PERFORMANCE LIMITS OF AMPLIFY-AND-FORWARD BASED FADING RELAY CHANNELS

Rohit U. Nabar, Felix W. Kneubühler, and Helmut Bölcskei

Swiss Federal Institute of Technology (ETH) Zürich
ETF E119, Sternwartstrasse 7, 8092 Zürich, Switzerland
Email: {nabar, fwk, boelcskei}@nari.ee.ethz.ch

ABSTRACT

In this paper, we examine the basic building block of cooperative diversity systems, a simple fading relay channel where the source, destination and relay terminals are each equipped with single antenna transceivers. We consider three different TDMA-based cooperative protocols that vary the degree of broadcasting and receive collision. For each protocol, the relay terminal simply amplifies-and-forwards the signal received from the source terminal to the destination. We study the ergodic and outage capacity behavior of each of the protocols assuming Gaussian code books and show that full spatial diversity (second-order in this case) is achieved by certain protocols provided that appropriate power control is employed. Finally, we establish the superiority (both from a capacity as well as a diversity point-of-view) of a new protocol proposed in this paper.

1. INTRODUCTION

Diversity is a powerful technique to mitigate fading in wireless channels and improve robustness to interference. A new way of realizing spatial diversity gain (in a distributed fashion) has recently been introduced in [1, 2, 3] under the name of *user cooperation diversity* or *cooperative diversity*. Here, multiple terminals in a network cooperate to form a virtual antenna array, realizing spatial diversity gain in a distributed fashion. In [4] it has been demonstrated that uplink capacity can be increased via user cooperation diversity. A variety of cooperation protocols for channels with a single relay terminal have been studied and analyzed in [5, 6, 7, 8]. In [5] it is shown that for channels with multiple relays, cooperative diversity with appropriately designed codes realizes full spatial diversity gain. We note that many cooperative diversity schemes can be cast into the framework of network coding [9, 10, 11]. Finally, we refer to [12] for fundamental results on non-fading relay channels and to [13, 14] for recent results on scaling laws in large (relay) networks.

Contributions. We study the information-theoretic performance limits of three different TDMA-based transmission protocols for an amplify-and-forward based fading single relay channel. The protocols we consider implement varying degrees of broadcasting and receive collision in the network[1]. Our detailed contributions can be summarized as follows.

- We establish a *unified framework* for the results on fading relay channels reported in [1]–[5], *propose a new protocol which is superior to existing protocols* for the single-relay fading channel, and put the performance gains achievable in the distributed multi-antenna case into the context of traditional MIMO gains.
- Assuming a *Gaussian code book*, we derive *closed form expressions* for *the mutual information* associated with each of the protocols analyzed. Based on these results, we compare the performance of the different protocols in terms of achievable rates and establish the superiority of protocols implementing maximum degrees of broadcasting and receive collision.
- Based on an outage capacity analysis, we investigate the *diversity performance* of the proposed protocols. In particular, we find that *full spatial diversity is achieved by certain protocols provided that appropriate power control is employed*.

Organization of the paper. The rest of this paper is organized as follows. Section 2 introduces the three different TDMA-based protocols analyzed in this paper as well as the corresponding channel and signal models. Section 3 provides an information-theoretic comparison of the different protocols along with numerical results. We conclude in Section 4.

Notation. The superscripts ^{T} and ^{H} stand for transposition and conjugate transposition, respectively. $\mathcal{E}$ denotes the expectation operator. $\mathbf{I}_m$ is the $m \times m$ identity matrix. $\mathbf{0}$ stands for an all zeros matrix of appropriate dimensions. A circularly symmetric complex Gaussian random variable is a random variable $Z = X + jY \sim \mathcal{CN}(0, \sigma^2)$, where X and Y are i.i.d. $\mathcal{N}(0, \frac{\sigma^2}{2})$.

2. PROTOCOLS, CHANNEL AND SIGNAL MODELS

Protocol descriptions. Data is to be transmitted from a source terminal S to a destination terminal D with the assistance of the relay terminal R. All terminals are equipped with single antenna transmitters and receivers. Throughout the paper, we assume that a terminal cannot transmit and receive simultaneously. The relay terminal simply amplifies and retransmits the signal received from the source terminal (the signal received at the relay terminal is corrupted by fading and additive noise).

We shall next describe three different cooperative protocols, which implement varying degrees of broadcasting and receive collision in the network. The degree of broadcasting is given by the number of nodes simultaneously (i.e., in the same time slot) listening to the source node (2 if both R and D listen, 1 if only R or D listens). Furthermore, receive collision is said to be maximum if the destination node receives information simultaneously from both S and R.

Protocol I: Terminal S communicates with R and D simultaneously during the first time slot. In the second time slot R and S simultaneously communicate with D. This protocol realizes maximum degrees of broadcasting and receive collision.

[1]The degree of broadcasting is determined by the number of nodes listening to a broadcasted message.

Protocol II: In this protocol terminal S communicates with terminals R and D simultaneously over the first time slot. In the second time slot, only R communicates with D. This protocol realizes a maximum degree of broadcasting and exhibits no receive collision.

Protocol III: The third protocol is identical to Protocol I apart from the fact that terminal D chooses not to receive the direct[2] S→D signal during the first time slot for reasons that will be motivated later in this section. This protocol does not implement broadcasting but realizes receive collision.

Protocols II and III were first proposed in [15] and [16], respectively. Protocol I appears to be new. Additional comments on the three protocols described above are in order. The conditions and setup for Protocol I are self-evident. Protocol II is logical in a scenario where the source terminal S engages in data reception from another terminal in the network over the second time slot thereby rendering itself unable to transmit. Similarly, for Protocol III terminal D may be engaged in data transmission to another terminal during the first time slot. Hence, the transmitted signal is received only at terminal R and buffered for subsequent forwarding. We assume that terminal S expends the same amount of power over the two time slots. In Protocol II the source terminal is silent over the second time slot, which implies that this protocol is more efficient than Protocols I and III in terms of battery life.

Channel and signal model. Throughout this paper we assume frequency-flat fading, no channel knowledge in the transmitters, perfect channel state information in the receivers and perfect synchronization. Perfect channel state information in the receivers implies that the S→R channel is known to terminal R, while the individual S→D, R→D and S→R channels are known to terminal D. The assumption on synchronization is most critical since synchronization becomes increasingly challenging in larger networks. Protocols II and III are essentially derivatives of Protocol I. We shall therefore first provide the input-output relation for Protocol I and then specialize to Protocols II and III.

Input-output relation for Protocol I: The signals transmitted by the source terminal during the first and second time slots are denoted as $x_1[n]$ and $x_2[n]$, respectively. In the following, we consider symbol-by-symbol transmission so that the time index n can be dropped and we simply write x_1 and x_2 for the symbols transmitted in the first and second time slots, respectively. We assume that $\mathcal{E}\{x_i\} = 0$ and $\mathcal{E}\{|x_i|^2\} = 1$ for $i = 1, 2$. The signal received at the destination terminal in the first time slot is given by

$$y_{D,1} = \sqrt{E_{SD}}\, h_{SD}\, x_1 + n_{D,1}, \tag{1}$$

where E_{SD} is the average signal energy at the destination terminal over one symbol period received through the S→D link (having accounted for path loss and shadowing in the S→D link), h_{SD} is the random, unit power, complex-valued[3] channel gain between source and destination terminals and $n_{D,1} \sim \mathcal{CN}(0, N_o)$ is additive white noise. The signal received at the relay terminal during the first time slot is given by

$$y_{R,1} = \sqrt{E_{SR}}\, h_{SR}\, x_1 + n_{R,1}, \tag{2}$$

where E_{SR} is the average received signal energy at the relay terminal over one symbol period (having accounted for path loss and shadowing in the S→R link), h_{SR} is the random, unit power, complex-valued channel gain between the source and relay terminals and $n_{R,1} \sim \mathcal{CN}(0, N_o)$ is additive white noise. Note that in general $E_{SD} \neq E_{SR}$ due to differences in path loss and shadowing between the S→R and S→D links.

The relay terminal normalizes the received signal by a factor of $\sqrt{\mathcal{E}\{|y_{R,1}|^2\}}$ (so that the average energy is unity) and retransmits the signal during the second time slot. The destination terminal receives a superposition of the relay transmission and the source transmission during the second time slot according to

$$y_{D,2} = \sqrt{E_{SD}}\, h_{SD}\, x_2 + \sqrt{E_{RD}}\, h_{RD}\, \frac{y_{R,1}}{\sqrt{\mathcal{E}\{|y_{R,1}|^2\}}} + n_{D,2}, \tag{3}$$

where E_{RD} is the average signal energy at the destination terminal over one symbol period received through the R→D link (having accounted for path loss and shadowing in the R→D link), h_{RD} is the random, unit power, complex-valued channel gain between the relay and destination terminals and $n_{D,2} \sim \mathcal{CN}(0, N_o)$ is additive white noise. We note that (3) contains the additional assumption of constant E_{SD} and h_{SD} over the two time slots. Using $\mathcal{E}\{|y_{R,1}|^2\} = E_{SR} + N_o$, we can rewrite (3) as

$$y_{D,2} = \sqrt{E_{SD}}\, h_{SD}\, x_2 + \sqrt{\frac{E_{SR}E_{RD}}{E_{SR} + N_o}}\, h_{SR}\, h_{RD}\, x_1 + \widetilde{n}, \tag{4}$$

where for a given channel realization h_{RD}, the effective noise term $\widetilde{n}|h_{RD} \sim \mathcal{CN}(0, N_o')$ with $N_o' = N_o\left(1 + \frac{E_{RD}|h_{RD}|^2}{E_{SR}+N_o}\right)$. Finally, we assume that the receiver normalizes $y_{D,2}$ by a factor[4] $\omega = \sqrt{1 + \frac{E_{RD}|h_{RD}|^2}{E_{SR}+N_o}}$. This normalization does not alter the signal-to-noise ratio (SNR) but simplifies the ensuing presentation. The effective input-output relation for Protocol I in the AF mode can now be summarized as

$$\mathbf{y}_{\mathit{1}} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{5}$$

where $\mathbf{y}_{\mathit{1}} = [y_{D,1}\ \ y_{D,2}/\omega]^T$ is the received signal vector[5], $\mathbf{H}$ is the effective 2×2 channel matrix given by

$$\mathbf{H} = \begin{bmatrix} \sqrt{E_{SD}}\, h_{SD} & 0 \\ \frac{1}{\omega}\sqrt{\frac{E_{SR}E_{RD}}{E_{SR}+N_o}}\, h_{SR}\, h_{RD} & \frac{\sqrt{E_{SD}}}{\omega}\, h_{SD} \end{bmatrix}, \tag{6}$$

$\mathbf{x} = [x_1\ \ x_2]^T$ is the transmitted signal vector, and $\mathbf{n}$ (when conditioned on the channel $\mathbf{H}$) is circularly symmetric complex Gaussian noise with $\mathcal{E}\{\mathbf{n}|\mathbf{H}\} = \mathbf{0}$ and $\mathcal{E}\{\mathbf{n}\mathbf{n}^H|\mathbf{H}\} = N_o\mathbf{I}_2$. We shall make use of the fact that $\mathbf{n}$ conditioned on $\mathbf{H}$ is Gaussian when calculating the mutual information in Section 3.

Input-output relation for Protocols II and III: The input-output relations for Protocols II and III may be derived from (5). For Protocol II, the received signal may be written as

$$\mathbf{y}_{\mathit{2}} = \mathbf{h}\, x_1 + \mathbf{n}, \tag{7}$$

where $\mathbf{h}$ is simply the first column of $\mathbf{H}$ and $\mathbf{n}$ (conditioned on $\mathbf{h}$) is the 2×1 additive white complex Gaussian noise vector with $\mathcal{E}\{\mathbf{n}|\mathbf{h}\} = \mathbf{0}$ and $\mathcal{E}\{\mathbf{n}\mathbf{n}^H|\mathbf{h}\} = N_o\mathbf{I}_2$. Similarly, the signal received at the destination terminal under Protocol III (the received signal is scalar in this case) satisfies

$$y_{\mathit{3}} = \mathbf{g}^T\, \mathbf{x} + n, \tag{8}$$

where $\mathbf{g}^T$ is simply the second row of $\mathbf{H}$ and n (conditioned on $\mathbf{g}$) is scalar $\mathcal{CN}(0, N_o)$ additive white noise.

[2] A→B signifies the link between terminals A and B.

[3] Unless specified otherwise, we do not make any assumptions on the precise fading statistics of the channel gains.

[4] Recall that we assumed perfect channel state information in the receiver.

[5] The subscript *1* in $\mathbf{y}_{\mathit{1}}$ reflects the fact that we are dealing with Protocol I.

Note that the three protocols convert the spatially distributed antenna system into effective SIMO (with Protocol II), MISO (with Protocol III), and MIMO (with Protocol I) channels allowing the fundamental gains [17] of multiple-antenna systems such as *diversity gain*, *array gain* and *interference canceling gain* to be exploited in a distributed fashion. We emphasize that *multiplexing gain* (i.e., a linear increase in achievable rate with the number of antennas in MIMO channels [18, 19, 20, 21]) is conspicuously absent, since time is expended to create a virtual MIMO channel thereby negating any multiplexing gain.

3. INFORMATION THEORETIC PERFORMANCE

Mutual information of protocols. In the following, we employ an ergodic block-fading channel model for h_{SD}, h_{SR} and h_{RD} (with independent blocks and the same block length for all channels) and assume an i.i.d. Gaussian code book with covariance matrix $\mathcal{E}\{\mathbf{x}\mathbf{x}^H\} = \mathbf{I}_2$. Moreover, we assume that the destination terminal has perfect knowledge of h_{SD}, h_{SR} and h_{RD}. The mutual information for the three protocols is obtained from (5), (7), and (8) as

$$I_j^{AF} = \frac{1}{2}\log_2 \det\left(\mathbf{I}_2 + \frac{1}{N_o}\mathbf{A}_j^H\mathbf{A}_j\right) \text{ bps/Hz}, \quad j = 1, 2, 3, \tag{9}$$

where $\mathbf{A}_1 = \mathbf{H}$, $\mathbf{A}_2 = \mathbf{h}$, $\mathbf{A}_3 = \mathbf{g}$, and the factor $1/2$ accounts for the fact that information is conveyed to the destination terminal over two time slots. If coding is performed over an infinite number of independent channel realizations, the capacity of each of the three protocols, C_j^{AF} ($j = 1, 2, 3$), is given by the ergodic capacity $C_j^{AF} = \mathcal{E}\{I_j^{AF}\}$ with the expectation carried out with respect to the random channel. On the other hand, if coding is performed only within a single block the Shannon capacity is zero. In this case we resort to the $p\%$ outage capacity [22, 23], $C_{j,p,out}^{AF}$ ($j = 1, 2, 3$), defined as

$$P(I_j^{AF} \leq C_{j,p,out}^{AF}) = p\%, \tag{10}$$

or equivalently, the rate $C_{j,p,out}^{AF}$ is guaranteed to be supported for $(100 - p)\%$ of the channel realizations. In the following, we compare the different protocols from a capacity (ergodic and outage) and a diversity point-of-view.

Comparison from a capacity point-of-view. We can show that the mutual information for the three protocols obeys the following ordering [24]

$$I_1^{AF} \geq I_2^{AF} \geq I_3^{AF}, \tag{11}$$

establishing the superiority of Protocol I over the other two protocols in terms of achievable rate. This result establishes the importance of receive collision for achieving high throughput. In the context of multi-access fading channels a similar observation has been made by Gallager in [25].

We can conclude that the ordering in (11) also applies to the ergodic and outage capacities for the three protocols. Note that $\omega \approx 1$ implies $I_2^{AF} \approx I_3^{AF}$. The factor ω may be viewed as a noise amplification factor. In order to have $\omega \approx 1$ we need $\frac{E_{RD}|h_{RD}|^2}{E_{SR}+N_o} \approx 0$, which is the case if the S→R link is good (i.e., $E_{SR}/N_o \gg 1$) and much stronger than the R→D link. Physically, this may occur when the source terminal is located very close to the relay terminal resulting in high SNR for the S→R link. On the other hand, if $E_{RD}|h_{RD}|^2 \gg (E_{SR} + N_o)$ the noise amplification will be substantial and the performance of Protocol III will deteriorate significantly compared to Protocol II. In Protocol II the destination terminal receives the source transmission over the first time slot without any added amplified noise from the relay terminal whereas in Protocol III the information transmitted in the first time slot arrives at the destination terminal through the noise amplifying relay link. Hence, Protocol II is expected to outperform Protocol III if the noise amplification is large.

From (9) we can see that the price to be paid for cooperative transmission over two time slots is a reduction in spectral efficiency (compared to a MIMO system with co-located antennas) accounted for by the factor 1/2 in front of the log term. Protocol I is the only protocol that can realize a multiplexing gain in the classical sense and hence recover (to a certain extent) from the 50% loss in spectral efficiency. We note, however, that the effective channel for Protocol I is not i.i.d. complex Gaussian as is the case in traditional MIMO systems [19, 26]. This implies that in general we may not recover fully from the loss in spectral efficiency. The corresponding difference in performance can be attributed to the fact that we are dealing with a distributed system where the individual terminals have to cooperate. Protocols II and III do not provide multiplexing gain, which explains their inferior performance when compared to Protocol I. Finally, the fact that Protocol II is superior to Protocol III can be attributed to the fact that Protocol II corresponds to a SIMO system realizing receive array gain whereas Protocol III corresponds to a MISO system devoid of array gain (recall that we assumed perfect channel knowledge in the receivers and no channel knowledge in the transmitters).

Comparison from a diversity point-of-view. Following the approach in [27] and [15] we shall interpret the outage probability at a certain transmission rate as the packet error rate (PER). The diversity order is then given by the magnitude of the slope of the PER as a function of SNR (on a log-log scale). More precisely, we define the diversity order for transmission rate R as

$$d(R) = \lim_{\text{SNR}\to\infty} -\log P_e(R, \text{SNR})/\log \text{SNR}, \tag{12}$$

where $P_e(R, \text{SNR})$ denotes the PER or outage probability at transmission rate R as a function of SNR. In the following, we assume that the channel gains h_{SD} and h_{SR} are independent $\mathcal{CN}(0, 1)$ which corresponds to Rayleigh fading on these two links. Furthermore, we assume that the channel between the relay terminal and the destination terminal is AWGN (i.e., $h_{RD} = 1$). We note that the latter assumption is conceptual and simplifies the performance analysis significantly. The general case seems very difficult to deal with analytically. Physically, this assumption could correspond to a scenario where the destination and relay terminals are static and have line-of-sight connection, while the source terminal is moving. We can show for each of the protocols that [24]

$$P(I_j^{AF} \leq R) \leq \left(\frac{2^{2R} - 1}{\beta_j^{AF}}\right)^2, \quad j = 1, 2, 3,$$

for β_j^{AF} large and where

$$\begin{aligned}
\beta_1^{AF} &= \min\left\{\left(1 + \frac{1}{\omega^2}\right)\frac{E_{SD}}{N_o}, \frac{1}{\omega^2}\frac{E_{SR}E_{RD}}{(E_{SR} + N_o)N_o}\right\} \\
\beta_2^{AF} &= \min\left\{\frac{E_{SD}}{N_o}, \frac{1}{\omega^2}\frac{E_{SR}E_{RD}}{(E_{SR} + N_o)N_o}\right\} \\
\beta_3^{AF} &= \min\left\{\frac{1}{\omega^2}\frac{E_{SD}}{N_o}, \frac{1}{\omega^2}\frac{E_{SR}E_{RD}}{(E_{SR} + N_o)N_o}\right\}
\end{aligned}$$

with $\omega^2 = 1 + \frac{E_{RD}}{E_{SR}+N_o}$. Using (12) it follows that all three protocols achieve second-order diversity in their corresponding effective

SNRs β_3^{AF} $(j = 1, 2, 3)$. We emphasize, however, that the diversity performance being determined by the effective SNR β_j^{AF} implies that careful power control [16] among terminals is necessary to ensure that the error rate indeed decays according to a second-order diversity behavior. Finally, by inspection we obtain the following ordering of effective SNRs

$$\beta_1^{AF} \geq \beta_2^{AF} \geq \beta_3^{AF}, \tag{13}$$

which demonstrates the superiority of Protocol I over the other two protocols from an effective SNR point-of-view. The ordering in (13) can be interpreted as reflecting the amount of array gain realized by the individual protocols.

Numerical results. We conclude our discussion of the performance limits of the individual protocols with numerical results quantifying some of our analytical findings. Fig. 1 shows the ergodic capacities (found through Monte Carlo simulation) for the three different protocols, respectively, as a function of E_{SR}/N_o with $E_{SD}/N_o = E_{RD}/N_o =$ 10dB. The complex channel gains h_{SR}, h_{SD}, and h_{RD} are assumed i.i.d. $\mathcal{CN}(0, 1)$. The ordering in (11) is verified. We point out that this ordering holds irrespective of the statistics of the individual channels (Rayleigh, Ricean or AWGN). For low E_{SR}/N_o (i.e., noise in the relay terminal undergoes large amplification) Protocol III performs significantly worse than Protocols I and II. When the noise amplification is low, i.e., E_{SR}/N_o is high, Protocols II and III perform equally well and are significantly outperformed by Protocol I, which again benefits from "multiplexing gain".

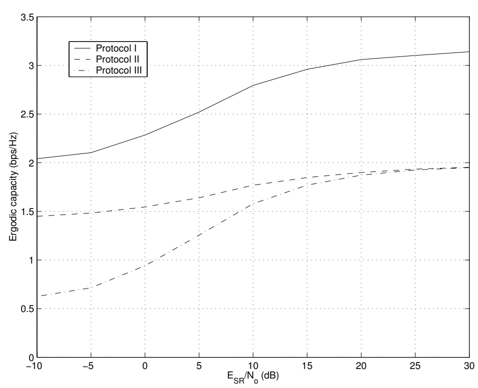

Fig. 1. Comparison of the ergodic capacities of the three protocols. Protocol I benefits from "multiplexing gain".

4. CONCLUSIONS

We studied the information-theoretic performance limits of a simple amplify-and-forward based fading single relay channel. Our results indicate that full broadcasting and receive collision is crucial for achieving high throughput. Furthermore, we showed that full spatial diversity (second-order in this case) can be realized provided that appropriate power control is employed.

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