Transmit Outage Pre-Equalization for Amplify-and-Forward Relay Channels

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***Abstract*—We consider amplify-and-forward (AF) on the two-hop channel. In contrast to existing schemes, we propose to perform pre-equalization at the source, which entails a channel-independent gain at the relay and simplifies the channel estimation process. If the power constraint does not allow for pre-equalization, the source refrains from transmitting and declares a transmit outage. Channel state information (CSI) is acquired at the source and at the destination based on a single pilot transmission from the relay. The advantages of the proposed method are an extremely simple relay, a reduced pilot overhead, huge power savings at the source, and high robustness against imperfect CSI.**

I. Introduction

Dual-hop communication between a source and a destination via an intermediate relay has evolved into a key paradigm in wireless network design, providing cooperative diversity or extended transmission range [1]–[3]. Amplify-and-forward (AF) is a particular relay transmission strategy that avoids the need to decode the source data at the relay (see [4] for a unified discussion of the state of the art, including an extensive bibliography). The end-to-end SNR of AF relaying over Rayleigh fading channels was analyzed in [5]–[7]. The case of dual-hop AF with multiple antennas at the source and the destination (but a single antenna at the relay) has been considered in [8]. The case of multiple antennas at either the source, the relay, or the destination has been studied analytically in [9]. A practical problem with conventional AF is the need to reliably estimate the compound source-relay/relay-destination channel [10]. Usually, this requires two time slots to transmit pilots from the source to the relay and from the relay to the destination; furthermore, estimating the compound channel potentially involves non-Gaussian distributions for the channel coefficient and the additive noise.

In this paper, we consider dual-hop AF transmissions without a direct link between source and destination. We propose a pre-equalization scheme that obviates the need for channel state information (CSI) at the relay and allows the relay to use a fixed gain that does not depend on the instantaneous channel. Our scheme requires the source-relay channel to be known at the source. Using the assumption that the source-relay channel be reciprocal, this is accomplished by letting the relay transmit a single pilot signal which is used by both the source and the destination to estimate their respective channels. If the source-relay channel is in outage, the source refrains from transmitting rather than wasting power on an unreliable link (this idea has previously been studied in the context of multiple antenna precoding [11]). Since the relay uses a fixed amplification factor, the effective channel seen at the destination is a simple AWGN channel, which allows for simple data detection. We henceforth refer to this scheme as AF with transmit outage pre-equalization (AF-TOPE). While its performance is similar to conventional AF, AF-TOPE offers the following advantages:

- reduced pilot overhead due to a single training phase for all channels;
- exceedingly simple relay processing via a fixed, channel-independent amplification factor;
- significant power savings due to pre-equalization and transmit outages;
- optimum channel estimation and data detection can be performed in a simple manner.

The rest of the paper is organized as follows. In Section II, we describe the system model and review conventional AF. In Section III, we discuss TOPE (both for perfect and imperfect CSI) and analyze its performance. Simulation result and conclusions are provided in Sections IV and V, respectively.

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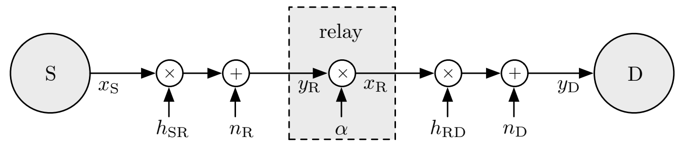

Fig. 1. System model for the relay channel without source-destination link and with an AF relay.

II. Background

A. System model

We consider a relay channel without direct link as illustrated in Fig. 1. The signal transmitted by the source is given by $x_S = \beta a$, where a is the unit-power data symbol and β is the power scaling factor. The source-relay (SR) channel is described by

$$y_R = h_{SR} x_S + n_R, \tag{1}$$

where y_R denotes the signal received at the relay, h_{SR} is the Rayleigh fading coefficient on the SR link, and n_R is additive Gaussian noise at the relay. We assume $h_{SR} \sim \mathcal{CN}(0, P_h)$

and $n_{\rm R} \sim \mathcal{CN}(0, \sigma^2)$. Similarly, the relay-destination (RD) channel is modeled as

$$y_{\rm D} = h_{\rm RD} x_{\rm R} + n_{\rm D}, \tag{2}$$

where $y_{\rm D}$, $h_{\rm RD}$, $x_{\rm R}$, and $n_{\rm D}$ respectively denote the signal received at the destination, the Rayleigh fading coefficient on the RD link, the signal transmitted by the relay, and the additive Gaussian noise at the destination (again, $h_{\rm RD} \sim \mathcal{CN}(0, P_h)$ and $n_{\rm D} \sim \mathcal{CN}(0, \sigma^2)$). We consider a simple AF relay for which the relay transmit and receive signals are related as

$$x_{\rm R} = \alpha y_{\rm R}, \tag{3}$$

with an appropriately chosen amplification factor α. The compound (end-to-end) channel is given by

$$y_{\rm D} = h_{\rm SD} a + n_{\rm SD}, \tag{4}$$

with

$$h_{\rm SD} = \alpha\beta h_{\rm SR} h_{\rm RD}, \quad n_{\rm SD} = \alpha h_{\rm RD} n_{\rm R} + n_{\rm D}.$$

The destination attempts to recover a from (4). In what follows, the maximum transmit power at the source and the relay are denoted by $P_{\rm S}$ and $P_{\rm R}$, respectively.

B. Conventional AF

With conventional AF, the source power scaling equals $\beta = \sqrt{P_{\rm S}}$ and the relay amplification factor is chosen as

$$\alpha_{\rm var} = \sqrt{\frac{P_{\rm R}}{P_{\rm S}\,|h_{\rm SR}|^2 + \sigma^2}} \quad \text{or} \quad \alpha_{\rm fix} = \sqrt{\frac{P_{\rm R}}{P_{\rm S} P_h + \sigma^2}}, \tag{5}$$

depending on whether the fading coefficient $h_{\rm SR}$ or only its mean power P_h is known at the relay. With either of these choices, $h_{\rm SD}$ in (4) is non-Gaussian.

For channel estimation, a training signal is transmitted by the source, allowing the relay to estimate $h_{\rm SR}$. The relay then forwards the training signal to the destination, which then estimates the compound channel coefficient $h_{\rm SD}$. This approach requires two time slots for training; furthermore, due to the non-Gaussianity of $h_{\rm SD}$, linear channel estimators perform suboptimally.

III. AF-TOPE

A. Transmission Protocol

1) Training Phase: Conventional AF schemes require two time slots for channel estimation. By contrast, our scheme involves only a single time slot for training. Specifically, we propose that the relay transmits a pilot signal that is received by both the source and the destination. We assume that the SR channel is reciprocal, so that the channel coefficient $h_{\rm SR}$ can be estimated by the source based on this pilot transmission. Furthermore, the destination simultaneously estimates the RD channel coefficient $h_{\rm RD}$. For simplicity of exposition, we first assume that perfect CSI is available, i.e., the source knows $h_{\rm SR}$ exactly and the destination knows $h_{\rm RD}$ exactly. The effect of channel estimation errors will be addressed in Subsection III-D.

2) SR Transmission: The source uses the estimated SR channel coefficient to pre-equalize the SR link. If the power constraint prohibits pre-equalization, the source refrains from transmitting. Hence,

$$x_{\rm S} = \begin{cases} \sqrt{P_{\rm S}}\dfrac{\eta}{h_{\rm SR}} a, & \text{if } |h_{\rm SR}| \geq \eta, \\ 0, & \text{if } |h_{\rm SR}| < \eta. \end{cases} \tag{6}$$

The power scaling and threshold parameter η is assumed to be known at the relay and the destination. Its choice is discussed in Subsection III-C.

We refer to the event $|h_{\rm SR}| < \eta$ as transmit outage [11] and denote it by $\mathcal{O}$. Similarly, $\bar{\mathcal{O}}$ denotes the non-outage event $|h_{\rm SR}|^2 \geq \eta^2$. At first sight, it may look strange to discard the data symbol in case of a transmit outage. However, in this case, the SR link is very poor anyways, i.e., $h_{\rm SR}$ and hence the receive SNR at the relay is very small. Reliable reception of the data symbol thus is highly unlikely anyways. Discarding the data symbol beforehand has the advantage of saving significant amounts of transmit power. We note that neither relay nor destination know whether a transmit outage has occurred or not.

Since $|h_{\rm SR}|$ is Rayleigh distributed with parameter P_h, the probability of a non-outage event is given by

$$\Pr\{\bar{\mathcal{O}}\} = \Pr\{|h_{\rm SR}| \geq \eta\} = \exp(-\eta^2/P_h).$$

Furthermore, $\Pr\{\mathcal{O}\} = 1 - \Pr\{\bar{\mathcal{O}}\}$. Note that the transmit signal $x_{\rm S}$ is designed to ensure that the power constraint is always satisfied. In fact, the instantaneous transmit power in the outage case is zero and in the non-outage case it equals $\mathbb{E}\{|x_{\rm S}|^2 \big| h_{\rm SR}, \bar{\mathcal{O}}\} = P_{\rm S}\eta^2/|h_{\rm SR}|^2 \leq P_{\rm S}$. The average transmit power can then be shown to equal

$$\bar{P}_{\rm S} = \mathbb{E}\{|x_{\rm S}|^2 \big| \bar{\mathcal{O}}\}\Pr\{\bar{\mathcal{O}}\} = P_{\rm S}\,\tilde{\eta}^2\,\mathrm{E}_1(\tilde{\eta}^2),$$

where $\tilde{\eta}^2 = \eta^2/P_h$ and $E_1(z) = \int_z^\infty t^{-1}\exp(-t)\,\mathrm{d}t$ denotes the exponential integral function. It can be shown that $\bar{P}_{\rm S} \leq 0.2815 P_{\rm S}$ for any η. Since the average transmit power with conventional AF equals $P_{\rm S}$, it follows that AF-TOPE saves at least $-10\log_{10} 0.2815 = 5.5\,\mathrm{dB}$ transmit power.

The signal received at the relay is obtained by inserting (6) into (1):

$$y_{\rm R} = \begin{cases} \sqrt{P_{\rm S}}\eta a + n_{\rm R}, & \text{if } |h_{\rm SR}| \geq \eta, \\ n_{\rm R}, & \text{if } |h_{\rm SR}| < \eta. \end{cases}$$

Hence, unless there is a transmit outage, the average receive SNR at the relay equals $\rho_{\rm R} = P_{\rm S}\eta^2/\sigma^2$ and hence is independent of the SR channel.

3) RD Transmission: The AF operation of the relay requires specification of the amplification factor α in (3). Since the receive power at the relay in the outage and non-outage case respectively equals $\mathbb{E}\{|y_{\rm R}|^2 \big| \mathcal{O}\} = \sigma^2$ and $\mathbb{E}\{|y_{\rm R}|^2 \big| \bar{\mathcal{O}}\} = P_{\rm S}\eta^2 + \sigma^2$, we have $\mathbb{E}\{|y_{\rm R}|^2\} = P_{\rm S}\eta^2\exp(-\eta^2/P_h) + \sigma^2$. In order to meet the relay power constraint both for outages and non-outages, we choose

$$\alpha = \sqrt{\frac{P_{\mathrm{R}}}{P_{\mathrm{S}}\eta^2 + \sigma^2}}.$$

This is a fixed gain, i.e., independent of the SR channel, for which the relay needs to know only the signal and noise powers and the scaling factor η; the latter can be designed offline in advance and only needs to be stored at the relay. We emphasize that channel estimation at the relay is not required, thereby further reducing the relay's complexity.

The received signal at the destination is given by (4) with

$$h_{\mathrm{SD}} = \begin{cases} h_{\mathrm{RD}}\sqrt{\dfrac{P_{\mathrm{R}}P_{\mathrm{S}}\eta^2}{P_{\mathrm{S}}\eta^2+\sigma^2}}, & \text{if } |h_{\mathrm{SR}}| \geq \eta, \\ 0, & \text{if } |h_{\mathrm{SR}}| < \eta. \end{cases}$$

Since the relay gain α is fixed and h_{RD} is known at the destination, (4) amounts to a simple AWGN channel in the non-outage case and hence simple ZF detection is optimal, i.e.,

$$\hat{a} = \mathcal{Q}\left(\frac{y_{\mathrm{D}}}{h_{\mathrm{RD}}\sqrt{\frac{P_{\mathrm{R}}P_{\mathrm{S}}\eta^2}{P_{\mathrm{S}}\eta^2+\sigma^2}}}\right). \tag{7}$$

Here, $\mathcal{Q}(\cdot)$ denotes quantization with respect to the symbol alphabet. In case of a transmit outage, the destination receives only noise ($y_{\mathrm{D}} = n_{\mathrm{SD}}$) and hence (7) amounts to picking a symbol at random.

B. Performance Analysis

1) End-to-end SNR: We denote the SNR on the RD link by $\rho_{\mathrm{D}} = P_{\mathrm{R}}|h_{\mathrm{RD}}|^2/\sigma^2$ and recall that the average SNR on the SR link equals $\rho_{\mathrm{R}} = P_{\mathrm{S}}\eta^2/\sigma^2$. Assuming that there is no transmit outage, the SNR on the compound (end-to-end) channel (4) can then be shown to equal

$$\rho_{\mathrm{SD}} = \frac{\rho_{\mathrm{R}}\rho_{\mathrm{D}}}{\rho_{\mathrm{R}}+\rho_{\mathrm{D}}+1}. \tag{8}$$

This expression can be upper bounded as

$$\rho_{\mathrm{SD}} \leq \min\{\rho_{\mathrm{R}}, \rho_{\mathrm{D}}\}.$$

As we increase the maximum transmit power at the relay, the upper bound will eventually saturate at $\rho_{\mathrm{R}} = P_{\mathrm{S}}\eta^2/\sigma^2$. This indicates that the scaling factor η should be optimized depending on the SNR per hop (see Subsection III-C).

2) Error Probability: By conditioning on the outage and non-outage events, the uncoded bit error probability can be expressed as

$$\begin{aligned}\Pr\{\mathcal{E}\} &= \Pr\{\mathcal{E}|\mathcal{O}\}\Pr\{\mathcal{O}\} + \Pr\{\mathcal{E}|\bar{\mathcal{O}}\}\Pr\{\bar{\mathcal{O}}\} \\ &= \frac{1}{2}\big(1-\exp(-\tilde{\eta}^2)\big) + \Pr\{\mathcal{E}|\bar{\mathcal{O}}\}\exp(-\tilde{\eta}^2),\end{aligned} \tag{9}$$

where in the second line we used the fact that in case of an outage, the destination performs random guesses and hence gets half of the bits wrong. It remains to assess the bit error

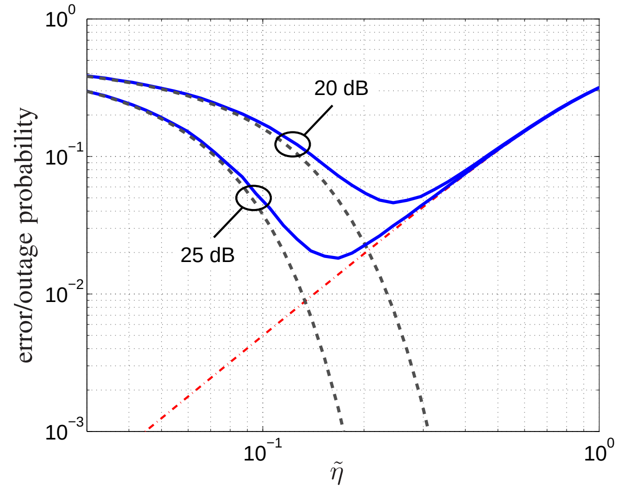

Fig. 2. Overall error probability $\Pr\{\mathcal{E}\}$ (solid line), non-outage error probability $\Pr\{\mathcal{E}|\bar{\mathcal{O}}\}$ (dashed line), and outage probability $\Pr\{\mathcal{O}\}$ (dash-dotted line) versus power scaling factor $\tilde{\eta}$ for nominal per-hop SNRs $\bar{\rho}$ of 20 dB and 25 dB.

probability in case of no outage. Conditioning on the RD channel coefficient, we obtain

$$\Pr\{\mathcal{E}|\bar{\mathcal{O}}\} = \int_0^\infty \Pr\{\mathcal{E}|\bar{\mathcal{O}}, |h_{\mathrm{RD}}|^2 = \xi\} f_{|h_{\mathrm{RD}}|^2}(\xi)\,\mathrm{d}\xi, \tag{10}$$

where we used that the RD channel coefficient is independent of outage events on the SR link. In the non-outage case, the error probability for a given RD channel is determined by the end-to-end SNR ρ_{SD} and by the minimum distance $d_{\min}$ of the underlying symbol constellation, i.e.,

$$\Pr\{\mathcal{E}|\bar{\mathcal{O}}, |h_{\mathrm{RD}}|^2\} \leq c\,Q\left(\frac{d_{\min}}{2}\sqrt{\rho_{\mathrm{SD}}}\right),$$

where c is a constellation-specific constant. Using this result, the exponential distribution of $|h_{\mathrm{RD}}|^2$, and (8), we obtain

$$\Pr\{\mathcal{E}|\bar{\mathcal{O}}\} \leq c\int_0^\infty Q\left(\frac{d_{\min}}{2\sigma}\sqrt{\frac{P_{\mathrm{R}}P_{\mathrm{S}}\eta^2\xi}{P_{\mathrm{R}}\xi + P_{\mathrm{S}}\eta^2+\sigma^2}}\right)\mathrm{e}^{-\xi}\,\mathrm{d}\xi.$$

C. Choice of Source Power Scaling

In the previous section, we have seen that the error probability involves two terms. The first term corresponds to errors due to outage on the SR link; it is a monotonically increasing function of $\tilde{\eta}$ but is independent of SNR. The second term quantifies the non-outage errors; it is an SNR-dependent monotonically decreasing function of $\tilde{\eta}$. Fig. 2 illustrates these two terms and the overall error probability for a system with QPSK modulation and identical nominal SNR per hop on the SR and RD link, i.e., $\bar{\rho} = P_{\mathrm{S}}P_h/\sigma^2 = P_{\mathrm{R}}P_h/\sigma^2$. Clearly, the overall error probability has an SNR-dependent pronounced minimum, for which the two error mechanisms are optimally balanced. The corresponding optimal source power scaling factor $\tilde{\eta}_{\mathrm{opt}}$ can be determined numerically for any per-hop-SNR and stored in a table by all nodes involved. The optimal power scaling $\tilde{\eta}_{\mathrm{opt}}$ versus the nominal per-hop-SNR $\bar{\rho}$ is shown

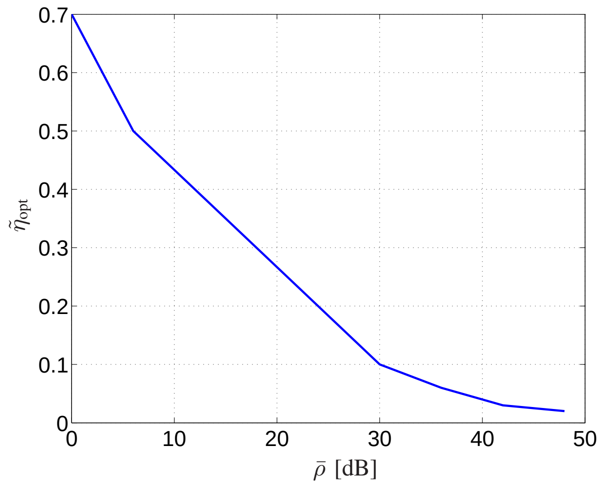

Fig. 3. Optimal power scaling factor $\tilde{\eta}_{\text{opt}}$ versus nominal per-hop-SNR $\bar{\rho}$.

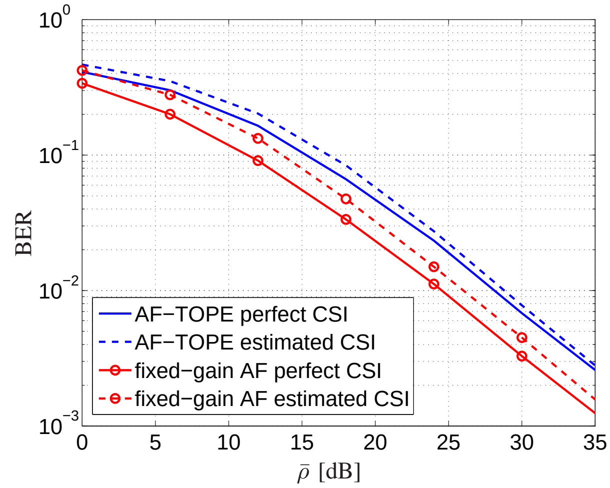

Fig. 4. BER versus nominal SNR $\bar{\rho}$. Note that the power savings in AF-TOPE are not taken into account in these plots.

in Fig. 3. It is seen that $\tilde{\eta}_{\text{opt}}$ is a decreasing function of $\bar{\rho}$. This is intuitive since $\Pr\{\mathcal{E}|\bar{\mathcal{O}}\}$ decreases with increasing SNR, and hence a smaller threshold is required in order for the source to experience fewer outages.

D. Imperfect CSI

We next discuss the effect of imperfect CSI on our AF scheme with transmit-outage pre-equalization. Recall that in the training phase, source and destination estimate their respective channels based on a single pilot transmission from the relay. Since both links are ordinary flat fading links, linear MMSE channel estimation is MSE-optimal and gives rise to

$$h_{\text{SR}} = \hat{h}_{\text{SR}} + \epsilon_{\text{SR}}, \qquad h_{\text{RD}} = \hat{h}_{\text{RD}} + \epsilon_{\text{RD}}.$$

Due to the orthogonality principle, the channel estimates and the associated estimation errors are statistically independent. Furthermore, the mean-square estimation errors (i.e., the powers of ϵ_{SR} and ϵ_{RD}) are completely determined by the mean SNR in the training phase, denoted ρ_p.

Using the channel estimates, the pre-equalization at the source is performed according to (6) with h_{SR} replaced by $\hat{h}_{\text{SR}}$. Note that the outage event now corresponds to $|\hat{h}_{\text{SR}}| \leq \eta$. At the relay, the channel estimation error ϵ_{SR} gives rise to an additional noise term,

$$y_{\text{R}} = \sqrt{P_{\text{S}}}\eta \frac{h_{\text{SR}}}{\hat{h}_{\text{SR}}} a + n_{\text{R}} = \sqrt{P_{\text{S}}}\eta a + \frac{\epsilon_{\text{SR}}}{\hat{h}_{\text{SR}}} \sqrt{P_{\text{S}}}\eta a + n_{\text{R}}. \quad (11)$$

This implies that in order for the relay to meet the power constraint, the amplification factor needs to be modified. In particular, the relay receive power for the case of no outage can be shown to equal

$$\mathbb{E}\{|y_{\text{R}}|^2 \big| \bar{\mathcal{O}}\} = P_{\text{S}}\eta^2(1+\varepsilon^2) + \sigma^2.$$

where the normalized mean square channel estimation error is

$$\varepsilon^2 = \mathbb{E}\bigg\{ \frac{|\epsilon_{\text{SR}}|^2}{|\hat{h}_{\text{SR}}|^2} \bigg| \bar{\mathcal{O}} \bigg\} = \mathbb{E}\{|\epsilon_{\text{SR}}|^2\}\, \mathbb{E}\{|\hat{h}_{\text{SR}}|^{-2} \big| \bar{\mathcal{O}}\}$$
$$= \frac{1}{\rho_p} \frac{1}{\Pr\{\bar{\mathcal{O}}\}} \mathrm{E}_1\big(\tilde{\eta}^2(1+\rho_p^{-1})\big).$$

Here, we have used the fact that the channel estimate and the associated error are statistically independent. To meet the relay power constraint, the AF gain is thus chosen as

$$\hat{\alpha} = \sqrt{\frac{P_{\text{R}}}{P_{\text{S}}\eta^2(1+\varepsilon^2)+\sigma^2}}. \quad (12)$$

Since the destination only disposes of imperfect CSI $\hat{h}_{\text{RD}}$, the channel estimation errors on the RD link effectively increase the noise power. More specifically, the signal received at the destination in the non-outage case can still be expressed as in (4) with the effective channel and the effective noise

$$h_{\text{SD}} = \hat{\alpha}\sqrt{P_{\text{S}}}\eta \hat{h}_{\text{RD}} \quad (13a)$$
$$n_{\text{SD}} = a\hat{\alpha}\sqrt{P_{\text{S}}}\eta\Big(h_{\text{RD}}\frac{\epsilon_{\text{SR}}}{\hat{h}_{\text{SR}}} + \epsilon_{\text{RD}}\Big) + \hat{\alpha} h_{\text{RD}} n_{\text{R}} + n_{\text{D}}. \quad (13b)$$

The destination then performs ZF equalization according to $\hat{a} = \mathcal{Q}\big(y_{\text{D}}/\hat{\alpha}\sqrt{P_{\text{S}}}\eta\hat{h}_{\text{RD}}\big)$. The end-to-end SNR and the error probability for the case of imperfect CSI can then be assessed via (13) (details omitted due to space constraints).

IV. Simulation Results

We illustrate the performance of AF-TOPE via numerical Monte Carlo simulations. We consider uncoded QPSK transmission with Gray mapping over a Rayleigh fading relay channel with identical nominal SNR $\bar{\rho}$ on the SR link and the RD link. The nominal per-hop SNR on the SR and RD link are identical, i.e., $\bar{\rho} = P_{\text{S}}P_h/\sigma^2 = P_{\text{R}}P_h/\sigma^2$. In addition to AF-TOPE, we simulated a conventional fixed-gain AF (FG-AF) scheme with relay gain α_{fix} (cf. (5)). The BER results versus nominal SNR are shown in Fig. 4, both for the case of perfect

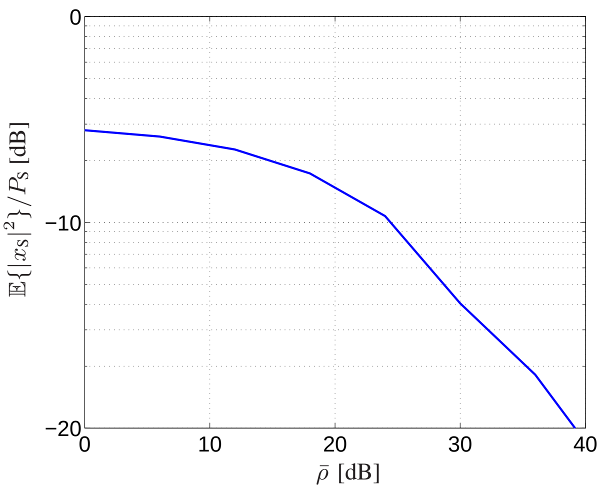

Fig. 5. Mean transmit power savings at the source achieved with AF-TOPE.

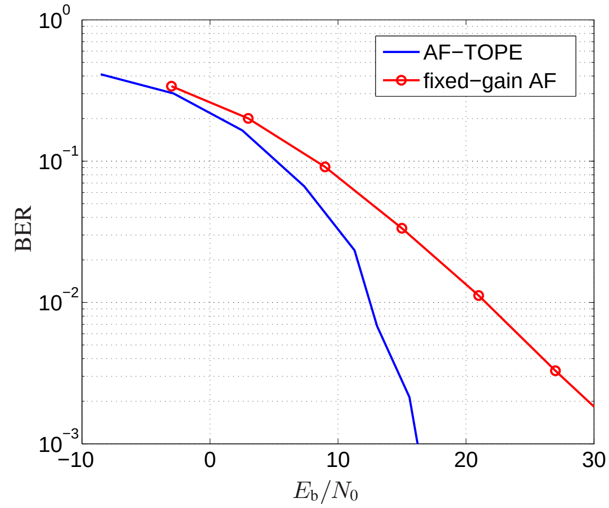

Fig. 6. Comparison of conventional fixed-gain AF and AF-TOPE in terms of BER versus E_b/N_0.

CSI and estimated CSI (for simplicity, we re-used the power scaling factor $\tilde{\eta}_\mathrm{opt}$ obtained for the perfect CSI case also in the case of imperfect CSI). The SNR for CSI estimation was the same as for data transmission, i.e., $\rho_p = \bar{\rho}$. It is seen that AF-TOPE, even though conceptually much simpler, performs only slightly poorer than FG-AF. Furthermore, AF-TOPE performs much more robust than FG-AF when operating with estimated CSI. We emphasize that this comparison ignores the power savings achieved with AF-TOPE. These savings are illustrated in Fig. 5 that depicts the quantity $\mathbb{E}\left\{|x_\mathrm{S}|^2\right\}/P_\mathrm{S}$ (i.e. the average source transmit power normalized by the maximum transmit power), as a function of the nominal SNR. For conventional AF, this ratio is always equal to $0\,\mathrm{dB}$. It can be seen that AF-TOPE offers at least $5.5\,\mathrm{dB}$ of power savings (at low SNRs) and the power savings become even larger at high SNR.

A fair comparison that takes into account the BER performance as well as the transmit power savings is obtained by plotting the BER versus E_b/N_0, i.e., the average energy per bit transmitted by the source normalized by the noise power spectral density. For FG-AF, we have $E_\mathrm{b}/N_0 = \bar{\rho}/2$ since we used QPSK and each symbol thus carries two bits. For AF-TOPE, the mean energy per bit is obtained by subtracting the power savings from the nominal transmit power and dividing the resulting actual power by 2 (bits/symbol) and N_0. The result is shown in Fig. 6. Clearly, in this representation AF-TOPE by far outperforms FG-AF, e.g., at a BER of 10^{-3}, AF-TOPE operates at an SNR that is more than $15\,\mathrm{dB}$ smaller than that for FG-AF.

V. Conclusions

We proposed an AF relaying scheme for two-hop scenarios that reduces the overhead due to pilots, employs a very simple relay, and achieves significant transmission power reductions. The proposed scheme pre-equalizes the signal transmitted by the source as long as this allows to meet the power constraint. Otherwise, the source declares a transmit outage and refrains from transmitting. The threshold parameter separating the outage from the non-outage case can be optimized offline and needs only to be stored by the source, relay, and destination. Numerical results have corroborated our claims. Our simulation results show that the proposed scheme has a better performance than conventional AF. Furthermore, AF-TOPE is very robust to imperfect CSI and offers significant power savings compared to classical schemes.

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