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Hybrid half-duplex/full-duplex multi-hop relaying schemes: Outage performance and power optimization

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ABSTRACT

Full-duplex (FD) relays can transmit and receive simultaneously over the same frequency band, hence enable a significant improvement of spectral efficiency compared to half-duplex (HD) relays and have attracted much research interests. However, there exists severe interference for FD multi-hop relay networks in which all the relays operate in FD mode. To overcome this problem, we propose hybrid HD/FD multi-hop decode-and-forward (DF) relaying schemes, where in each time block two nodes communicate directly with each other in HD mode or communicate with the help of an FD relay. Assuming that all the channels including the residual self-interference (RSI) channel are subject to Rayleigh fading, we derive the outage probabilities of FD multi-hop relay networks and hybrid HD/FD multi-hop relaying schemes, respectively. Then we optimize the power allocation of the hybrid HD/FD relaying scheme under individual power constraint with the aim of minimizing the outage probability. Finally, we compare the performance of different transmission schemes and validate our analysis by simulation results.

1. Introduction

Multi-hop relay networks, which can improve system capacity, extend coverage area and enhance transmission reliability [1–4], play an important role in *ad hoc* wireless networks [5–8]. In the earlier studies, most researchers assume that the multi-hop relay networks work on half-duplex (HD) mode, which means each relay receives and retransmits the signals over different time slots or frequency bands. Although this assumption can simplify the system design and implementation, it results in significant loss of spectrum efficiency.

In recent years, encouraged by the advances in antenna design and self-interference cancellation (SIC) technologies [9–13], full-duplex (FD) relay networks, where the relay node receives and transmits at the same time and over the same frequency band, has been considered as a promising way to overcome the spectrum efficiency loss of HD mode and therefore has attracted increasing research interests.

So far, most works on FD relay networks have been restricted to a single relay case (i.e., dual-hop relay system), and focused on SIC technologies. In [14], the authors proposed FD relay systems which are constructed based on time and antenna-sharing at the relay node, and SIC by precoding. Riihonen et al. investigated the SIC for multiple-input multiple-output (MIMO) relay system and considered three spatial domain SIC solutions, i.e., antenna and beam selection, null-space projection, and MMSE filtering [15]. In [16], a spatial-domain joint-nulling SIC method was proposed by solving the optimal relay processing matrix over a continuous domain for both amplify-and-forward (AF) and decode-and-forward (DF) type relays. Even though there have been many works on SIC technologies, the self-interference cannot be completely mitigated in practice. As such, several works have taken the effect of residual self-interference (RSI, i.e., the effect of the SI after mitigation) into account. In [17], the outage probabilities of infrastructure-based FD relay networks were derived for both downlink and uplink. In [18], the exact outage probability of FD relay systems was derived by modeling the RSI as a Rayleigh fading channel. In [19], the authors analyzed the outage performance of a selective DF FD relay system that captures the joint effect of RSI and direct link. Different from [17–19], which assumed that the variance of the RSI is proportional to the relay transmit power, references [20] and [21] assumed that the variance of RSI was proportional to the λth power of the average transmit power and investigated the bit error rate (BER) and capacity of AF FD relay systems, respectively.

For multi-hop relay networks with more than two hops or more than one relays, the use of FD relays is different from the dual-hop case. This is because, in multi-hop FD relay networks, the relay nodes suffer not only from RSI but also from inter-relay interference. Therefore, the design and performance analysis of multi-hop FD relay networks are more challenging. In [22], the authors

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considered all the inter-relay signals as interference and investigated the outage performance of multi-hop FD relay networks. It was shown in [22] that multi-hop FD relaying outperforms multi-hop HD relaying only for sufficiently large values of path-loss-to-interference ratio.

In this paper, we propose a hybrid HD/FD multi-hop relaying scheme, which consists of more than one time block. There exist two cases in each time block: (i) two nodes communicate directly with each other in HD mode; (ii) two nodes communicate with the help of an FD relay. Assuming that all the channels including the RSI channel are subject to Rayleigh fading, the outage probabilities of FD multi-hop relay networks and hybrid HD/FD multi-hop relaying schemes are derived, respectively, and the power allocation of hybrid HD/FD relaying scheme is optimized under individual power constraint. Note that although reference [23] proposed a hybrid relaying which could switch between full-duplex and half-duplex mode, and reference [24] proposed an optimal transmission scheduling scheme for a hybrid half-duplex and full-duplex relaying, both of them were restricted to a single relay case and could not be used in multi-hop relay networks.

The rest of the paper is organized as follows. In Section 2, we introduce the system model of multi-hop relay networks. Three duplex schemes are considered, i.e., HD scheme, FD scheme, and hybrid HD/FD scheme. In Section 3, we analyze the outage performance for these three different schemes respectively. Then we optimize the power allocation of hybrid HD/FD scheme in Section 4. Afterward, in Section 5, we present some simulation results to validate our analysis. Finally, Section 6 concludes this paper.

2. System model

Consider a multi-hop relay network, where a source node S communicates with a destination node D through $N-1$ relay nodes $R_1, R_2, \ldots, R_{N-1}$. For notational convenience, S and D are denoted as R_0 and R_N, respectively. We assume that DF relaying scheme is adopted, in which each relay node will decode the received signal and then forward the decoded information to the respective successor node if it is correctly decoded.

We denote the channel between node R_i and R_m by $h_{i,\,m}$, and assume the channel experiences block fading, i.e., $h_{i,\,m}$ remains constant over one block and varies independently from one block to another block. Note that for different i and m, $h_{i,\,m}$ represents different meanings. When $i = m-1$, $h_{m-1,m}$ denotes the communication channel; when $i = m$, $h_{m,\,m}$ denotes the RSI channel; when $i \neq m$ and $i \neq m-1$, $h_{i,\,m}$ denotes the interference channel caused by other relays. Moreover, we assume all the channels including the self-interference channel follow Rayleigh fading, then the channel coefficient $h_{i,\,m}$ is a zero-mean complex Gaussian random variable. When $i \neq m$, the variance of $h_{i,\,m}$ is denoted by $L_{i,\,m}$, which represents the path loss between R_i and R_m; when $i = m$, the variance of $h_{m,\,m}$ denotes the RSI and is assumed to be equal to L_0 for different relays.

2.1. HD multi-hop relay networks

For HD multi-hop relay networks, we can use time-division duplex (TDD) and frequency-division duplex (FDD) mode. In this paper, we only consider TDD mode. It is assumed that channel state information (CSI) is only known at the receive nodes. As such, the total transmission time is divided into N time blocks, which are allocated to the source node and all the relay nodes. For simplicity, we assume only node R_{m-1} transmits in time block m and R_m receives the signal only form R_{m-1}. Therefore, the received signal at R_m in time block m is given as

$$\mathbf{y}_m^{HD} = h_{m-1,m}\mathbf{x}_{m-1} + \mathbf{n}_m, \quad (1)$$

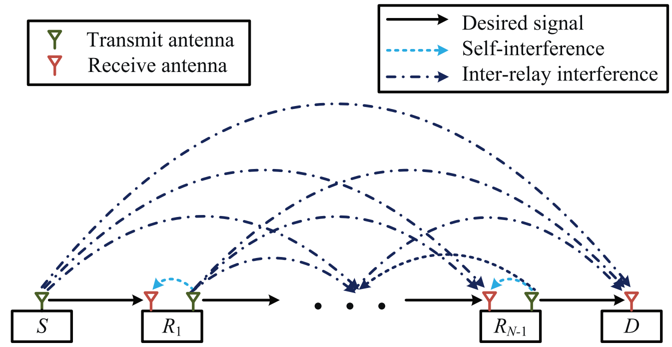

Fig. 1. System model of FD multi-hop relay networks.

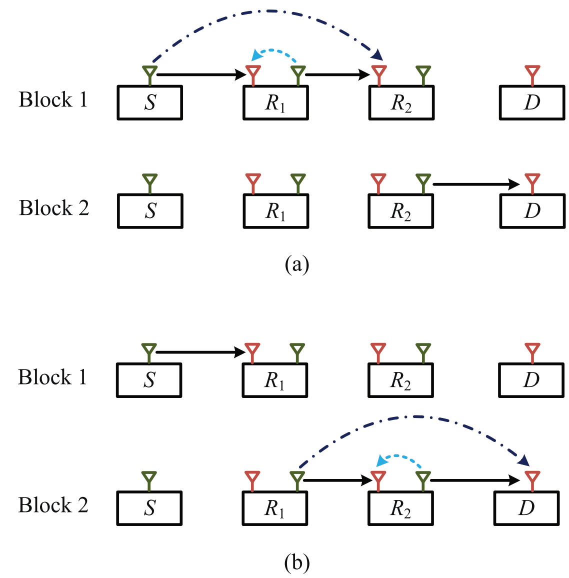

Fig. 2. System model of two hybrid HD/FD multi-hop relaying schemes for $N = 3$.

where $\mathbf{x}_{m-1} = \left[x_{m-1}^1, x_{m-1}^2, \ldots, x_{m-1}^L\right]$ denotes the transmit signal block of L symbols from R_{m-1} and $\mathbf{n}_m$ denotes the complex additive white Gaussian noise (AWGN) with zero mean and variance N_0 at R_m.

2.2. FD multi-hop relay networks

The FD multi-hop relay network is depicted in Fig. 1. We assume that S and D are equipped with a single antenna, and R_m is equipped with two antennas (one for receiving and one for transmitting). Since all the nodes operate in FD mode, the received signal at R_m, $m = 1, 2, \ldots N$, in any time block can be written as

$$\mathbf{y}_m^{FD} = h_{m-1,m}\mathbf{x}_{m-1} + \sum_{i=0, i\neq m-1}^{N-1} h_{i,m}\mathbf{x}_i + \mathbf{n}_m, \quad (2)$$

where $\mathbf{x}_i$ denotes the transmit signal block from R_i.

2.3. Hybrid HD/FD multi-hop schemes

Both HD multi-hop relay networks and FD multi-hop relay networks have their own disadvantages: HD multi-hop networks result in significant loss of spectrum efficiency while FD multi-hop networks lead to severe interference. Therefore, we investigate hybrid HD/FD multi-hop schemes in this paper. For simplicity, we assume only one relay can operate in FD mode in each time block.

In Fig. 2, we illustrate two possible hybrid HD/FD multi-hop relaying schemes for $N = 3$. For scheme (a), R_1 operates in FD mode