Comparing the Outage Capacity of Transmit Diversity and Incremental Relaying

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***Abstract*— We derive the ϵ-outage capacity of a wireless relay network where relaying only takes place if the destination has not been able to decode the source message. We refer to this scheme as incremental relaying. The relays use space-time block coding and perform decode-and-forward. We compare incremental relaying to transmit diversity in terms of ϵ-outage capacity and signal-to-noise ratio gain. It is demonstrated that incremental relaying outperforms transmit diversity only in certain regions that determine the relay locations.**

***Keywords*— cooperative communications, outage capacity, incremental relaying.**

I. Introduction

A lot of research is going on in the field of relaying and user cooperation. See, for instance, [1], [2], [3], [4], [5] and the references therein. The idea of relaying was introduced by van der Meulen in [6] and a concise information-theoretic analysis was done by Cover and El Gamal in [7]. The idea behind relaying and user cooperation is that several nodes pool their resources to form a virtual antenna array. Thus, spatial diversity is created at the destination. This fact brought up the idea of comparing relaying schemes, like incremental relaying in our case, to other transmission schemes that create spatial diversity, e.g., transmit diversity.

Main Results: We show that incremental relaying indeed outperforms transmit diversity in terms of ϵ-outage capacity and signal-to-noise ratio (SNR) gain, but only in limited regions of relay locations.

The paper is organized as follows. In Section II we describe the system model. Section III and IV deal with outage rates and SNR gain for the one-relay case, respectively. In Section V, we extend our results to networks with an arbitrary number of transmit antennas or an arbitrary number of relays. Finally, Section VI concludes the paper.

II. System Model

In this paper, we consider a general relay network consisting of one source S, K relays $\mathrm{R}_1, \ldots, \mathrm{R}_K$, and one destination D. However, we first focus on the one-relay case and later derive extensions for an arbitrary number of relays. Channel gains h_{ij} between node i and node j are modeled as independent and circular-symmetric Gaussian random variables with zero mean, variance σ_{ij}^2, and $ij \in \{\mathrm{sd}, \mathrm{sr}_1, \ldots, \mathrm{sr}_K, \mathrm{r}_1\mathrm{d}, \ldots, \mathrm{r}_K\mathrm{d}\}$. For the one-relay case, which we investigate first, we use $ij \in \{\mathrm{sd}, \mathrm{sr}, \mathrm{rd}\}$ for the sake of description. The magnitudes $|h_{ij}|$ then follow a Rayleigh distribution and $|h_{ij}|^2$ are exponentially distributed with mean σ_{ij}^2 and uniformly distributed phases over $[0, 2\pi)$. A block-fading model is assumed, which means that magnitude and phase do not change during transmission of one block. The noise values are drawn independently from a circular complex Gaussian distribution with zero mean and one-sided power spectral density N_0 (additive white Gaussian noise, AWGN). The relays perform decode-and-forward and operate in the half-duplex mode, which means that they cannot receive and transmit at the same time. Nodes transmit with power P and SNR is defined as

$$\mathsf{SNR} := \frac{P}{N} = \frac{P}{N_0 \cdot B}$$

with B being the bandwidth. Instantaneous SNR is then represented by $|h_{ij}|^2\mathsf{SNR}$ and the average SNR becomes $\mathbb{E}(|h_{ij}|^2)\mathsf{SNR} = \sigma_{ij}^2\mathsf{SNR}$. We use a common path-loss model to describe fading effects on channels where $\sigma_{ij}^2 \sim d_{ij}^{-\alpha}$. The distance between two nodes is described by d_{ij} and α represents the path-loss factor usually between 3 and 5.

We compare incremental relaying to transmit diversity with respect to ϵ-outage capacity and SNR gain. The investigated transmission schemes are depicted in Fig. 1. On the left-hand side, transmission for transmit diversity is shown, where A_i, $i = 1, \ldots, K+1$, describes the i-th transmit antenna, $\mathbf{x}_\mathrm{s}^{(i)}(w)$ describes the corresponding source message and $\mathbf{0}$ denotes the fact that the destination is in receive mode. On the right-hand side, transmission for incremental relaying is shown where all relays transmit in the second block employing space-time block coding if the destination has not been able to decode the source message in the first block. The reason why we compare incremental relaying to transmit diversity is the following. Both systems create spatial diversity. However, in contrast to transmit diversity, where the 'channel' between the transmit antennas is perfect, the source-relay links suffer from fading. Hence, a reasonable question is if there exists a region where incremental relaying outperforms transmit diversity. Along comes the practical concern of finding suitable relay loca-

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tions.

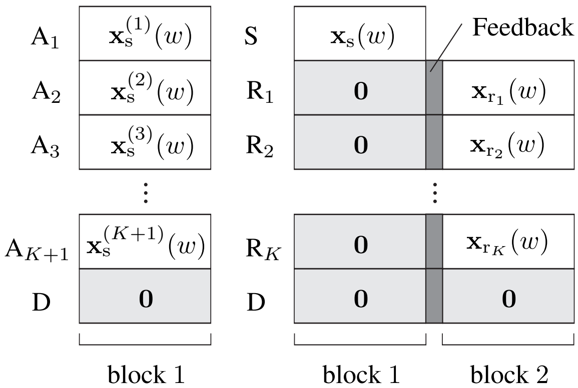

Fig. 1. Investigated transmission schemes. Transmit diversity on the left-hand side and incremental relaying on the right-hand side.

III. Achievable Outage Rates

A. Transmit Diversity

Let us consider a 2×1 multiple-input single-output (MISO) system where no channel knowledge is available at the transmitter. We apply Alamouti coding which achieves full order of diversity of 2 and has the optimal outage performance for independent and identically distributed (i.i.d.) Rayleigh fading channels. Both transmit antennas A_1 and A_2 transmit for the whole block duration T and with power $P/2$ each. Accordingly, mutual information becomes [8]

$$I^{(\mathrm{TD})} = \log_2\left(1 + ||\mathbf{h}||_2^2 \frac{\mathsf{SNR}}{2}\right), \quad (1)$$

where $||\cdot||_2$ is the Euclidean norm and $\mathbf{h} := [h_{\mathrm{sd}}^{(1)}, h_{\mathrm{sd}}^{(2)}]^T$ describes the channel coefficients from A_1 and A_2 to the destination, respectively, and the superscript T denotes transposition. Channel coefficients are considered to be i.i.d. An outage event occurs if the mutual information $I^{(\mathrm{TD})}$ cannot serve a required target rate R, i.e., the event $I^{(\mathrm{TD})} < R$ occurs. Thus,

$$p_{\mathrm{out}}^{(\mathrm{TD})} = \Pr\left(||\mathbf{h}||_2^2 < \frac{2^R - 1}{\mathsf{SNR}/2}\right) = F\left(\frac{2^R - 1}{\mathsf{SNR}/2}\right), \quad (2)$$

where $F(\cdot)$ denotes the cumulative distribution function of the sum of two exponentially distributed random variables. In order to calculate the outage probability, we first state the following lemma (see [8], Appendix A, for the proof).

Lemma 1: Let $W = U + V$, where U and V are independent exponentially distributed random variables with mean σ_u^2 and σ_v^2, respectively. If $g(x)$ is a continuous function at $x = 0$ and $g(x) \to 0$ as $x \to 0$, then the cumulative distribution function F of W satisfies

$$\lim_{x \to 0} \frac{1}{g(x)^2} F(g(x)) = \frac{1}{2\,\sigma_u^2\,\sigma_v^2}. \quad (3)$$

Using Lemma 1, we can conclude that the outage probability in the high SNR regime may be approximated as

$$p_{\mathrm{out}}^{(\mathrm{TD})} = F\left(\frac{2^R - 1}{\mathsf{SNR}/2}\right) \overset{(\mathsf{SNR}\text{ large})}{\approx} \frac{2}{\sigma_{\mathrm{sd}}^4}\left(\frac{2^R - 1}{\mathsf{SNR}}\right)^2. \quad (4)$$

Now, using ϵ-outage capacity $C_\epsilon^{(\mathrm{TD})}$ as the highest rate for which outage probability is less than ϵ [9], $C_\epsilon^{(\mathrm{TD})} = \sup_{p_{\mathrm{out}}^{(\mathrm{TD})} \le \epsilon} R$, we finally get

$$C_\epsilon^{(\mathrm{TD})} = \log_2\left(1 + \sigma_{\mathrm{sd}}^2\,\mathsf{SNR}\sqrt{\frac{\epsilon}{2}}\right), \quad (5)$$

which is well known in the literature.

B. Incremental Relaying

In this section, we derive the ϵ-outage capacity of incremental relaying. This protocol was first introduced in [8] where it was called protocol with feedback. The protocol leads to a more efficient use of degrees of freedom of the channel. This is due to the fact that the relay does not transmit all the time. The destination broadcasts a one-bit feedback that indicates success or failure of source transmission. Hence, this protocol can be seen as a variation of automatic repeat request (ARQ). Analysis of this protocol is somehow involved since rate is variable in nature. If only the source transmits, transmission rate equals R since there is only one channel use. If the relay has to transmit additionally, we have a transmission rate of $R/2$ due to two channel uses. In order to be able to compare this protocol to transmit diversity, we have to average transmission rate over several channel realizations. This leads to the definition of the long-term data rate $\overline{R}$:

$$\overline{R} = (1 - \Pr(\mathcal{A}))\,R + \Pr(\mathcal{A})\,\frac{R}{2}, \quad (6)$$

where $\mathcal{A}$ describes the event that the source-destination link is in outage and thus

$$\Pr(\mathcal{A}) = \Pr\left(|h_{\mathrm{sd}}|^2 < \frac{2^R - 1}{\mathsf{SNR}}\right). \quad (7)$$

We see that depending on SNR, there are several values of R which result in the same $\overline{R}$ (see Fig. 2). We define a transformation $\overline{R} = \mathcal{T}(R)$ as in (6) and the inverse $R' = \mathcal{T}^{-1}(\overline{R}) = \inf\{\tilde{R} : \mathcal{T}(\tilde{R}) \ge \overline{R}\}$. If we choose an $\overline{R}$ and fix it, we take the smallest R possible (cf. also [8]).

An outage event occurs if a required data rate cannot be served. However, we now have to consider the variable rate $\overline{R}$ in order to make a fair comparison to transmit diversity. It has been shown that indeed $\overline{R}$ is approximately R in the high SNR regime [10]. Therefore, outage is analyzed using the mean rate $\overline{R}$, an assumption which is inherent to our analysis since large SNR is already assumed in later

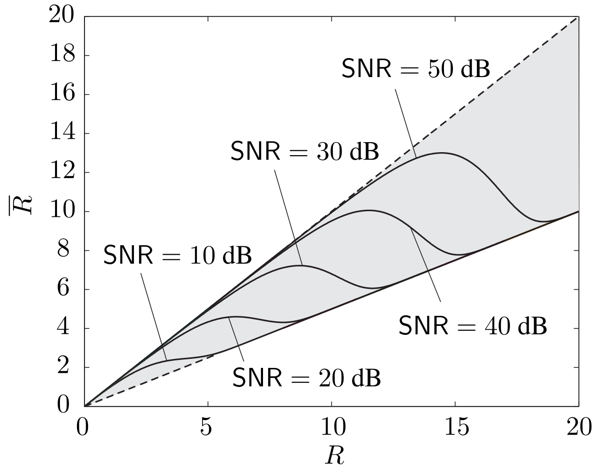

Fig. 2. Mapping of R to $\overline{R}$. Dashed lines illustrate upper and lower bounds. Upper bound is given by $\overline{R} = R$ and lower bound is given by $\overline{R} = R/2$.

simplifications.[1] Using the mean rate $\overline{R}$ and defining

$$\gamma = \frac{2^{\overline{R}} - 1}{\mathsf{SNR}} \tag{8}$$

for the sake of shorter notation, outage probability for incremental relaying becomes

$$\begin{aligned} p_{\text{out}}^{(\text{IR})} &= \Pr\left(|h_{\text{sr}}|^2 < \gamma\right) \cdot \Pr\left(|h_{\text{sd}}|^2 < \gamma\right) \\ &\quad + \Pr\left(|h_{\text{sr}}|^2 \geq \gamma\right) \cdot \Pr\left(|h_{\text{sd}}|^2 + |h_{\text{rd}}|^2 < \gamma\right) \\ &\approx \left(\frac{2^{\overline{R}} - 1}{\mathsf{SNR}}\right)^2 \cdot \frac{\sigma_{\text{sr}}^2 + 2\sigma_{\text{rd}}^2}{2\sigma_{\text{sr}}^2\sigma_{\text{sd}}^2\sigma_{\text{rd}}^2}, \end{aligned} \tag{9}$$

where we assumed SNR to be large, used Lemma 1 and the fact that the cumulative distribution function $F(u) = \Pr(U < u)$ of an exponentially distributed random variable U with mean σ_u^2 satisfies

$$\lim_{x \to 0} \frac{1}{g(x)} F(g(x)) = \frac{1}{\sigma_u^2}, \quad g(x) \to 0 \text{ as } x \to 0. \tag{10}$$

Noteworthy, that (9) is only valid in the high SNR regime. Moreover, outage probability in this case does not describe an outage event that occurs directly in the network, but is related to the average outage performance. Hence, the correct outage expression would be $p_{\text{out}}^{(\text{IR})}(\min \mathcal{T}^{-1}(\overline{R}), \mathsf{SNR}) = p_{\text{out}}^{(\text{IR})}(R', \mathsf{SNR})$. However, this expression is not used in the paper for the sake of presentation. More information on this subject can be found in Appendix A of [8].

After simple algebraic manipulation, ϵ-outage capacity can be expressed as

$$\overline{C}_\epsilon^{(\text{IR})} = \log_2\left(1 + \mathsf{SNR}\sqrt{\frac{2\sigma_{\text{sr}}^2\sigma_{\text{sd}}^2\sigma_{\text{rd}}^2}{\sigma_{\text{sr}}^2 + 2\sigma_{\text{rd}}^2}\epsilon}\right). \tag{11}$$

[1]The idea of having an *average* outage expression rather than one that directly occurs in the network has also been considered in [11], where the authors defined the *effective* ARQ multiplexing gain as $r_e := \lim_{\mathsf{SNR} \to \infty} \eta(\mathsf{SNR}) / \log \mathsf{SNR}$ with $\eta(\mathsf{SNR})$ being the long-term average throughput.

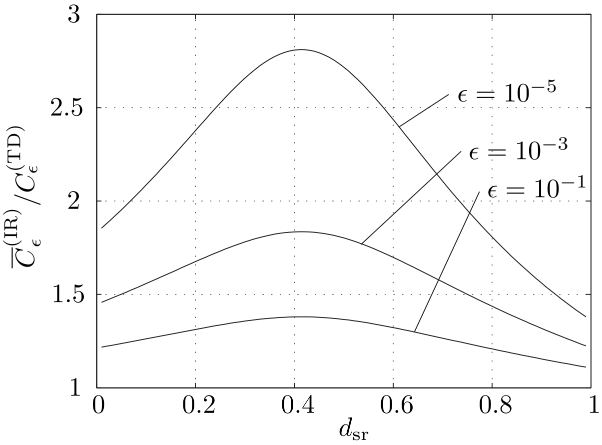

Fig. 3. Ratio of ϵ-outage capacity of incremental relaying and transmit diversity with $\alpha = 3$ and $\mathsf{SNR} = 20$ dB. Source-destination distance has been normalized to 1.

Fig. 3 shows the ratio of ϵ-outage capacity for incremental relaying and transmit diversity with respect to the relay position d_{sr}. Source-destination distance has been normalized to 1 and the relay has been placed on a straight line between source and destination ($0 \leq d_{\text{sr}} \leq 1$). Incremental relaying performs better than transmit diversity if $\overline{C}_\epsilon^{(\text{IR})}/C_\epsilon^{(\text{TD})} > 1$. We can see that incremental relaying outperforms transmit diversity for all positions of the relay. This may be due to the fact that mean rate was assumed for incremental relaying. Nevertheless, since in the high SNR regime the mean rate converges to the actual rate, the result is true in the high SNR regime. Later the result will be generalized to the two-dimensional situation confirming the result.

IV. Signal-to-Noise Ratio Gain

In this section, we derive the SNR gain of incremental relaying over transmit diversity. We define SNR gain as follows:

Definition 1: SNR gain of incremental relaying over transmit diversity for the same outage probability $p_{\text{out}} = \epsilon$ expressed in dB is

$$\Delta_{\mathsf{SNR}}(\epsilon) := 10 \log_{10} \frac{\mathsf{SNR}^{(\text{TD})}}{\mathsf{SNR}^{(\text{IR})}}. \tag{12}$$

After algebraic manipulations of (5) and (11), we get for large SNR:

$$\Delta_{\mathsf{SNR}}(\epsilon) \approx 10 \log_{10}\left(\sqrt{\frac{4\sigma_{\text{sr}}^2\sigma_{\text{rd}}^2}{\sigma_{\text{sd}}^2(\sigma_{\text{sr}}^2 + 2\sigma_{\text{rd}}^2)}}\right) \tag{13}$$

As can be seen, SNR gain does not depend on the outage probability.

Incremental relaying achieves an SNR gain over transmit diversity if $\Delta_{\mathsf{SNR}}(\epsilon) > 0$. Accordingly,

$$4\sigma_{\text{sr}}^2\sigma_{\text{rd}}^2 > \sigma_{\text{sd}}^2(\sigma_{\text{sr}}^2 + 2\sigma_{\text{rd}}^2) \tag{14}$$

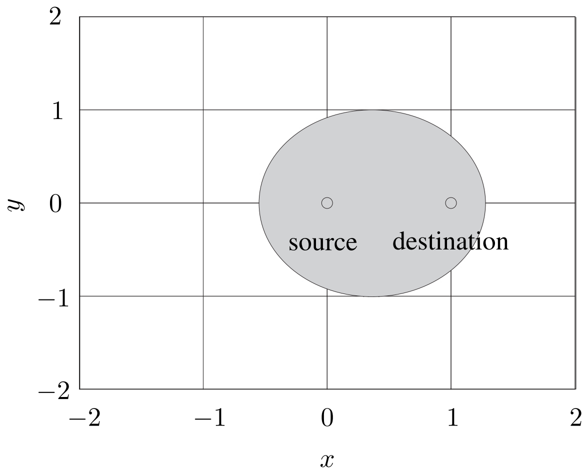

Fig. 4. SNR gain region of incremental relaying over transmit diversity for $\alpha = 3$. Source-destination distance has been normalized to 1.

and by inserting $\sigma_{ij}^2 \sim d_{ij}^{-\alpha}$, this translates into

$$4 > d_{\mathrm{rd}}^{\alpha} + 2d_{\mathrm{sr}}^{\alpha}, \tag{15}$$

where the source-destination distance has been normalized to $d_{\mathrm{sd}} = 1$. Results are illustrated in Fig. 4 for $\alpha = 3$. It can be seen that incremental relaying outperforms transmit diversity as long as the relay is in 'vicinity' of source and destination. The appropriate definition of vicinity depends on the propagation coefficient α.

V. Extensions

We now extend our results to networks with either an arbitrary number of transmit antennas ($K+1$) or an arbitrary number of K relays. We first repeat a lemma that will be helpful for the following investigations. It is a generalization of Lemma 1 and can also be found, e.g., in [12].

Lemma 2: Let $W = \sum_{k=0}^{K} U_k$, where U_k are independent exponentially distributed random variables with mean σ_k^2. If $g(x)$ is a continuous function at $x = 0$ and $g(x) \to 0$ as $x \to 0$, then the cumulative distribution function F of W satisfies

$$\lim_{x \to 0} \frac{1}{g(x)^{K+1}} F(g(x)) = \frac{1}{(K+1)! \prod_{k=0}^{K} \sigma_k^2}. \tag{16}$$

Application of this lemma gives the ϵ-outage capacity for transmit diversity and the approximation (by using the mean rate) of ϵ-outage capacity for incremental relaying.

A. Transmit Diversity with $K+1$ antennas

Mutual information of a MISO-system with $K+1$ transmit antennas and no channel knowledge at the transmitter is

$$I^{(\mathrm{TD})} = \log_2\left(1 + ||\mathbf{h}||_2^2 \frac{\mathsf{SNR}}{K+1}\right), \tag{17}$$

where $\mathbf{h} := [h_{\mathrm{sd}}^{(1)}, h_{\mathrm{sd}}^{(2)}, \dots, h_{\mathrm{sd}}^{(K+1)}]^T$. We have isotropic transmission of energy from the transmit antennas to the destination and mutual information shows a logarithmic relationship with the amount of transmit antennas [13].

Outage probability becomes

$$p_{\mathrm{out}}^{(\mathrm{TD})} = \Pr\left(||\mathbf{h}||_2^2 < \frac{2^R - 1}{\mathsf{SNR}/(K+1)}\right) \tag{18a}$$

$$= F\left(\frac{2^R - 1}{\mathsf{SNR}/(K+1)}\right). \tag{18b}$$

With Lemma 2, we finally get an approximation of outage probability in the high SNR regime of

$$p_{\mathrm{out}}^{(\mathrm{TD})} \approx \frac{1}{(K+1)!\, \sigma_{\mathrm{sd}}^{2(K+1)}} \cdot \left(\frac{2^R - 1}{\mathsf{SNR}/(K+1)}\right)^{K+1}. \tag{19}$$

Accordingly, ϵ-outage capacity results in

$$C_{\epsilon}^{(\mathrm{TD})} = \log_2\left(1 + \sigma_{\mathrm{sd}}^2 \frac{\mathsf{SNR}}{K+1} \sqrt[K+1]{(K+1)!\, \epsilon}\right). \tag{20}$$

This shows to be a straightforward extension of (5). ϵ-outage capacity has a $\sqrt[K+1]{\epsilon}$ behavior and SNR is distributed equally over $K+1$ transmit antennas.

B. Network with K Relays

If the source-destination link is in deep fade, i.e., destination cannot decode the source message, then all relays that have received the destination's request for cooperation and have been able to decode the source message send simultaneously using space-time block coding. Hence, we have a maximum of two transmission blocks (channel uses) and the long-term data rate equals that of a network with only one relay. This scheme is then comparable to that investigated in [14]. The difference is, however, that we have to deal with the variable nature of rate, whereas in [14] there are *always* two transmission blocks. Assuming transmission power to be equally distributed,[2] it can be verified that mutual information is upper bounded by

$$I^{(\mathrm{IR})} \le \log_2\left(1 + \frac{1}{K+1}|h_{\mathrm{sd}}|^2 \mathsf{SNR}\right) + \log_2\left(1 + \frac{1}{K+1}\sum_{k=1}^{K} |h_{\mathrm{r}_k\mathrm{d}}|^2 \mathsf{SNR}\right), \tag{21}$$

where we assume correct decoding of the source message at the relays. The derivation of outage probability follows exactly the same steps as in [14]. We get as an approximation for the high SNR regime

$$p_{\mathrm{out}}^{(\mathrm{IR})} \approx \left(\frac{2^{\overline{R}} - 1}{\mathsf{SNR}/(K+1)}\right)^{K+1} \frac{1}{\sigma_{\mathrm{sd}}^2} \prod_{k=1}^{K} \frac{1}{\sigma_{\mathrm{r}_k\mathrm{d}}^2} A_K(2^{\overline{R}} - 1), \tag{22}$$

[2] In fact, this assumption degrades the rate for IR, since more power could be allocated to the first phase, depending on the expected number of retransmission phases.

where

$$A_K(2^{\overline{R}}-1) = \frac{1}{(K-1)!}\int_0^1 \frac{a^{K-1}(1-a)}{1+(2^{\overline{R}}-1)a}\mathrm{d}a \quad (23)$$

for $K > 0$ and $A_0(2^{\overline{R}}-1) = 1$. Derivation of ϵ-outage capacity gets involved due to $A_K(2^{\overline{R}}-1)$, but upper bounds can be found. The integrand in $A_K(2^{\overline{R}}-1)$ can easily be upper bounded by $\frac{(K-1)^{K-1}}{K^K}$ if $\overline{R} > 0$. The bound is quite loose since only the maximum of the function is considered and it is not taken into account that for large K the function concentrates around a small region at 1. It can be seen numerically that multiplication with $1/K$ – and thus taking the decreased width into account – gives a much tighter bound resulting in

$$A_K(2^{\overline{R}}-1) \leq \frac{(K-1)^{K-1}}{(K-1)!\cdot K^{K+1}} \approx \frac{1}{e\sqrt{K(K-1)}\cdot K!} \quad (24)$$

where Stirling's formula was applied, implicitly assuming that K is large. Accordingly, ϵ-outage capacity can be bounded by

$$\overline{C}_\epsilon^{(\mathrm{IR})} \leq \log_2\left(1+\frac{\mathsf{SNR}}{K+1}\cdot \sqrt[K+1]{\sigma_{\mathrm{sd}}^2\prod_{k=1}^{K}\sigma_{\mathrm{r}_k\mathrm{d}}^2\cdot e\sqrt{K(K-1)}K!\cdot\epsilon}\right). \quad (25)$$

Inserting, SNR gain of incremental relaying versus transmit diversity becomes

$$\Delta_{\mathsf{SNR}}^{(K)}(\epsilon) \approx 10\log_{10}\frac{1}{\sigma_{\mathrm{sd}}^2}\sqrt[K+1]{\frac{\sigma_{\mathrm{sd}}^2\prod_{k=1}^{K}\sigma_{\mathrm{r}_k\mathrm{d}}^2\cdot e\sqrt{K(K-1)}}{K+1}}. \quad (26)$$

Again translating into distances and assuming $d_{\mathrm{sd}} = 1$, incremental relaying achieves an SNR gain over transmit diversity if

$$\prod_{k=1}^{K} d_{\mathrm{r}_k\mathrm{d}}^\alpha \leq \frac{e\sqrt{K(K-1)}}{K+1} \to e \text{ for } K \text{ large}, \quad (27)$$

confirming results of Fig. 4 that for most positions of the relays 'close to source and destination' incremental relaying outperforms transmit diversity. Note, that we implicitly assume that the relays have been able to decode. Hence, we suppose that for the multi-relay case the region in which incremental relaying outperforms transmit diversity with respect to SNR gain is also of elliptical shape. This is quite intuitive since by employing incremental relaying, the channel from source to relays is a receive diversity channel und the remaining channel from relays to destination (itself being a virtual transmit diversity channel) performs better than the original source to destination transmit diversity. It should be noted that the results are based upon several approximations. Tighter bounds, e.g., of (21), have to be found in order to improve the goodness of the approximations.

VI. Conclusions

We showed that incremental relaying outperforms transmit diversity in terms of ϵ-outage capacity and SNR gain in certain regions of relay locations. Investigations in this paper assume that the systems operate in the high SNR regime so that mean rate is approximately equal to the actual rate. Furthermore, we assume degradedness of the relay channel. We are currently generalizing our results to the non-degraded relay channel. We stress that the authors are aware of the fact the investigating the high SNR regime is rather critical since then most of the time the source-destination link will *not* be in outage. However, the applied method allows the treatment of this variable-rate protocol from an information-theoretic perspective similar to [8]. Results on the behavior of incremental relaying in the low SNR regime can be found in [15].

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