Throughput and Energy Efficiency of Cooperative Diversity with Relay Selection

Nikolaj Marchenko [1] and Christian Bettstetter [1,2]

[1] University of Klagenfurt, Institute of Networked and Embedded Systems, Austria
[2] Lakeside Labs GmbH, Klagenfurt, Austria

***Abstract*—Cooperative diversity is a communication technique where a relay node provides signal diversity to the destination by retransmitting the signal received from the source. To find an optimal relay and maximize the resulting performance, a relay selection procedure is used with channel state information as a selection metric. In this paper, we model cooperative diversity with relay selection as a Markov chain, and study the impact of selection timing on throughput and energy efficiency in Rayleigh fading channels. Based on obtained results, we determine optimal relay selection schemes for various network scenarios.**

***Index Terms*—Cooperative relay selection, Markov process.**

I. INTRODUCTION

Cooperative diversity is a form of wireless communication where a message can be delivered from a source to a destination via different paths with help of assisting relays. This implies that one or several neighboring nodes overhear direct source-to-destination transmission and may retransmit the message (or a modification of it) to the destination. Such diversity at the receiver can be particularly beneficial in fading-rich environments, where channel quality can experience high variations over time. Cooperative diversity can also be advantageously applied in small and low-cost radios (such as in sensors) where use of multiple antennas and complex signal equalization methods for fading mitigation are hardly possible due to strict hardware constraints [1].

An information theoretical framework of cooperative diversity protocols is proposed in [2]. Benefits of cooperative relaying highly depend on the quality of source-to-relay and relay-to-destination channels, which in wireless networks involve relay selection mechanisms. Numerous selection protocols have been proposed so far. In most existing proposals, the performance of cooperative diversity is compared with non-cooperative or pure multi-hop schemes. Some works also showed the benefits of supplementary metrics such as distances and residual energy for additional "intelligence" in the selection process (e.g., [3]–[5]).

In this study, we analyze how the time point of the relay selection procedure affects the performance of cooperative diversity. We limit our analysis to the usage of one cooperative relay at a time. Three relay selection schemes can be distinguished:

1) *Fixed relay*: A cooperative relay is selected for a relatively long period of time (e.g., during network start-up). It always overhears direct transmissions and acts as a relay if necessary (see [6] and [7]).
2) *Proactive selection*: A cooperative relay is selected among neighboring nodes before each direct transmission. Here, instantaneous channel state information (ICSI) to potential relays is used to optimally choose a relay. Corresponding schemes are e.g., [6] and [8].
3) *Reactive selection*: A relay is selected from a set of listening nodes only if the direct transmission fails. The retransmitting relay is required to have a correct copy of the message from the source and a good channel to the destination (e.g., [3], [9], [10]).

We evaluate all three schemes in terms of throughput and energy efficiency in Rayleigh fading channels and discuss benefits and drawbacks of their usage. Relays can be selected in a distributed way, e.g., by using back-off timers [8] or contention windows for probabilistic nomination [4]. Although, a particular protocol implementation can further influence the performance results, to distinctly analyze the impact of the selection timing, we assume the optimal outcome from the considered selection procedures.

The rest of the paper is organized as follows. Section II gives modeling assumptions of the channel, network scenario and protocol operation. Section III presents the system model of relay selection schemes. In Section IV we compare performance results of the evaluated schemes. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A. Channel Model

We consider signal transmission between a source node s and a destination node d over a wireless channel as a series of signal-to-noise ratio (SNR) samples $\{\mathrm{SNR}_{\mathrm{sd}}(k)\}$ of frame duration T, during which the signal level remains constant. A binary random process $\{\mathcal{C}(k)\}$ characterizing the channel state is defined as

$$\mathcal{C}(k) = \begin{cases} \text{Good if } \mathrm{SNR}_{\mathrm{sd}}(k) \geq \mathrm{SNR}_{\min}, \\ \text{Bad} \quad \text{if } \mathrm{SNR}_{\mathrm{sd}}(k) < \mathrm{SNR}_{\min}. \end{cases} \tag{1}$$

The channel between two nodes is in the *bad* state when the SNR at the receiver is lower than the threshold $\mathrm{SNR}_{\min}$.

For a Rayleigh channel the frame error (outage) probability between s and d is

$$\epsilon = \mathrm{P}[\mathrm{SNR}_{\mathrm{sd}} < \mathrm{SNR}_{\min}] = 1 - \exp\left(-\frac{1}{\psi}\right), \tag{2}$$

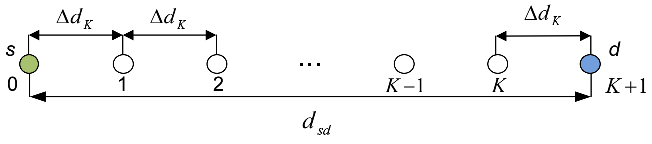


Fig. 1. Network scenario.

where ψ is the source-to-destination *fading margin*. It is the ratio of the expected SNR to the receiver SNR threshold,

$$\psi = \frac{E\left[\mathrm{SNR_{sd}}\right]}{\mathrm{SNR_{min}}}, \tag{3}$$

with

$$E\left[\mathrm{SNR_{sd}}\right] = \begin{cases} \mathrm{SNR_s}\left(\frac{d_{sd}}{d_0}\right)^{-\alpha} & d_{sd} > d_0 \\ \mathrm{SNR_s} & d_{sd} \leq d_0 \end{cases}. \tag{4}$$

Here, $\mathrm{SNR_s}$ is the SNR at the transmitter, d_{sd} is the distance between the source and the destination, $d_0 = 1\,\mathrm{m}$ is a reference distance, and α is the pathloss exponent.

In this paper, we consider two boundary cases of fading dynamics: 1) an independent and identically distributed (i.i.d.) channel and 2) a fully time-correlated channel [7]. In an i.i.d. channel, the state of a channel is independent of any previous channel states and is defined by the frame error rate ϵ. In a fully correlated channel, the state of a channel remains constant over the whole observation time and is also defined by ϵ. A moderately time-correlated Rayleigh fading channel between the two bounds can be modeled as a Markov process (see [11], [12], [7]).

B. Network Topology Model

We use a one-dimensional setup shown in Figure 1, which can be found in transportation or production systems. The most left node is the sender s that transmits data to the most right node, the destination d. By K we denote the number of nodes located on the line between s and d. These nodes can serve as relays to assist the transmission. They are located so that the distance Δd_K between any two consecutive nodes is the same,

$$\Delta d_K = \frac{d_{sd}}{K+1}. \tag{5}$$

The distance from s to node $i \in \{0, 1, 2, \cdots, K+1\}$ is $d_{si} = i\Delta d_K$, and the distance from node i to d is $d_{id} = (K+1-i)\,\Delta d_K$. The corresponding frame error probabilities are calculated by (2)–(4) and denoted as ϵ_{si} and ϵ_{id} for the source-relay and relay-destination channels, respectively.

C. General Protocol Assumptions

In addition to strict time-orthogonality (characteristic for low-cost radios), we make the following assumptions on the operation of cooperative relaying protocols:

- Relays operate in the decode-and-forward mode.
- All nodes use the same transmission rate and power.

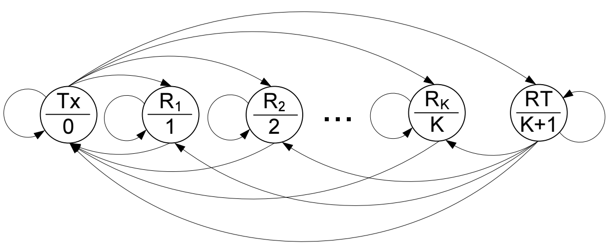


Fig. 2. Markov chain for cooperative relaying with K relay candidates.

- At a receiving node, selection combining on the frame level is performed. No energy accumulation is possible.
- Energy used for a frame transmission is E_{Tx}. Without loss of generality, we normalize it to one.
- Energy for a correct packet reception is $\gamma E_{Tx} = \gamma$. The receiver can detect when $\mathrm{SNR} < \mathrm{SNR_{min}}$ and hold back from reception. Then no energy is used for receiving.
- Signaling messages are error-free. Their energy usage and duration are negligible or included into data frames.
- Relay selection process provides the best possible relay.
- There is no constraint on delay and number of frame retransmissions.

III. COOPERATIVE RELAYING AS A MARKOV PROCESS

The channel states between nodes in Figure 1 are independent from each other and define the operation of cooperative transmissions from source to destination. We can model the considered cooperative relaying schemes with multiple relay candidates as a Markov process shown in Figure 2. State Tx corresponds to a new data packet transmission by the source. State RT is the retransmission of the failed packet by the source. State R_k occurs when node k ($k \in \{1, 2, \cdots, K\}$) is selected as a relay and retransmits the packet to the destination. Transition probabilities from one state to another are described by a $(K+2)\times(K+2)$ transition matrix $\mathbf{P}$. A particular relay selection scheme together with a channel model determine $\mathbf{P}$. We assume that at any time slot there is at least one new frame available for transmission, and each transition has a duration of one frame slot.

If the Markov process described by $\mathbf{P}$ is irreducible and aperiodic, its limiting-state probabilities (stationary probabilities of the protocol to be in each state) described by a vector $\boldsymbol{\pi} = [\pi_0 \ \pi_1 \ \ldots \ \pi_{K+1}]$ can be obtained by solving the following set of linear equations:

$$\begin{aligned} \boldsymbol{\pi}\mathbf{P} &= \boldsymbol{\pi}, \\ \sum_{k=0}^{K+1} \pi_k &= 1. \end{aligned} \tag{6}$$

The value of π_0 is the probability of a new packet transmission and, therefore, provides the normalized throughput η of the corresponding cooperative relaying protocol,

$$\eta = \pi_0. \tag{7}$$

To calculate the energy used for a successful packet delivery, we introduce energy rewards for each state transition. Reward

E_{ij} corresponds to the energy consumed during the transition from state i to state j, including energy for data transmission and receiving. In case the energy reward is a probabilistic value, the expected energy for this transition is taken. The energy reward matrix $\mathbf{E}$ has same dimensions as $\mathbf{P}$. Since each transition takes one frame slot, according to the fundamental theorem of renewal reward processes [13], the expected energy per delivered packet can be written as

$$\mathcal{E} = \frac{1}{\eta} \lim_{\tau\to\infty} \frac{E(\tau)}{\tau} = \frac{1}{\eta} \sum_{i=0}^{K+1} \pi_i \sum_{j=0}^{K+1} P_{ij} E_{ij}. \tag{8}$$

A. Fixed Relay

In cooperative communication with a fixed relay, a relay node is selected to assist the transmission for a relatively long time period. Whenever a direct transmission fails, and the relay gets the message correctly, it forwards the message to the destination. Otherwise, the source retransmits the message. Assuming the expected SNRs between all nodes are known or can be estimated, we always select a relay closest to the center. This is a good approximation for optimal relay location, especially at lower fading margins, when cooperation becomes particularly useful [7]. If several nodes are equally close to the center, the one nearest to the destination is chosen.

For this protocol, the Markov process in Figure 2 reduces to a three-state Markov chain with Tx, R, and RT states, where state R corresponds to the retransmission state with the optimally selected relay. The transition matrix of this protocol for i.i.d. channels is

$$\mathbf{P} = \begin{bmatrix} 1-\epsilon_{sd} & \epsilon_{sd}\left(1-\epsilon_{sr}\right) & \epsilon_{sd}\epsilon_{sr} \\ 1-\epsilon_{rd} & \epsilon_{rd} & 0 \\ 1-\epsilon_{sd} & \epsilon_{sd}\left(1-\epsilon_{sr}\right) & \epsilon_{sd}\epsilon_{sr} \end{bmatrix}. \tag{9}$$

The resulting throughput is obtained from (6) and (7):

$$\eta_{\text{fix}} = \pi_0 = \frac{1+\epsilon_{sd}\epsilon_{sr}\epsilon_{rd} - \epsilon_{sd}\epsilon_{sr} - \epsilon_{rd}}{1+\epsilon_{sd} - \epsilon_{sd}\epsilon_{sr} - \epsilon_{rd}}. \tag{10}$$

Next, we evaluate the energy needed for successful delivery of one data frame including energy for receiving. The corresponding energy rewards matrix in i.i.d. channels is

$$\mathbf{E} = \begin{bmatrix} 1+\gamma\left(2-\epsilon_{sr}\right) & 1+\gamma & 1 \\ 1+\gamma & 1 & 0 \\ 1+\gamma\left(2-\epsilon_{sr}\right) & 1+\gamma & 1 \end{bmatrix}. \tag{11}$$

The resulting expected energy per delivered packet $\mathcal{E}_{\text{fix}}$ is calculated according to (8).

B. Proactive Selection

In proactive relay selection procedure, ICSI is available through signaling preceding each direct transmission (e.g., via Request-to-Send (`RTS`) – Clear-to-Send (`CTS`) message exchange). A relay is selected only if both source-to-relay and relay-to-destination channels are good. We assume that after a successful selection the source-to-relay channel remains in the good state and the relay always gets the packet correctly. Despite the good relay-to-destination channel during the selection, its state might change before relaying, since ICSI estimation takes place two slots before that. However, in time-correlated channels, the change becomes less probable. In addition, from the set of relays with good channels to s and d we select the closest one to the destination. If direct transmission fails, the relay retransmits the message to the destination until a successful reception occurs. If the selection fails, the source transmits without relay assistance.

Cooperative relaying with proactive relay selection can also be described by the Markov chain in Figure 2. The corresponding transition probabilities for i.i.d. channels are

$$P_{ij} = \begin{cases} 1-\epsilon_{id}, & \forall i;\ j=0; \\ \epsilon_{sd}\prod_{k=1}^{K}\left[1-\left(1-\epsilon_{sk}\right)\left(1-\epsilon_{kd}\right)\right], & \\ & i\in\{0,K+1\};\ j=K+1; \\ \epsilon_{sd}\left(1-\epsilon_{sj}\right)\left(1-\epsilon_{jd}\right) & \\ \times\prod_{k=j+1}^{K}\left[1-\left(1-\epsilon_{sk}\right)\left(1-\epsilon_{kd}\right)\right], & \\ & i\in\{0,K+1\};\ 1\le j\le K; \\ \epsilon_{id}, & i=j;\ 1\le j\le K; \\ 0, & \text{otherwise}. \end{cases} \tag{12}$$

Respective energy rewards for i.i.d. channels are

$$E_{ij} = \begin{cases} 1+\gamma, & i=0;\ 1\le j\le K; \\ 1+\gamma, & 1\le i\le K;\ j=0; \\ 1+\gamma\Big(2-\prod_{k=1}^{K}\left[1-\left(1-\epsilon_{sk}\right)\left(1-\epsilon_{kd}\right)\right]\Big), & \\ & i\in\{0,K+1\};\ j=0; \\ 1, & i=j;\ 1\le j\le K+1; \\ 0, & \text{otherwise}. \end{cases} \tag{13}$$

Resulting throughput and energy per packet delivery are calculated as above in (6)–(8).

In case of many potential relays, $K\to\infty$, there always exists a relay with the good channel to the source and error-free channel to the destination which can always successfully relay data. We use this limiting case to indicate the upper limit of cooperative relaying throughput. For i.i.d channels it can be obtained by

$$\eta_{\text{pro}}(K\to\infty) = \frac{1}{1+\epsilon_{sd}}. \tag{14}$$

Corresponding energy usage per delivered packet is

$$\mathcal{E}_{\text{pro}}(K\to\infty) = 1+2\gamma+\epsilon_{sd}. \tag{15}$$

C. Reactive Selection

In reactive relay selection, all nodes are assumed to be listening to the direct transmission. Relay selection takes place after the direct transmission fails. In such a case, the destination sends a negative acknowledgment, which can serve as ICSI estimation of relay-destination channels (assuming symmetrical channels). A relay is chosen from the neighboring nodes that have successfully decoded the data message and have a good channel to the destination.

We assume that the ICSI estimation is perfect, and after the selection process the relay-to-destination channel state remains constant for at least one frame. In case of multiple good relay candidates, for simplicity of mathematical expressions, we choose the one closest to the destination. However, the resulting performance does not change if a random selection is employed - once selected the relay always delivers data to the destination. If no relay can be selected, the source retransmits the message.

In i.i.d. channels the transition matrix probabilities are

$$P_{ij} = \begin{cases} 1-\epsilon_{sd}, \quad i \in \{0, K+1\};\ j=0; \\ \epsilon_{sd} \prod_{k=1}^{K} \left[1-(1-\epsilon_{sk})(1-\epsilon_{kd})\right], \\ \qquad\qquad i \in \{0, K+1\};\ j=K+1; \\ \epsilon_{sd}(1-\epsilon_{sj})(1-\epsilon_{jd}) \\ \times \prod_{k=j+1}^{K} \left[1-(1-\epsilon_{sk})(1-\epsilon_{kd})\right], \\ \qquad\qquad i \in \{0, K+1\};\ 1 \le j \le K; \\ 1, \qquad\quad 1 \le i \le K;\ j=0; \\ 0, \qquad\quad \text{otherwise.} \end{cases} \tag{16}$$

Corresponding energy rewards are assigned by

$$E_{ij} = \begin{cases} 1+\gamma\left(1+\sum_{k=1}^{K}(1-\epsilon_{sk})\right), i \in \{0, K+1\}; j=0; \\ 1+\gamma\sum_{k=1}^{K}(1-\epsilon_{sk})\epsilon_{kd}, i \in \{0, K+1\}; j=K+1; \\ 1+\gamma\left(1+\sum_{k=1}^{j-1}(1-\epsilon_{sk})+\sum_{k=j+1}^{K}(1-\epsilon_{sk})\epsilon_{kd}\right) \\ \qquad\qquad i \in \{0, K+1\};\ 1 \le j \le K; \\ 1+\gamma, \quad 1 \le i \le K;\ j=0; \\ 0, \qquad\quad \text{otherwise.} \end{cases} \tag{17}$$

The resulting throughput and energy values are calculated according to (6)–(8). For $K \to \infty$, throughput efficiency is the same as for proactive relaying in (14), because the selection of a good relay is always possible. However, the consumed energy per delivered frame goes to infinity for $\gamma > 0$, since infinitely many nodes overhear the message.

D. Throughput in Time-Correlated Channels

To better understand the throughput behavior of cooperative diversity in time-correlated channels, we use the correlation scenario of static fading channels. Cooperative relaying throughput achievable in moderately time-correlated channels lies between the limiting boundaries for i.i.d. and fully time-correlated channels [7].

For a fixed relay the throughput in static scenario is

$$\eta_{\text{fix}} = 1-\epsilon_{sd}+\frac{1}{2}\epsilon_{sd}(1-\epsilon_{sr})(1-\epsilon_{rd}). \tag{18}$$

Due to static channels the ICSI timing becomes irrelevant, so that reactive and proactive selection provide the same throughput:

$$\begin{aligned} \eta &= 1-\epsilon_{sd}+\frac{1}{2}\epsilon_{sd}\sum_{i=1}^{K}\Big[(1-\epsilon_{si})(1-\epsilon_{id}) \\ &\times \prod_{j=i+1}^{K}\big(1-(1-\epsilon_{sj})(1-\epsilon_{jd})\big)\Big], \end{aligned} \tag{19}$$

and for $K \to \infty$

$$\eta(K \to \infty) = 1-\frac{1}{2}\epsilon_{sd}. \tag{20}$$

IV. RESULTS

The presented results are obtained from analytical expressions in the previous section, with pathloss exponent $\alpha = 3$. We assume the energy for a packet reception equals the energy for its transmission, $\gamma = 1$. In the fixed-relay scheme, the relay node is always located in the middle between s and d.

A. Throughput Performance

Figure 3 shows throughput performance of the three relay selection schemes in i.i.d. channels. We observe that for a high fading margin ($\psi > 5\,\text{dB}$) all cooperative diversity schemes perform very similar. The number of nodes ($K > 0$) in proactive and reactive selection has negligible impact on throughput.

Cooperation with an optimally located fixed relay starts outperforming proactive and reactive selections for $K = 1$ and a low source-destination fading margin. Proactive and reactive relay selection require both source-to-relay and relay-to-destination channels to be good. At very low fading margins such strict selection becomes rarely possible, and the source operates without an assisting relay most of the time. In the fixed relay mode, after the relay gets the data correctly, it simply has a higher delivery probability to the destination than the source. However, for $\psi < 5\,\text{dB}$ the increase of the number of nodes results in throughput improvement for both proactive and reactive relaying due to higher path diversity.

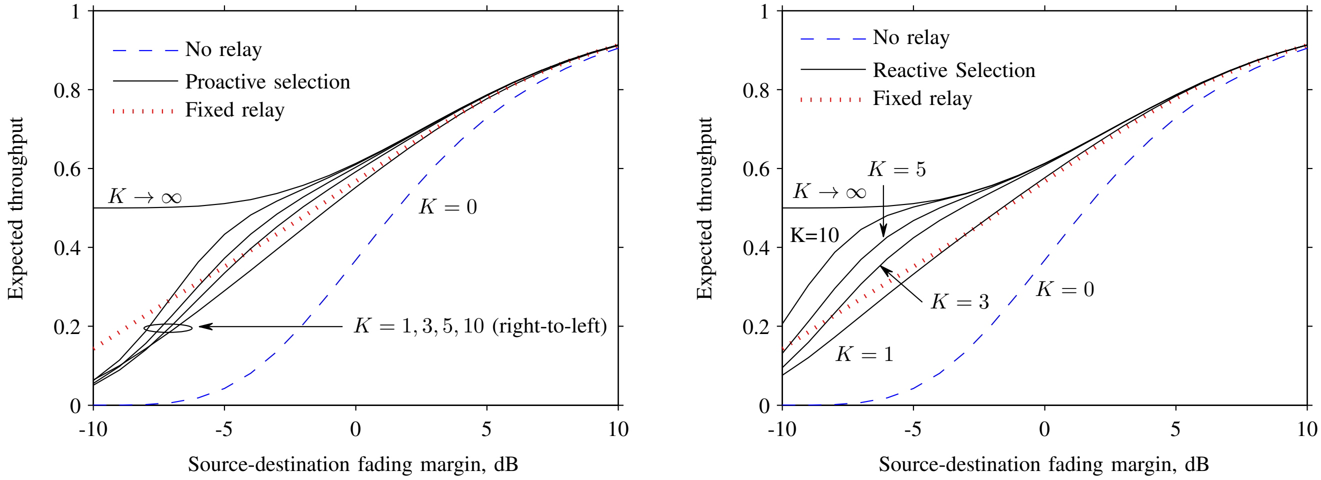
Figure 5 shows the throughput ratio of relaying with reactive selection to relaying with proactive selection. Reactive selection performs better at low source-destination SNR ($\psi < 0\,\text{dB}$). In proactive selection, even if a relay is successfully selected and receives the message, its channel to the destination might change after the first time slot and the retransmission will fail. In reactive selection, in turn, the selected relay always delivers data to the destination.

As shown in Figure 6, in fully time-correlated channels, reactive and proactive relay selection provide the same throughput and outperform the fixed-relay scheme (for $K > 1$). Thus, in increasingly time-correlated channels, the throughput difference between reactive and proactive selection decreases.

B. Energy Efficiency

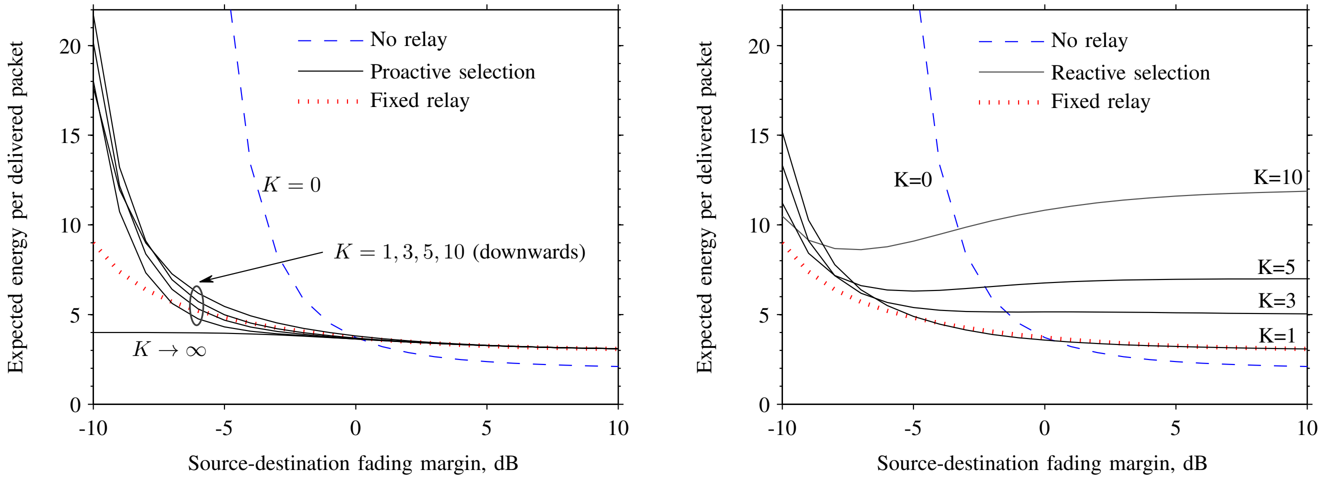
Figure 4a depicts the expected energy used per successfully delivered frame for cooperative diversity with proactive relay selection. For $\psi > 0\,\text{dB}$, there is a marginal difference in energy efficiency for $K > 0$. But the consumed energy sharply increases with the decrease of the source-destination margin. This increase is lower for a larger number of relay candidates K due to better throughput. The lowest required energy is at $K \to \infty$, when a data frame is always delivered in at most two time slots.

Figure 4b shows the corresponding expected energy per delivered frame for reactive relay selection. For $\psi > 0\,\text{dB}$, the



(a) (b)

Fig. 3. Expected throughput of cooperative diversity in i.i.d. channels with fixed relay, reactive and proactive relay selection schemes.



(a) (b)

Fig. 4. Expected energy used for a packet delivery by cooperative relaying in i.i.d. channels with fixed relay, reactive and proactive relay selection schemes.

increasing number of nodes leads to an almost proportional increase of the energy use, since almost all neighboring nodes can successfully overhear transmitted data. But for $\psi < -5\,\mathrm{dB}$, the increase of K and resulting throughput gain can lead to energy benefits (compare $K = 1$ and $K = 10$ in Figure 4b). However, for $K \to \infty$ energy goes to infinity.

Figure 7 shows the energy efficiency ratio of the reactive selection (Figure 4b) to the energy efficiency of proactive selection (Figure 4a). For $K = 1$, the reactive selection is slightly better, since after a relay is selected, its retransmission always succeeds and a better throughput is achieved. But for $K > 1$ and $\psi > -5\,\mathrm{dB}$ proactive relaying is more energy efficient since it uses only one node to overhear direct transmissions. Reactive relay selection still can use less energy at very low SNR margins and low K, where its energy gain from throughput increase overcomes energy used by not relaying nodes.

As mentioned in Section III-D, in fully time-correlated channels, proactive and reactive relay selection provide the same throughput. But proactive selection is more energy efficient, since only one node is used to overhear data. Proactive relaying with $K > 1$ also uses less energy than fix-selected relay, due to better throughput.

V. CONCLUSIONS

We studied three cooperative diversity schemes with different timing of relay selection: fixed relay, proactive selection, and reactive selection.

For optimal operation of the fixed-relay scheme, topology or expected SNR estimation between the nodes is required. The scheme is simple to implement and requires low overhead in signaling and energy, but is not well-suited for mobile networks. It performs relatively well when the source-destination fading margin is above 0 dB and a properly located relay can

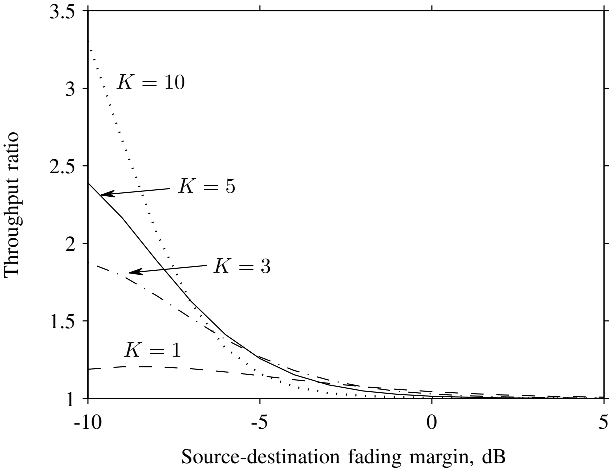


Fig. 5. Throughput ratio of reactive relaying to proactive relaying.

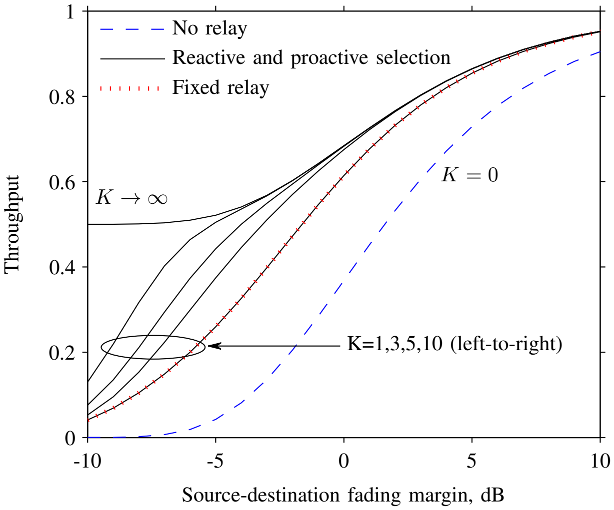


Fig. 6. Throughput in fully time-correlated channels.

be selected.

When SNR values are low, reactive or proactive relay selection become beneficial. They provide better path diversity and make use of instantaneous channel knowledge. They also work better in dynamic networks, where topology information may not be easy to obtain. However, although disregarded here, signaling overhead for relay selection may reduce the resulting efficiency. In addition, reactive relay selection utilizes more energy, since many relays overhear the direct transmission but only one is used later for retransmission.

Our study shows that all three analyzed selection schemes have some inefficiencies and further development of relay selection schemes for particular network applications should be done.

ACKNOWLEDGMENTS

This work was performed in the research cluster Lakeside Labs and was partly funded by the European Regional Development Fund, the Carinthian Economic Promotion Fund (KWF), and the state of Austria under grant 20214/15935/23108.

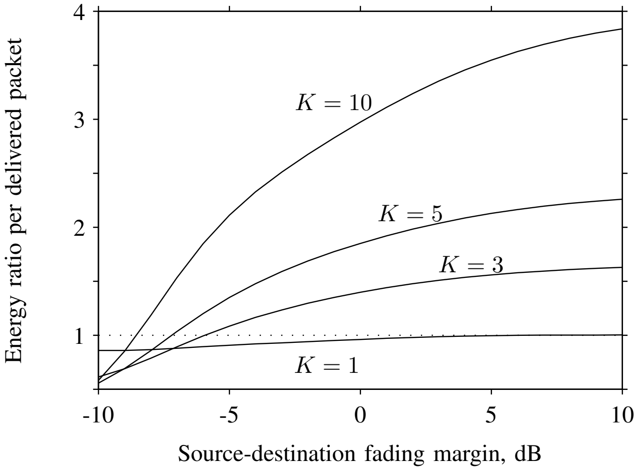


Fig. 7. Energy used for frame delivery with reactive selection divided by the corresponding energy of proactive selection.

REFERENCES

[1] A. Bletsas, A. Khisti, and M. Z. Win, "Opportunistic cooperative diversity with feedback and cheap radios," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1823–1827, May 2008.

[2] N. J. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, Dec. 2004.

[3] M. Zorzi and R. R. Rao, "Geographic random forwarding (GeRaF) for ad hoc and sensor networks: multihop performance," *IEEE Trans. Mobile Comput.*, vol. 2, no. 4, pp. 337–348, 2003.

[4] N. Marchenko, E. Yanmaz, H. Adam, and C. Bettstetter, "Selecting a spatially efficient cooperative relay," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, HI, USA, Dec. 2009.

[5] Y. Wei, F. Yu, M. Song, and V. Leung, "Energy efficient distributed relay selection in wireless cooperative networks with finite state Markov channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, HI, USA, Dec. 2009.

[6] A. Ibrahim, A. Sadek, W. Su, and K. Liu, "Cooperative communications with relay-selection: When to cooperate and whom to cooperate with?" *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2814 –2827, Jul. 2008.

[7] N. Marchenko, C. Bettstetter, and W. Elmenreich, "Incremental cooperative relaying in time-correlated Rayleigh fading channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Miami, FL, USA, Dec. 2010.

[8] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[9] B. Zhao and M. Valenti, "Practical relay networks: A generalization of Hybrid-ARQ," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 7 – 18, Jan. 2005.

[10] S. Ikki and M. Ahmed, "Performance analysis of adaptive decode-and-forward cooperative diversity networks with best-relay selection," *IEEE Trans. Commun.*, vol. 58, no. 1, pp. 68 –72, Jan. 2010.

[11] H. S. Wang and P.-C. Chang, "On verifying the first-order Markovian assumption for a Rayleigh fading channel model," *IEEE Trans. Veh. Technol.*, vol. 45, no. 2, pp. 353–357, Aug. 1996.

[12] R. Carruthers and N. Beaulieu, "On an improved Markov chain model of the Rayleigh fading channel," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Nov. 2007, pp. 1529 –1534.

[13] M. Zorzi and R. R. Rao, "On the use of renewal theory in the analysis of ARQ protocols," *IEEE Trans. Commun.*, vol. 44, no. 9, pp. 1077–1081, Sep. 1996.