.1) is thus

$$\boldsymbol{H}_{\mathrm{NAF}} = \begin{pmatrix} h_0 & 0 \\ \sqrt{P_r} b h_1 h_2 & h_0 \end{pmatrix}, \tag{2.2}$$

and the equivalent noise vector $\boldsymbol{n} = [n_1, n_2]^\top = [n_{d,1}, \sqrt{P_r} b h_2 n_{r,1} + n_{d,2}]^\top \sim \mathscr{CN}(\boldsymbol{0}, \boldsymbol{K})$ with

$$\boldsymbol{K} = \begin{pmatrix} N_d & 0 \\ 0 & N_d + P_r b^2 \alpha_2 N_r \end{pmatrix}. \tag{2.3}$$

Let the temporal covariance matrix of the input vector $\boldsymbol{x}$ be denoted as $\boldsymbol{Q} = \mathbb{E}[\boldsymbol{x}\boldsymbol{x}^\dagger] = \begin{pmatrix} q_1 & q_{12} \\ q_{12}^\dagger & q_2 \end{pmatrix} \succeq \boldsymbol{0}$. From the covariance matrix and (2.1), it is straightforward to see that S allocates a power of $q_1 P_s$ to x_1 in the first phase and $q_2 P_s$ to x_2 in the second phase. The average transmitted power at S is then $P_s \cdot \mathrm{tr}(\boldsymbol{Q}) = P_s(q_1 + q_2)$ per transmission frame or $(P_s/2) \cdot \mathrm{tr}(\boldsymbol{Q}) = P_s(q_1 + q_2)/2$ per symbol period. Now, let $z_2 P_r$ be the average power constraint at R in the second phase, i.e., $\mathbb{E}[b^2 |\sqrt{P_s} h_1 x_1 + n_{r,1}|^2] = z_2$. The amplification coefficient can then be expressed as

$$b = \sqrt{\frac{z_2}{q_1 P_s \Xi_1 + N_r}}, \tag{2.4}$$

where the parameter Ξ_1 depends on the CSI available at the relay. For instance, when the relay only knows the second order statistics of the S-R channel, the FG CDI coefficient is obtained by setting $\Xi_1 = \phi_1$. On the other hand, when the relay has instantaneous knowledge of the $S - R$ link, the VG CI coefficient is given with $\Xi_1 = \alpha_1$.

As a shorthand notation, let the mutual information between the input $\boldsymbol{x}$ and output $\boldsymbol{y}$ vectors of (2.1) conditioned on a realization of $\boldsymbol{h}$ be given by $I|\boldsymbol{h}$. Assuming Gaussian codebooks at the source, the conditional achievable rate (in b/s/Hz) can be written from (2.1) as in [3]:

$$I|\boldsymbol{h} = \frac{1}{2} \log \det(\boldsymbol{I}_2 + P_s \boldsymbol{H}_{\mathrm{NAF}}^\dagger \boldsymbol{K}^{-1} \boldsymbol{H}_{\mathrm{NAF}} \boldsymbol{Q}), \tag{2.5}$$

with $\boldsymbol{K}$ as in (2.3) and $\boldsymbol{H}_{\mathrm{NAF}}$ as in (2.2). In (2.5), the $1/2$ pre-log factor is due to the fact that the transmission protocol is carried over two phases. The unconditional mutual information or ergodic achievable rate can then be obtained by averaging (2.5) over the channel gains, i.e., $I = \mathbb{E}[I|\boldsymbol{h}]$. Note that the NAF protocol introduced above is general, in the sense that it includes the direct transmission scheme and other OW relay protocols as explained below.

2.2.2 DT Protocol

In the *direct transmission* (DT) protocol, the relay is not used for transmission $b = 0$ and the source simply communicates its information through the direct S-D link. Although the DT scheme is not a relay protocol, it is an important alternative in cooperative systems where using the relay might not always be beneficial. By substituting $z_2 = 0$ in (2.1), the input-output relation for the DT scheme is given by

$$\boldsymbol{y} = \sqrt{P_s}\begin{pmatrix} h_0 & 0 \\ 0 & h_0 \end{pmatrix}\boldsymbol{x} + \boldsymbol{n}_d. \tag{2.6}$$

The conditional rate in (2.5) when x_1 and x_2 are independent ($q_{12} = 0$) and $z_2 = 0$ reduces to

$$I|\boldsymbol{h} = \frac{1}{2}\left[\log\left(1 + \frac{q_1\alpha_0 P_s}{N_d}\right) + \log\left(1 + \frac{q_2\alpha_0 P_s}{N_d}\right)\right]. \tag{2.7}$$

2.2.3 OAF Protocol

We now describe the *orthogonal AF* (OAF) in which the source and relay alternate for transmission. This protocol is given by combining orthogonal transmission in Fig. 1.1 with AF relaying and can be obtained by setting $q_2 = 0$ in the NAF protocol. Specifically, the input-output relation in (2.1) simplifies when $q_2 = 0$ to

$$\boldsymbol{y} = \sqrt{P_s}\boldsymbol{h}_{\mathrm{OAF}}x_1 + \boldsymbol{n}, \tag{2.8}$$

where $\boldsymbol{h}_{\mathrm{OAF}} = [h_0, \sqrt{P_r}bh_1h_2]^\top$ is the first column of (2.2) and the covariance matrix of $\boldsymbol{n}$ is still given as in (2.3). The conditional achievable rate of the OAF system is then given from (2.8) as

$$I|\boldsymbol{h} = \frac{1}{2}\log\left(1 + \frac{q_1\alpha_0 P_s}{N_d} + \frac{\alpha_1\alpha_2 q_1 b^2 P_s P_r}{N_d + \alpha_2 b^2 P_r N_r}\right). \tag{2.9}$$

2.2.4 DHAF Protocol

In the *dual-hop AF* (DHAF) protocol in Fig. 1.1, the direct link from source to destination is either ignored or heavily shadowed so that it cannot be used for communication. The input-output relation in this case can be obtained by setting $q_2 = 0$ and $h_0 = 0$ in (2.1) as

$$y = \sqrt{P_s P_r} b h_1 h_2 x_1 + n_2, \tag{2.10}$$

where $n_2 \sim \mathscr{CN}(0, N_d + b^2 \alpha_2 P_r N_r)$. The conditional rate of the DHAF system is then given by

$$I|\boldsymbol{h} = \frac{1}{2} \log \left(1 + \frac{\alpha_1 \alpha_2 q_1 b^2 P_s P_r}{N_d + \alpha_2 b^2 P_r N_r} \right). \tag{2.11}$$

2.2.5 TWAF Protocol

We now turn our attention to the *two-way AF* (TWAF) protocol in which S_1 and S_2 want to exchange information as in Fig. 1.1. In particular, we consider the two-phase TW system in [6, 8] as it provides a higher multiplexing gain than the three-phase scheme [5]. Transmission in this protocol is again carried in frames divided in two unit-time phases (where $T_c \geq 2$ is a multiple of two). In the first phase, also referred to as the multiple-access phase, S_1 and S_2 transmit simultaneously their respective symbols x_1 and x_2 to R. The received signal at R is given by

$$y_{r,1} = \sqrt{P_{s1}} h_1 x_1 + \sqrt{P_{s2}} h_2 x_2 + n_{r,1},$$

where $n_{r,1} \sim \mathscr{CN}(0, N_r)$, and P_{si} is constant related to the power transmitted at node S_i ($i \in \{1, 2\}$). In the second phase, denoted as the broadcasting phase, R simply amplifies the received signal and broadcasts it to S_1 and S_2. The signal received at S_i can be written as

$$y'_i = \sqrt{P_r} b h_i y_{r,1} + n_{d,i} = \sqrt{P_r} b h_i (\sqrt{P_{s1}} h_1 x_1 + \sqrt{P_{s2}} h_2 x_2 + n_{r,1}) + n_{d,i},$$

where $n_{d,i} \sim \mathscr{CN}(0, N_{di})$ is the noise sample at node i. Assuming perfect knowledge of $\boldsymbol{h}$ and b at S_i, the self-interference term created by its own transmitted signal x_i can be removed as $y_i = y'_i - \sqrt{P_{si} P_r} b h_i^2 x_i$. The received signal at S_i after removing the self-interference can then be written as

$$y_i = \sqrt{P_{sk} P_r} b h_1 h_2 x_k + \sqrt{P_r} b h_i n_r + n_{d,i} = \sqrt{P_{sk} P_r} b h_1 h_2 x_k + n_i, \tag{2.12}$$

where $k = 3 - i$ and the equivalent noise $n_i \sim \mathscr{CN}(0, N_{di} + \alpha_i b^2 P_r N_r)$.

Let $q_i = \mathbb{E}[|x_i|^2]$ so that the average power allocated at S_i in the first phase is $q_i P_{si}$. As before, two types of amplification coefficient can be used at relay depending on the availability of channel knowledge:

$$b = \sqrt{\frac{z_2}{q_1 P_{s1} \Xi_1 + q_2 P_{s2} \Xi_2 + N_r}}. \tag{2.13}$$

In the case of the FG CDI technique $\Xi = \phi$, whereas $\Xi = \alpha$ for the VG CI coefficient.

The conditional achievable rate in the $S_k \rightarrow S_i$ direction can be expressed from (2.12) as in [6, 8]:

$$I_i|\boldsymbol{h} = \frac{1}{2} \log \left(1 + \frac{q_k \alpha_1 \alpha_2 b^2 P_{sk} P_r}{N_{di} + \alpha_i b^2 P_r N_r} \right). \tag{2.14}$$

The conditional sum rate is then given as $I_{\text{sum}}|\boldsymbol{h} = I_1|\boldsymbol{h} + I_2|\boldsymbol{h}$ and the unconditional achievable sum rate is $I_{\text{sum}} = \mathbb{E}[I_{\text{sum}}|\boldsymbol{h}]$. It should be noted that the OW schemes introduced above can also be seen as TW protocols carried over four transmission phases, i.e., $S_1 \rightarrow S_2$ over the first two phases and $S_2 \rightarrow S_1$ over the remaining two.

2.3 FD Protocols

We now introduce the FD protocols of interest.

2.3.1 LR Protocol

First, we describe the *linear relaying* (LR) protocol introduced in [4], which is obtained by combining cooperative relaying in Fig. 1.2 with AF transmission. The LR protocol can be considered as a generalization of NAF relaying to FD operation and has only been studied in terms of achievable rate under no self-interference [2, 4]. As before, we assume that S_1 is the source S and S_2 the destination D. The transmission in LR is carried in frames composed of L symbol periods (where $T_c \geq L$ is a multiple of L). In each symbol period i ($1 \leq i \leq L$), S transmits the information signal x_i to both the relay R and the destination D. At the same time, R transmits a linear combination of symbols previously received in the same frame to D.

Specifically, the signal received at the relay at time i can be expressed as

$$y_{r,i} = \sqrt{P_s} h_1 x_i + n_{r,i} + v_i, \tag{2.15}$$

where $n_{r,i} \sim \mathcal{CN}(0, N_r)$; and v_i is the residual self-interference term due to FD operation and after self-interference cancellation. In the following, we assume that this term is Gaussian as $v_i \sim \mathcal{CN}(0, V)$. Detailed discussions about the distribution and variance of v_i are provided in Chap. 7. The signal transmitted from the relay at time $i \geq 2$ can be written as

$$t_i = \sum_{k=1}^{i-1} b_{i,k} y_{r,k},$$

where $b_{i,k}$ is the coefficient used at time i to amplify the signal received at time k, $y_{r,k}$, $1 \leq k \leq i-1$. The signal received at the destination is thus given by

$$y_i = \sqrt{P_s} h_0 x_i + \sqrt{P_r} h_2 t_i + n_{d,i},$$

where $n_{d,i} \sim \mathcal{CN}(0, N_d)$. It should be noted that the relay operates in HD mode in the first time slot, i.e., it receives $y_{r,1}$ but does not transmit ($t_1 = 0$). As such, $y_{r,1}$ in (2.15) does not have the extra residual self-interference term and $v_1 = 0$.

The amplification coefficients $b_{i,k}$ can be grouped into a strictly lower triangular $L \times L$ amplification matrix $\boldsymbol{B}$ as

$$\boldsymbol{B} = \begin{cases} b_{i,k}, \; 2 \leq i \leq L, \;\; 1 \leq k \leq i-1 \\ 0, \quad \text{o.w.} \end{cases}$$

The signal transmitted by the relay, $\boldsymbol{t} = [0, t_2, \ldots, t_L]^\top$, can then be written in vector form as

$$\boldsymbol{t} = \boldsymbol{B}\boldsymbol{y}_r = \boldsymbol{B}(\sqrt{P_s} h_1 \boldsymbol{x} + \boldsymbol{n}_r + \boldsymbol{v}), \tag{2.16}$$

where $\boldsymbol{y}_r = [y_{r,1}, \ldots, y_{r,L}]^\top$ is the vector received at the relay; $\boldsymbol{x} = [x_1, \ldots, x_L]^\top$; $\boldsymbol{n}_r = [n_{r,1}, \ldots, n_{r,L}]^\top \sim \mathcal{CN}(\boldsymbol{0}, N_r \boldsymbol{I}_L)$; and $\boldsymbol{v} = [0, v_2, \ldots, v_L]^\top \sim \mathcal{CN}(\boldsymbol{0}, \boldsymbol{K}_v)$ is the self-interference vector due to FD operation with

$$\boldsymbol{K}_v = V \cdot \begin{pmatrix} 0 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I}_{L-1} \end{pmatrix}. \tag{2.17}$$

The signal received at the destination over the L time slots can be similarly expressed in matrix form as

$$\boldsymbol{y} = \sqrt{P_s} \underbrace{(h_0 \boldsymbol{I}_L + \sqrt{P_r} h_1 h_2 \boldsymbol{B})}_{\boldsymbol{H}_{\mathrm{LR}}} \boldsymbol{x} + \underbrace{\sqrt{P_r} h_2 \boldsymbol{B}(\boldsymbol{n}_r + \boldsymbol{v}) + \boldsymbol{n}_d}_{\boldsymbol{n}} = \sqrt{P_s} \boldsymbol{H}_{\mathrm{LR}} \boldsymbol{x} + \boldsymbol{n}, \tag{2.18}$$

where $\boldsymbol{n}_d = [n_{d,1}, \ldots, n_{d,L}]^\top \sim \mathscr{CN}(\boldsymbol{0}, N_d \boldsymbol{I}_L)$. The equivalent $L \times L$ channel matrix in (2.18) is then given by

$$\boldsymbol{H}_{\mathrm{LR}} = h_0 \boldsymbol{I}_L + \sqrt{P_r} h_1 h_2 \boldsymbol{B}, \tag{2.19}$$

and the equivalent $L \times 1$ noise vector $\boldsymbol{n} \sim \mathscr{CN}(\boldsymbol{0}, \boldsymbol{K})$ with

$$\boldsymbol{K} = P_r \alpha_2 \boldsymbol{B} (N_r \boldsymbol{I}_L + \boldsymbol{K}_v) \boldsymbol{B}^\dagger + N_d \boldsymbol{I}_L. \tag{2.20}$$

Interestingly, the LR protocol in (2.18) reduces to the NAF in (2.1) for $L = 2$.

Let $\boldsymbol{Q} = \mathbb{E}[\boldsymbol{x}\boldsymbol{x}^\dagger]$ with diagonal elements q_i $(1 \leq i \leq L)$. The source then transmits an average power of $P_s \cdot \mathrm{tr}(\boldsymbol{Q})$ per transmission frame or $(P_s/L) \cdot \mathrm{tr}(\boldsymbol{Q})$ per symbol period. Similarly, let the covariance matrix of the signal transmitted by the relay be denoted as

$$\boldsymbol{Z} = \mathbb{E}[\boldsymbol{t}\boldsymbol{t}^\dagger] = \boldsymbol{B}(\alpha_1 P_s \boldsymbol{Q} + N_r \boldsymbol{I}_L + \boldsymbol{K}_v) \boldsymbol{B}^\dagger, \tag{2.21}$$

with diagonal elements z_i, $(1 \leq i \leq L)$. The relay then transmits an average power of $P_r \cdot \mathrm{tr}(\boldsymbol{Z})$ per transmission frame or $(P_r/L) \cdot \mathrm{tr}(\boldsymbol{Z})$ per symbol period.

Depending on the CSI available at the relay and on how the symbols $y_{r,k}$ are superimposed, different amplification matrices $\boldsymbol{B}$ can be considered as discussed before. For instance, one can assume that the relay only amplifies the signal received in the previous period similar to [2]. In this case, $b_{i,k} = b$ when $k = i - 1$ and $b_{i,k} = 0$ otherwise $(2 \leq i \leq L)$, where

$$b = \sqrt{\frac{\mathrm{tr}(\boldsymbol{Z})}{N_r(L-1) + V(L-2) + P_s \Xi_1 \sum_{i=2}^{L} q_{i-1}}}. \tag{2.22}$$

As before, $\Xi = \alpha$ when the relay has instantaneous knowledge of the S-R link and $\Xi = \phi$ when only second order statistics are known.

Assuming Gaussian codebooks at the source, the conditional achievable rate can be written from (2.18) as

$$I|\boldsymbol{h} = \frac{1}{L} \log\det(\boldsymbol{I}_L + \boldsymbol{H}_{\mathrm{LR}}{}^\dagger \boldsymbol{K}^{-1} \boldsymbol{H}_{\mathrm{LR}} \boldsymbol{Q}), \tag{2.23}$$

with $\boldsymbol{K}$ as in (2.20) and $\boldsymbol{H}_{\mathrm{LR}}$ as in (2.19).

2.3.2 DHAF Protocol

Next, we consider the FD DHAF protocol in Fig. 1.2. In this protocol, the direct S-D link is either non-existent $\alpha_0 = 0$ due to heavy shadowing or treated as a source of interference. In particular, the source continuously transmits its information symbol x_i while the relay amplifies and forwards the signal received in the previous time slot with a power amplification b. Specifically, the signal received at R at time i can be written as in (2.15), whereas the signal transmitted by R is now $t_i = by_{r,i-1}$ The signal received at D can then be written as

$$y_i = \sqrt{P_s P_r} h_1 h_2 b x_{i-1} + \sqrt{P_r} h_2 b(n_{r,i-1} + v_{i-1}) + \sqrt{P_s} h_0 x_i + n_{d,i}, \tag{2.24}$$

where x_i is treated as interference when $\alpha_0 > 0$ and x_{i-1} is the desired symbol.

Let $\mathbb{E}[|x_i|^2] = q_1$ so that an average power of $q_1 P_s$ is spent at the source. Assuming an average power of $z_2 P_r$ at the relay, the amplification coefficient in (2.24) can be expressed as

$$b = \sqrt{\frac{z_2}{q_1 P_s \Xi_1 + N_r + V}}. \tag{2.25}$$

Assuming Gaussian codebooks at S, the conditional achievable rate can now be written from (2.24) as

$$I|\boldsymbol{h} = \left(1 + \frac{\alpha_1 \alpha_2 q_1 P_s P_r b^2}{\alpha_2 P_r b^2 [N_r + V] + N_d + \alpha_0 q_1 P_s}\right). \tag{2.26}$$

It can be observed that similar to the LR protocol, the relay of the DH protocol operates in HD mode in the first time slot. However, assuming that the DH transmission is carried continuously over several time slots, the effect of this transient state is negligible and can thus be ignored in (2.24).

2.4 Concluding Remarks

This chapter introduced the HD and FD protocols of interest. The achievable rate and error performance of these protocols are analyzed in the following chapters.

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