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Amplify-and-Forward Relaying in Wireless Communications

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To our families

Preface

Relaying techniques, in which a source node communicates to a destination node with the help of a relay, have been proposed as a cost-effective solution to address the increasing demand for high data rates and reliable services over the air. As such, it is crucial to design relay systems that are able to not only provide high spectral efficiency, but also fully exploit the diversity of the relay channel. With this objective in mind, this brief aims to report on recent advances on achievable rates, power allocation schemes, and error performance for half-duplex (HD) and full-duplex (FD) amplify-and-forward (AF) single-relay systems. First, assuming the relay operates in HD mode, we discuss the capacity and respective optimal power allocation for a wide range of AF protocols over static and fading channels. Then, optimal amplification coefficients in terms of achievable rate are presented. Turning our attention to the performance with finite constellations, the error and diversity performance of AF systems are also discussed. Finally, the capacity and error performance analysis is extended to the FD relay mode of operation, where the residual self-interference due to FD transmission is explicitly taken into account.

The target audience of this Springer Brief is researchers and professionals working on current and next-generation wireless systems. The content is also valuable for advanced students interested in wireless communications and signal processing for communications.

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Acronyms

3GPP	Third Generation Partnership Project
AF	Amplify-and-forward
AWGN	Additive white Gaussian noise
BER	Bit error rate
BF	Beamforming
BICM	Bit-interleaved coded modulation
BICM-ID	Bit-interleaved coded modulation with iterative decoding
CDI	Channel distribution information
CF	Compress-and-forward
CI	Channel inversion
CSI	Channel state information
dB	Decibels
DF	Decode-and-forward
DH	Dual-hop
DHAF	Dual-hop amplify-and-forward
DT	Direct transmission
EXIT	Extrinsic information transfer
FD	Full-duplex
FG	Fixed-gain
FR	Full-rank
HD	Half-duplex
KKT	Karush–Kuhn–Tucker
LLR	Log-likelihood ratio
LR	Linear relaying
LTE	Long Term Evolution
MAP	Maximum *a posteriori* probability
MIMO	Multiple-input multiple-output
ML	Maximum likelihood
MRC	Maximal-ratio combining
multi-D	Multidimensional
NAF	Non-orthogonal amplify-and-forward

OAF	Orthogonal amplify-and-forward
OW	One-way
PEP	Pairwise error probability
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase-shift keying
RA	Relay adaptation
SISO	Soft-input soft-output
SNR	Signal-to-noise ratio
TW	Two-way
TWAF	Two-way amplify-and-forward
VG	Variable-gain

Chapter 1
Relaying: An Overview

Current wireless communications systems face increasing challenges due to the ever growing demand for high data rates and reliable services over the air. As new applications for small wireless devices arise, such rates are expected to be attained using as low power consumption as possible. In addition, bandwidth is a scarce resource and thus wireless systems are also expected to transmit high data rates in a spectrally-efficient manner. All of these requirements need to be considered in the design of emerging and future generations of wireless networks.

Relaying techniques, in which helper nodes aid in transmission from one node to another, have been recently proposed as a cost-effective solution to meet some of the demands in next generations of wireless systems [20, 27, 30, 38]. In particular, in the context of cellular networks, the deployment of relay nodes has been shown to extend and/or improve the coverage, enhance the reliability, and improve the spectral efficiency per unit area. This can be achieved without incurring the associated high costs of adding extra base stations, e.g., site acquisition and backhaul costs. As such, relaying is one of the key features currently being considered in several wireless standards such as the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE), among others [27, 38]. Consequently, it is important for future wireless standards to have relay schemes that not only increase the reliability of the wireless network, but also present a high spectral efficiency [10, 29].

1.1 Half-Duplex Relaying

The relay channel, in which a source node communicates to a destination node with the help of a relay, was first introduced by van der Meulen in [36]. Earlier information theoretical works assumed that the relay is capable of operating in

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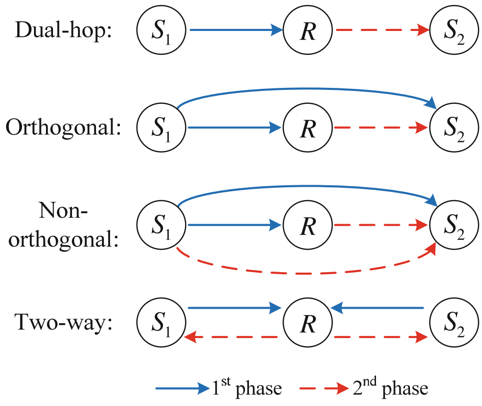


Fig. 1.1 HD relay protocols

full-duplex (FD) mode, i.e., the relay is able to transmit and receive at the same time and over the same frequency band [8, 19, 24, 36, 37]. This assumption was generally believed to be impractical due to the great difference in transmit and receive signal powers levels, which results in self-interference. Thus, motivated by wireless scenarios, the focus on the relay channel was shifted to *half-duplex* (HD) operation.

Seminal works on HD relaying concentrated on the *dual-hop* (DH) strategy, e.g., [6, 15–18]. In DH protocols, information is transmitted from source to destination via the relay in two phases as shown in Fig. 1.1. In the first phase, the source node S_1 transmits to the relay node R, whereas in the second phase, the relay communicates to the destination node S_2 and the source remains silent. Such a DH strategy can be easily implemented in practice to improve the coverage of the network and has already been considered for next-generation mobile communication standards [27, 38]. Furthermore, DH schemes are the only alternative when the *direct* link from source to destination is under severe shadowing. However, when the direct link is available for transmission, DH techniques present two main limitations. First, due to the HD constraint, DH systems are not spectrally-efficient as the source is only allowed to transmit every other phase. Second, although path-loss savings can be obtained, DH protocols provide no diversity gain as there exists only one path from source to destination.

By considering the direct source-destination link, *cooperative* relaying protocols have been introduced to counteract the drawbacks of DH relaying when the direct link is available [2, 25, 26, 28, 29, 35]. Pioneering works on cooperative relaying focused on *orthogonal* schemes in which the source and relay alternate for transmission as in DH systems. However, contrary to DH schemes, the destination also listens to the source node in the first phase as shown in Fig. 1.1. Two independent paths between the source and the destination (the direct and the relay link) are thus created. With proper combining at the destination, rate and diversity advantages over DH protocols can be obtained. This diversity gain, commonly referred to as *cooperative diversity*, is particularly important for small devices which cannot accommodate multiple antennas due to practical constraints. In this case, spatial diversity can still be realized through cooperative relaying in a distributed fashion.

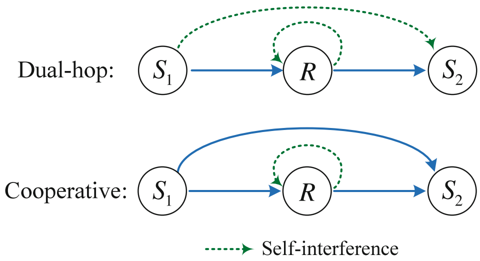
Although orthogonal schemes provide rate and diversity advantages compared to DH transmission, the spectral efficiency of these cooperative protocols still suffers from the HD constraint of the relay. This is because similar to DH relaying, the source must remain silent in the second transmission phase. To mitigate the impact of HD relaying, *non-orthogonal* schemes in which the source is allowed to transmit continuously have been proposed in the literature [2, 28]. In non-orthogonal protocols, as illustrated in Fig. 1.1, the source and relay transmit concurrently in the second phase, maximizing the degrees of broadcasting and receive collision [28]. Moreover, non-orthogonal protocols are general in that they include orthogonal schemes and even direct transmission (i.e., when the relay is not used) as special cases. Unfortunately, the analysis and optimization of non-orthogonal networks are more challenging than their orthogonal counterparts and therefore have received less attention in the literature [2, 9, 28].

In the protocols discussed above, the node S_1 wants to communicate to S_2 via the relay, i.e., information flows from S_1 to S_2 ($S_1 \to S_2$). These protocols can thus be broadly classified as *one-way* (OW) relaying schemes. On the other hand, several applications require the nodes S_1 and S_2 to exchange information in a bidirectional or *two-way* (TW) fashion. A simple method to achieve this is by applying any of the above OW protocols, i.e., $S_1 \to S_2$ over the first two phases and $S_2 \to S_1$ over the remaining two. This exchange would require four transmission phases and only two symbols would be exchanged if we were to use orthogonal or DH schemes. To mitigate the impact of HD relaying for bidirectional communication, two-phase and the three-phase TW protocols have recently been proposed in the literature [23, 32]. Specifically, in the two-phase scheme, both source nodes simultaneously communicate to the relay in the first phase, whereas the relay broadcasts in the second phase (see Fig. 1.1). In the three-phase scheme, the source nodes take turns to communicate to the relay in the first two phases and the relay broadcasts in the third. Similar to OW non-orthogonal protocols, the potential benefits of TW protocols have just started to be investigated.

1.2 Full-Duplex Relaying

It can be seen from the above discussion that the HD constraint of the relay has a great impact on the spectral efficiency of relaying protocols. As explained before, this HD constraint is motivated by the fact that the transmit signal power is usually orders of magnitude larger than the received signal power, resulting in heavy self-interference. Although originally believed to be impractical, FD wireless operation has been recently shown to be feasible through novel combinations of self-interference mitigation schemes (see for example [1, 4, 5, 7, 11–14, 21, 22, 31, 33, 34] and references within). In particular, to avoid saturating the receiver

Fig. 1.2 FD relay protocols



front end, several techniques prior to analog-to-digital conversion have been proposed. For instance, basic analog cancellation methods include antenna separation [11, 12, 14, 33], orientation [33, 34] and directionality [13, 31]. More involved methods include asymmetric placement of transmit antennas [7], symmetric placement of antennas with phase shifters [1, 22], the use of a balanced/unbalanced transformer [21], the use of a circulator [4], and analog time domain subtraction [4, 11–13, 31, 34], among others. These analog techniques can be combined with digital methods after quantization such as time domain subtraction for further mitigation [4, 11–13, 21]. Despite these advances in cancellation techniques, the self-interference remains a challenge as it cannot be completely mitigated in practice. As such, different from earlier information theoretical works, the *residual self-interference* must be explicitly taken into account when assessing, designing and analyzing FD protocols.

Similar to HD schemes, FD protocols can be classified depending on whether the direct source-destination link is used for transmission. In fact, the idea of cooperative relaying can be traced back to the works of van der Meulen and Cover in [8, 36] which make use of the direct link for FD communication. Specifically, in cooperative FD schemes, the source transmits to the relay and the destination, while the relay simultaneously receives the signal from the source and transmits to the destination, as shown in Fig. 1.2. Analogous to the HD DH scheme, the direct link is not used in FD DH protocols. Similar to their HD counterparts, FD DH relaying has two main limitations when the direct link is not under heavy shadowing. First, although the source is allowed to transmit continuously, the rate of the FD DH scheme might be degraded due to the self-interference created at the destination node from the direct link. Furthermore, this protocol does not provide any diversity benefits. Thus, as in the HD scenario, cooperative FD techniques that make use of the direct link for transmission might be able to provide rate and diversity advantages.

1.3 Relay Functions

To this day, the capacity of the general relay channel along with its respective optimal relay function are unknown. Thus, several relay functions have been proposed in the literature. Common relay functions include *decode-and-forward*

(DF), *compress-and-forward* (CF), and *amplify-and-forward* (AF). In DF, the relay first decodes the information received from the source node, encodes it and then forwards it to the destination node [8]. On the other hand, in CF, the relay forwards a quantized version of the received signal to the destination [8]. Finally, the relay simply amplifies the signal received in the previous phase and forwards it to the destination in AF [26]. Among these three strategies, the AF technique is of practical interest as it requires lower implementation and computational complexity, it carries less delay at the relay terminal, and it is transparent to the modulation/coding used by the source nodes [3]. As such, the focus of this brief is on AF relay protocols.

AF relaying can be further classified according to the availability of channel side information (CSI) at the relay node. In particular, to maintain a long-term average power constraint at the relay, most previous studies on AF relaying considered two power amplification techniques. The first method assumes that the relay has only channel distribution information (CDI) of the source-relay link and amplifies the received signal using a *fixed-gain* (FG) coefficient [28]. The second technique assumes that the relay has an instantaneous knowledge of the source-relay channel and uses this channel gain to normalize the received signal to the desired power level [26]. The latter variable-gain (VG) method is therefore referred to as the *channel inversion* (CI) coefficient.

1.4 Organization of this Brief

As noted before, future wireless networks require relaying protocols that are able to fully exploit the diversity of the channel as well as provide high spectral efficiency. Motivated by this fact, the objective of this brief is to report on recent advances on achievable rates, power allocation schemes, and error performance of HD and FD AF relay systems. The outline of this brief is as follows.

First, Chap. 2 introduces the input-output relations of the considered relay protocols.

Then, Chap. 3 discusses the capacity of the static HD non-orthogonal AF (NAF) channel under both per-node and joint power constraints. In particular, by deriving and comparing all local solutions, the optimal input covariance matrix at the source and the optimal power allocation scheme at the relay are characterized. The capacity of the NAF system is also analyzed for some concrete examples, such as under different transmission power levels and several network models.

Considering Rayleigh fading channels, Chap. 4 presents a general method to analyze the achievable rate and to characterize the optimal power allocation scheme for a wide range of HD AF protocols. By exploiting the capacity of a two-branch maximal-ratio combining (MRC) system and a simple approximation to the logarithm, tight yet simple approximations to the achievable rates are obtained in high and low transmission power regimes. Then, using the derived approximations,