© IEEE, 2009. This is the author's version of the work. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purpose or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.
The definite version is published in Proc. IEEE Workshop on Cooperative Mobile Networks (CoCoNet), Dresden, Germany, June 14, 2009.

# On Radio Resource Allocation in Proactive Cooperative Relaying

Nikolaj Marchenko*, Christian Bettstetter*+, and Evsen Yanmaz*
*Mobile Systems Group, Institute for Networked and Embedded Systems, University of Klagenfurt, Austria
+Lakeside Labs GmbH, Klagenfurt, Austria

***Abstract*—Cooperative relaying has drawn great interest to mitigate the negative effects of small-scale fading in distributed wireless networks. This paper analyzes radio resource allocation in cooperative relaying with proactive relay selection. Due to the introduction of the relay into the communication link an over-expenditure of resources can take place similar to the classical exposed terminal problem. In this work we derive the overall network throughput in two simple scenarios and determine the regions of packet-error-rates where cooperative relaying yields a throughput gain.**

***Index Terms*—Cooperative relaying, cooperative diversity, radio resource allocation, medium access control**

## I. Introduction

Cooperative relaying is considered to be an untapped means to mitigate the negative effects of multipath propagation in wireless communications. It uses the well-known concept of spatial diversity in a distributed manner [1]. The basic building block of this emerging area is the relay channel (see Fig. 1): a source $S$ transmits a signal to a destination $D$; a third node $R$ overhears this transmission and relays the signal to $D$. In this way, the broadcast nature of the wireless channel is exploited.

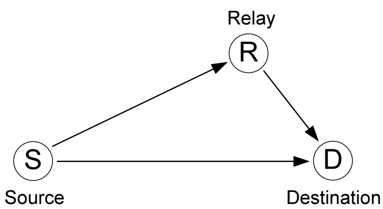



Fig. 1. Cooperative relay channel

The benefits of cooperative relaying have mainly been studied from physical layer and information theory points of view. For instance, the articles [1] and [2] show performance gains in terms of outage and signal-to-noise ratio (SNR). Theoretical bounds for the relay channel capacity have been derived in [3], [4].

Only recently, efforts were made in analyzing the impact and requirements of cooperative relaying *above the physical layer*. One aspect in this research domain is to analyze how relaying works together with commonly used Medium Access Control (MAC) protocols: What is the influence of cooperative relaying on MAC layer functionality? How should resource allocation for cooperative relaying be optimally done? Are new MAC protocols or extensions to existing MAC protocols needed? The article [5] enhances slotted ALOHA with cooperative relaying and evaluates its performance gains. The articles [6], [7], and [8] propose modifications to the IEEE 802.11 Distributed Coordination Function (DCF) [9].

However, existing MAC protocols are designed to operate in a non-cooperative communication environment, and simple extensions do not necessarily give optimal results for cooperative transmissions. Thus, optimization of resource allocation and impact of cooperative relaying in networks with more than three nodes are needed to be studied further. In this paper, we discuss and analyze problems of resource allocation for cooperative relaying similar to the well-known exposed terminal problem observed in wireless networks with distributed control. The study shows that a new approach for MAC layer design is needed to optimally utilize radio resources in cooperative relaying.

The rest of the paper is organized as follows. In Section II, first the classical exposed terminal problem in wireless ad hoc networks is explained. Then we introduce the related problem of resource utilization in cooperative relaying. In Section III, a performance analysis for two simple network setups is made. Finally, Section IV concludes the paper.

## II. Resource Allocation Problem

### A. Classical Exposed Terminal Problem

The exposed terminal problem is a medium over-reservation problem emerging from the lack of coordination among nodes in wireless networks [10]. Figure 2 shows a classical example of the exposed terminal problem. Node $A$ is out of transmission range of $C$ and $D$, and node $D$ is out of range of $A$ and $B$. Thus, during the transmission from $B$ to $A$, node $C$ could also transmit to $D$ without disturbing the other transmission. However, due to the `Request-to-Send` (`RTS`) and `Clear-to-Send` (`CTS`) handshake of the DCF, such parallel transmission is impossible, as node $B$ blocks all transmissions in its range after winning the contention and sending an `RTS` message. Solutions of the exposed terminal problem include the introduction of additional coordination messages or tones (see [10], [11]).


Fig. 2. Classical exposed terminal problem

This work was supported by the European Regional Development Fund and the Carinthian Economic Promotion Fund (KWF) under grant 20214/15935/23108 within the Lakeside Labs project.

### B. Resource Allocation Dilemma in Cooperative Relaying

In addition to the direct wireless link between the source and destination, in cooperative relaying two other links are used: source-to-relay and relay-to-destination. To achieve maximal benefit of these two relay links, a well-suited *relay selection protocol* is needed. Generally, relay selection protocols can be classified in two groups [12]:

- *Proactive relay selection* is performed prior to the direct transmission: a particular node is selected to listen to the direct transmission and relays the data when required.
- *Reactive relay selection* is performed after the direct transmission: a relay is chosen from the set of nodes that could correctly overhear the message from the source.

In this paper we focus on proactive relay selection and illustrate the impact of its resource allocation on system performance. In proactive relay selection a message is sent by the relay after the `RTS-CTS` handshake, confirming that the relay is ready to listen to the direct transmission. There are different names for this confirmation message in the literature (see [6], [7], [8]); in this paper, we call it `Relay Ready` (`RR`) message. A relay always sends an `RR` message to inform the source and destination that cooperative relaying is possible. Also other neighboring nodes are notified about the relay transmission. In order to allow the relay to receive the message correctly and retransmit it to the destination, neighboring nodes are required to remain silent for a certain time period.

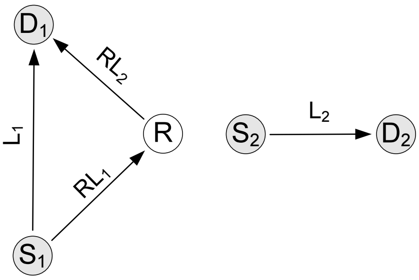
Once relay selection has been performed and the relay has overheard the direct transmission, the actual *relay transmission* takes place. Two strategies are as follows:

- *Fixed relaying*. A message is always retransmitted by the relay, independently of the success on the direct source-destination link (see [6]). This approach has a disadvantage of over-expenditure of resources.
- *On-demand relaying*. A message is only retransmitted by the relay, if an explicit or implicit notification (absence of `ACK` messages, timer expired) instructs the relay to do so (see [7], [8]). Potentially, this approach uses the radio resources in a more efficient manner. However, as there are certain time constraints for a relay to perform its transmission, the relay-destination link requires resource allocation in parallel with the one for the source-destination transmission.

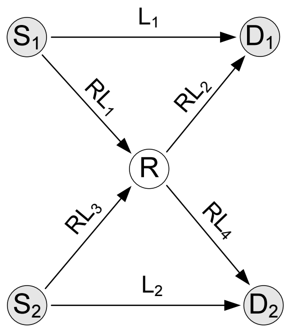
A dilemma in the protocol design can be observed: in both cases radio resources are pre-allocated to the relay to correctly receive and then, if necessary, to retransmit the data message. The necessity of cooperative relaying depends on the channel quality on the direct link. Basically, a cooperative retransmission is needed only when the direct link fails.

Figure 3 shows two simple scenarios, where nodes are located at such distances that transmissions on links $L_1$ and $L_2$ can happen simultaneously without disturbing each other if cooperative relaying is not employed. While the scenarios are very simple, they provide an important insight into the resource allocation problem in cooperative relaying.

In Scenario A, node $R$ is in the range of $S_1$ and $D_1$. It is proactively chosen to assist as a relay to the direct transmission. In addition, node $R$ is also in the range of $S_2$ but is out of the range of $D_2$. In the case of cooperative relaying, to ensure that $R$ can receive the data message from $S_1$, transmissions on link $L_2$ need to be blocked, since a parallel transmission from $S_2$ would lead to a collision at the relay. However, at this point it is still not known whether the retransmission from relay is needed. For $S_2$ and $D_2$ it looks as if the communication link between $S_1$ and $D_1$ is expanded in space and time, incorporating an additional node and physical communication channels to it, so that previously hidden links $L_1$ and $L_2$ become exposed to each other. If the direct packet transmission on $L_1$ fails, the relay retransmits the correctly received message to $D_1$. At this time a classical exposed terminal problem takes place, and $S_2$ is blocked to transmit again due to the lack of synchronization. Until the packet is correctly received at the destination or dropped out due to a time-out, transmissions between $S_2$ and $D_2$ are not possible since their link is exposed to that expanded communication link of $L_1$.




(a) Scenario A.




(b) Scenario B.

Fig. 3. Extended exposed terminal problem in cooperative relaying. Scenario A shows an asymmetrical setup with only one direct transmission exposed to the relay $R$. Scenario B shows a symmetrical case with both transmissions exposed to the cooperative relay.

In Scenario B, a symmetrical example of the problem is presented. Node $R$ is used as a cooperative relay on both links $L_1$ and $L_2$. Clearly, in such usage of the relay only one of both transmissions is possible at the same time. In both scenarios in addition to classical exposed terminal problems, extended blockage of neighboring transmissions by the relay node takes place, although the need for cooperative retransmission remains probabilistic in nature.

## III. Performance Analysis

In our performance analysis we focus on data packet transmissions on the MAC layer. Data throughput is measured in packets/s. We assume that the size of data packets is the same at all sources and that all sources have always at least one packet in their queue ready to be sent. We do not specify the size of data packets, since it is not relevant for the general problem presentation. We assume that the channel occupancy time required for overhead (e.g. contention for medium, collision resolutions and control messages) is much smaller than that required for data packets transmission, and is neglected in our calculations.

We consider a decode-and-forward relaying scheme, where the relay needs to successfully decode the message for re-transmitting it. There exist various techniques to re-encode the message at the relay before forwarding it further to the destination. In this work we assume the message is retransmitted by the relay at the same rate as it is received.

In this study we do not consider any packet combining technique, although it can give an additional SNR gain at the receiver. The reason to ignore packet combining is that in our scenarios a cooperative retransmission is done only when the direct transmission fails, usually due to small-scale fading. Normally, before combining, the received packets are weighted according to the channel conditions they came through. Thus, the packet received via a very bad direct link is discarded to avoid additional errors during combination.

### A. Scenario A

Let us study Scenario A in Figure 3 first. We assume that links $L_1$ and $L_2$ have maximal achievable throughput $T_1$ and $T_2$, respectively. If average packet error rates (PER) on the links $L_1$ and $L_2$ are $p_1$ and $p_2$, respectively, then the total system throughput without cooperative relaying is:

$$T = T_1 \left(1 - p_1\right) + T_2 \left(1 - p_2\right). \tag{1}$$

Using cooperative relaying, we assume that relay links $RL_1$ and $RL_2$ have such maximal channel capacities that theoretically they are able to satisfy the traffic demand from the source. All PERs are uncorrelated to each other.

If the direct transmission succeeds, the cooperative relaying is not used and a new contention for the medium access starts. If the direct transmission fails, packet retransmission by a relay is performed only once in the following time slot. If the cooperative relaying also fails, the data packet is dropped out of the MAC queue. We assume the probability for each link to win the contention for the medium access is $50\,\%$. As a result, the total throughput of the presented setup consists of two parts that are weighted with coefficient 0.5 according to the averaged contention outcome. If $S_1$ wins the channel contention, it proactively chooses node $R$ as a cooperative relay, which then transmits an RR message and blocks the transmission from $S_2$ until the cooperative transmission to $D_1$ is over. If $S_2$ wins the contention, link $L_1$ can be also used simultaneously but without cooperative relaying via $R$. The resulting average system throughput is:

$$\begin{aligned} T_A &= \tfrac{1}{2}\left(T_1\left(1-p_1\right) + T_2\left(1-p_2\right)\right) \\ &+ \tfrac{1}{2}\tfrac{T_1}{\alpha}\left(\left(1-p_1\right) + \tfrac{1}{2}p_1\left(1-p_r\right)\right). \end{aligned} \tag{2}$$

The term $p_r$ indicates the joint PER of the path via relay $R$.

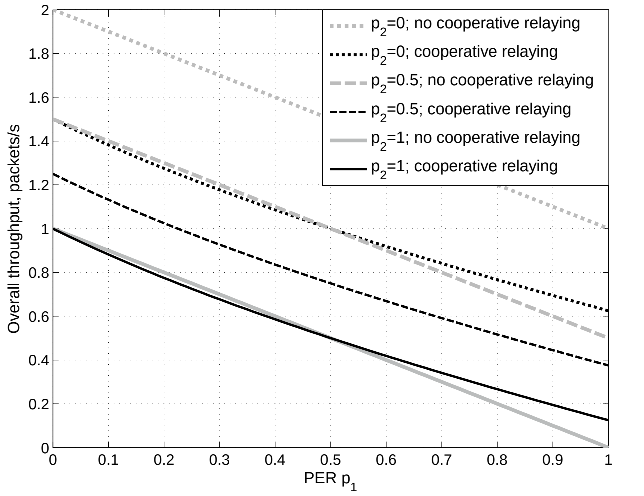



Fig. 4. Overall system throughput for Scenario A. Maximal throughputs on direct links are normalized $T_1 = T_2 = 1$. Curves depict best possible cases for cooperative relaying with perfectly error-free relay link, $p_r = 0$.

It is given by

$$p_r = 1 - \left(1 - p_{RL1}\right)\left(1 - p_{RL2}\right). \tag{3}$$

However, a direct comparison of cooperative and non-cooperative cases is not fair, since the former implies an additional retransmission of the same data packet after the failure. To reflect that data transmission takes on average $1 + p_1$ times longer when cooperative relaying is enabled, the term $\alpha$ is introduced in (2):

$$\alpha = 1 + p_1. \tag{4}$$

We assume $T_1 = T_2$, which is generally true if nodes have same transmit characteristics. Without loss of generality, we can normalize throughputs in the following as $T_1 = T_2 = 1$. First we consider the best possible case for cooperative relaying with $p_r = 0$.

Figure 4 shows system throughput versus PER $p_1$ and different values of $p_2$. It can be observed that even when both direct links are error-free ($p_1 = p_2 = 0$), and cooperative relaying is not needed, the overall throughput in the case of cooperation corresponds to $3/4$ of the throughput in the non-relaying case. Transmissions on $L_2$ are not allowed while $S_1$ is transmitting to ensure the relay receives its copy of the packet without interference from $S_2$.

On the other hand cooperative relaying can significantly improve throughput at $D_1$ when $p_1$ is very high. During cooperative relaying, a relay takes all space-time resources away from link $L_2$ and allocates them to help on the direct transmission on $L_1$. Let us thus study how efficiently the resource redistribution is done by cooperative relaying. We define $T_{D_i}^{CR}$ and $T_{D_i}$ as achieved data throughput at the destination $D_i$ with and without cooperative relaying in the system, respectively. The efficiency $E_A$ of resource reutilization for Scenario A is defined as:

$$E_A \triangleq -\frac{T_{D_1}^{CR} - T_{D_1}}{T_{D_2}^{CR} - T_{D_2}}, \quad T_{D_1}^{CR} \geq T_{D_1}. \tag{5}$$

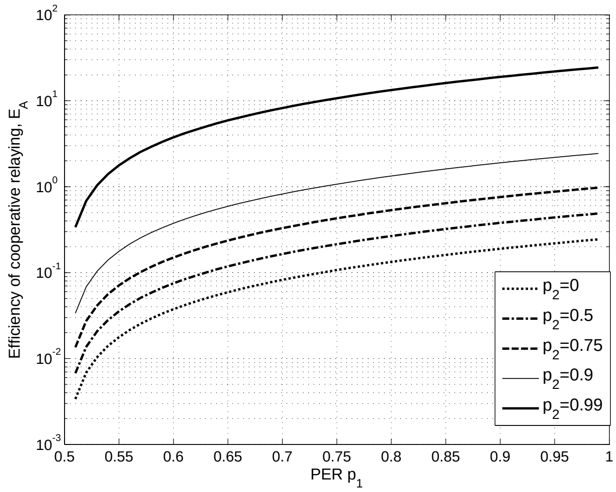



Fig. 5. Efficiency of cooperative relaying in resource utilization in Scenario A. A perfectly error-free relay link is assumed assumed, $p_r = 0$.

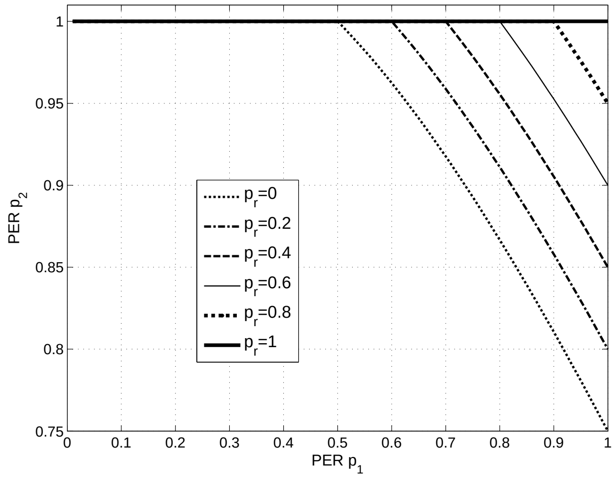



Fig. 6. PER conditions according to inequation (6). Curves indicate borders for particular $p_r$ above which cooperative relaying is more beneficial in the overall throughput than direct transmissions only.

The defined efficiency metric $E_A$ cannot be used when cooperative relaying results in throughput degradation on $L_1$ ($T_{D_1}^{CR} \leq T_{D_1}$), which is valid when $p_1 < 0.5$. Throughputs at destinations are calculated in the same way as in (1) and (2). Table I explains main value regions for $E_A$. Only if $E_A > 1$ cooperative relaying improves $L_1$ more than it degrades on $L_2$, and thus an increase in the total throughput is achieved.

TABLE I
EFFICIENCY METRIC

| Value of $E_A$ | Explanation |
|---|---|
| $E_A > 1$ | CR improves $L_1$ more than it degrades $L_2$ |
| $E_A = 1$ | CR improves $L_1$ and degrades $L_2$ equally |
| $0 < E_A < 1$ | CR improves $L_1$ but degrades $L_2$ more |

Figure 5 shows the efficiency of cooperative relaying in reusing resources taken from $L_2$. Two aspects can be observed. First, the efficiency metric grows with growing $p_2$ on $L_2$, because blockage of a bad link does not harm the throughput on it as much as blockage of a good link. Second, efficiency improves with growing $p_1$ on $L_1$, since cooperative retransmission by $R$ is more probable.

We should again notice that for results in Figures 4 and 5 ideal channel conditions for relay links are assumed. However, for a more realistic analysis it is necessary to study how the system performance changes when all links are not error-free. By comparing (1) with (2), after some mathematical manipulations, we can determine the PER conditions at which the cooperative relaying becomes more desirable for overall throughput compared to conventional direct communication. We obtain:

$$T_A > T \Leftrightarrow p_2 > \frac{2 - 2p_1^2 + 3p_1 + p_1 p_r}{2\,(1 + p_1)}. \qquad (6)$$

Figure 6 illustrates this inequation for some values of the parameter $p_r$. For a given $p_r$, the area above the curve corresponds to $(p_1, p_2)$-pairs where the use of cooperative relaying results in improved overall throughput. Areas below the curves correspond to PER values where cooperative relaying worsens the overall throughput. We observe that cooperative relaying can never be beneficial for overall throughput when $p_2 \leq 0.75$, which can also be seen in Figure 5. In addition, cooperative relaying cannot provide any throughput gain when $p_r \leq 2\,(p_1 - 0.5)$, since then cooperative relaying uses more resources than direct transmission.

## B. Scenario B

Following the same assumptions as in Scenario A, we derive overall throughput for Scenario B in Figure 3. The link wining the contention first reserves the channel for the cooperative relay, which blocks transmissions on the other link. We have:

$$\begin{aligned} T_B &= \tfrac{1}{2} \cdot \tfrac{1}{1+p_1} \cdot T_1 \left((1 - p_1) + \tfrac{1}{2} p_1 \,(1 - p_{r1})\right) \\ &+ \tfrac{1}{2} \cdot \tfrac{1}{1+p_2} \cdot T_2 \left((1 - p_2) + \tfrac{1}{2} p_2 \,(1 - p_{r2})\right). \end{aligned} \qquad (7)$$

In a similar manner as $p_r$ in Scenario A, $p_{r1}$ and $p_{r2}$ represent joint PERs on paths via $R$ when the relay cooperates with $L_1$ and $L_2$, respectively. To simplify the analysis to the best performance bound of the cooperative relaying, we assume ideal conditions on all relay links: $p_{r1} = p_{r2} = 0$. Figure 7 compares overall throughputs with normalized traffic demands for Scenario B with and without cooperative relaying. As in Scenario A, cooperative relaying decreases the overall throughput substantially when the PERs on the direct links are good. In case PER on one or both direct links is high enough, the blockage of a bad direct link does not harm the overall throughput that much, and, in addition, cooperative relaying improves such bad links significantly. That can be seen again in the efficiency metric in Figure 8. Due to symmetry, resources are especially efficiently reused if at least one of the direct links is bad. Since in this scenario both links take turns using cooperative relaying and blocking each other, the total efficiency is calculated as a sum of two efficiency metrics corresponding to each relaying case separately:

$$E_B \triangleq \frac{T_{D_1}^{CR} - T_{D_1}}{T_{D_2}} + \frac{T_{D_2}^{CR} - T_{D_2}}{T_{D_1}}. \qquad (8)$$

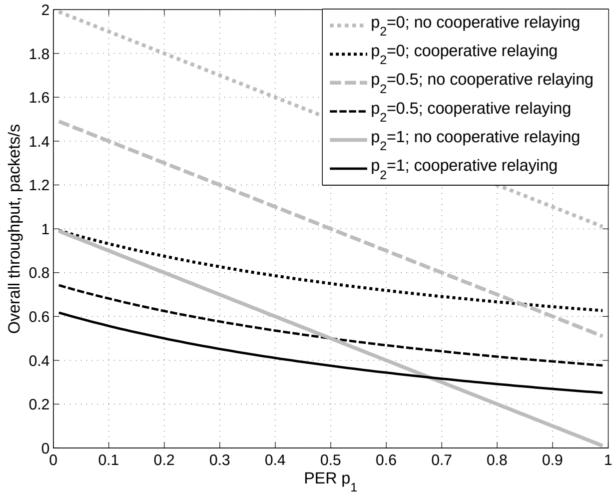



Fig. 7. Overall system throughput for Scenario B. Maximal throughputs on direct links are normalized $T_1 = T_2 = 1$. Curves depict best possible cases for cooperative relaying with perfectly error-free relay links, $p_{r1} = p_{r2} = 0$.

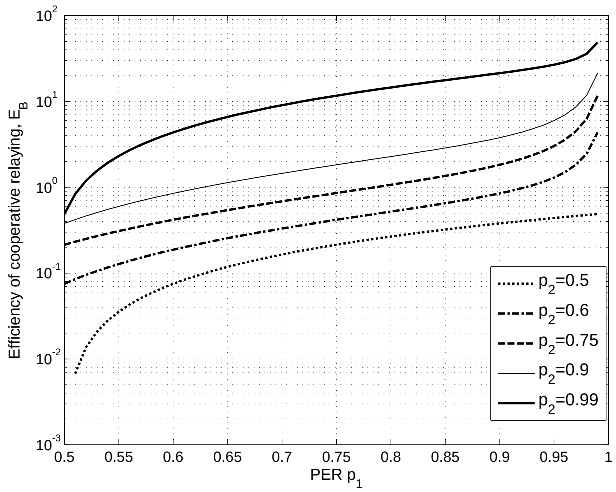



Fig. 8. Efficiency of cooperative relaying in resource utilization in Scenario B. Perfectly error-free relay links are assumed, $p_{r1} = p_{r2} = 0$.

Similar to $E_A$ in Scenario A, the definition of $E_B$ applies only when both components are positive: $T_{D_1}^{CR} \geq T_{D_1}$ and $T_{D_2}^{CR} \geq T_{D_2}$; i.e., when $p_1 \geq 0.5$ and $p_2 \geq 0.5$.

### *C. Summarizing the Results*

The provided analysis of two simple scenarios shows that network performance gain or loss introduced by the cooperative relaying is largely determined by PERs of individual links. So far we intentionally have not specified how PERs of communication channels are averaged. If PER is averaged over a short-time period corresponding to just a few data transmissions, then PER reflects a more dynamic wireless channel. Links can get into deep-fades which results in high PER. According to results in previous subsections, in such situations cooperative relaying becomes more beneficial for the network, although the extended exposed terminal problem still takes place. In such cases resources allocated to ensure cooperative transmission are used with high probability. However, in a longer term the channel quality is normally not as bad as in deep fade. As a result, $p_1$ and $p_2$ are lower and cooperative relaying is less beneficial or even disadvantageous for the overall throughput.

In the approach presented above a higher priority for transmission is always given to the cooperative relay. The results show that cooperative relaying is not needed for most transmissions. Therefore, resource allocation for relay links is only necessary when the direct link is rather bad. How to modify the MAC layer according to such channel estimations is a question for future research. A direct approach is to give a higher transmission priority to direct links. So if the source $S_2$ receives a reservation message from $R$, it does not change its transmission behavior, and sends out a data packet from its queue. Then, of course, a collision at $R$ can happen and relay retransmission is not possible. However, hidden direct links can be used simultaneously.

## IV. Conclusion

In this paper we present a problem of over-expenditure of radio resources in cooperative relaying. The problem appears when proactive relay selection schemes are used, for example as modification of DCF-based MAC. Our study shows on two simple scenarios that depending on channel conditions of individual links cooperative relaying can significantly decrease the total network performance. The results are expected to be even worse if MAC overhead is taken into account. To overcome this problem and use cooperative relaying efficiently, a better approach of radio resource allocation needs to be developed and analyzed also for more complex network scenarios.

## References

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

[2] E. Zimmermann, P. Herhold, and G. Fettweis, "On the performance of cooperative relaying protocols in wireless networks," *European Trans. Telecommun.*, vol. 16, no. 1, pp. 5–16, 2005.

[3] A. Høst-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 2020–2040, Jun. 2005.

[4] A. Høst-Madsen, "Capacity bounds for cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 52, no. 4, pp. 1522–1544, Apr. 2006.

[5] W.-H. Wong, J. M. Shea, and T. F. Wong, "Cooperative-diversity slotted ALOHA," *Wireless Networks*, vol. 13, no. 3, pp. 361–369, Jun. 2007.

[6] C.-T. Chou, J. Yang, and D. Wang, "Cooperative MAC protocol with automatic relay selection in distributed wireless networks," in *Proc. IEEE Intern. Conf. Pervasive Comput. Commun. Workshops (PerCom)*, 2007, pp. 526–531.

[7] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, Feb. 2007.

[8] H. Adam, C. Bettstetter, and S. M. Senouci, "Adaptive relay selection in cooperative wireless networks," in *Proc. IEEE Intern. Symp. Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Sep. 2008, pp. 1–5.

[9] IEEE LAN MAN Standard, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) specifications," 1999.

[10] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media access protocol for wireless LAN's," in *ACM Proc. Special Interest Group on Data Commun. (SIGCOMM)*, 1994, pp. 212–225.

[11] Z. J. Haas and J. Deng, "Dual busy tone multiple access (DBTMA): a multiple access control scheme for ad hoc networks," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 975–985, 2002.

[12] 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.