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Cooperative Relaying in Car-to-Car Communications: Initial Results from an Experimental Study

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***Abstract*—This paper reports on an experimental study about some benefits of cooperative relays in mobile wireless communications. A basic technique for cooperative relaying is implemented in the programmable hardware platform WARP. Using this implementation, measurements are made for mobile car-to-car communications in a suburban environment. Each of three cars is equipped with a transceiver and serves as sender, relay, or destination, respectively. Results demonstrate that cooperative relaying communications exhibit performance gains over conventional direct communications and time-diversity communications in terms of packet delivery rate, bit error rate, and packet error rate. We account for energy fairness by using half transmission power for cooperative relaying and time diversity communications.**

***Index Terms*—Wireless networks, mobile networks, cooperative relaying, car-to-car communications, diversity, measurements, experimental study.**

I. Introduction

The concept of cooperative relaying in wireless systems promises performance gains. The basic idea is simple: A device in the communication range of a transmitting device overhears the communication to a destination device. It subsequently acts as a relay, i.e., it forwards the received data to the destination device. The inherent spatial diversity of the two transmissions can be exploited at the destination.

The design space of cooperative relaying systems is large. The system requires, for instance, appropriate modulation and coding techniques [1]–[3], relay selection protocols [4]–[6], and enhanced medium access control [7]–[10], to mention a few building blocks. The huge majority of studies in this research area has focused on performance evaluations using analytical models and approaches [11]–[13], simulations [9], or combinations of both [14], [15].

This paper addresses the *experimental* evaluation of cooperative relaying. Using a programmable hardware platform we investigate the gains of cooperative relaying communications with selection combining in comparison to conventional direct communications and simple time-diversity communications in a mobile car-to-car scenario. Relying on initial measurements, we demonstrate the gains in terms of bit and packet error rates as well as packet delivery rates.

The paper is structured as follows: Section II explains the measurement setup and methodology. Section III presents and interprets the major results. Section IV gives some insight into challenges that we faced during the implementation and measurements and briefly explains how we solved them. Section V addresses related work on testbeds for cooperative relaying and real-world measurements for car-to-car communications.

II. Measurement Setup and Methodology

Our goal is to evaluate the performance gains of cooperative relaying in a typical mobile radio environment. To do so, we compare three communication strategies:

- Conventional direct communication: The source transmits each packet *once* with *full* transmission power.
- Time-diversity direct communication: The source transmits each packet *twice*, where each transmission is made with *half* transmission power
- Cooperative relaying: The source transmits each packet *once* with *half* transmission power; the relay transmits each received packet *once* with *half* transmission power.

The intention of sending packets at half or full transmission power is to achieve a fair comparison between cooperative relaying and direct communication in terms of energy consumption.

We perform measurements in the 2.4 GHz band using three WARP boards [16]. These boards are based on field-programmable gate arrays (FPGAs) and enable the programmability of low-layer protocols. Each board is assigned to a car and serves as either source, destination, or relay. The full transmission power is 10 dBm, the half transmission power is 7 dBm. The antennas, which have a gain of 7 dBi, are attached to the roofs of the cars. The packet size is 1048 bytes, consisting of a payload of 1024 bytes and a header of 24 bytes. Furthermore, we use quadrature phase-shift keying (QPSK) as the modulation scheme and do not employ channel coding. The orthogonal frequency-division multiplexing (OFDM) reference design, which we employ, uses 64 subcarriers from which 48 are data-bearing. The used bandwidth is 12.5 MHz, and the data rate is 12 Mbit/s.

The following packets are transmitted in a round-robin fashion (see Figure 1):

(1) a full-power packet from the source to the destination,
(2) a half-power packet from the source to the destination,
(3) a second half-power packet from the source to the destination and the relay, and finally
(4) a half-power packet from the relay to the destination.

The relay only sends packet (4), if it received packet (3), no matter if there have been bit errors in packet (3).

There is a time interval of approximately 9 ms between each packet in a given cycle. 20 ms after packet (4) is sent, the cycle

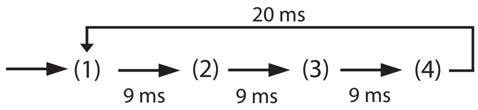

Fig. 1. Sequence of transmissions

restarts with the transmission of a packet of type (1) by the source. Therefore, about 80 packets are transmitted per second. The results of this paper are based on approximately $400\,000$ packets transmitted by the source.

The implementation on the WARP boards is a customized version of the OFDM reference design (version 12), which we extended to

- calculate the bit error rate in hardware and
- receive the payload of packets even if the header contains bit errors.

For calculating bit and packet error rates we initialize the payload with a predefined bit structure. The measurements are carried out in a suburban environment in a way such that the car serving as the source is driving in front followed by the relay and destination cars, where the relay car is always located between source and destination. To keep track of the position of the three cars and, in particular, to be able to calculate the distances between them, we use GPS receivers to capture the GPS coordinates for any packet sent or received. The GPS receivers have a update rate of $4\,\mathrm{Hz}$. In our measurements the maximum distance between source and destination is $186\,\mathrm{m}$; the mean distance is about $59\,\mathrm{m}$. The maximum distance between source and relay is $149\,\mathrm{m}$; between relay and destination it is $142\,\mathrm{m}$.

III. Measurement Results

In this section we present the results of the measured performance of the three communication strategies in terms of packet loss and end-to-end packet delivery rate (Section III-A) as well as bit error rate and packet error rate (Section III-B).

A. Packet Loss and Packet Delivery Rate

A packet is lost if the signal strength at the receiver falls below a certain threshold. Our measurements have shown that this threshold is approximately at $-80\,\mathrm{dBm}$. The percentage of lost packets for different transmission paths is shown in Figure 2.

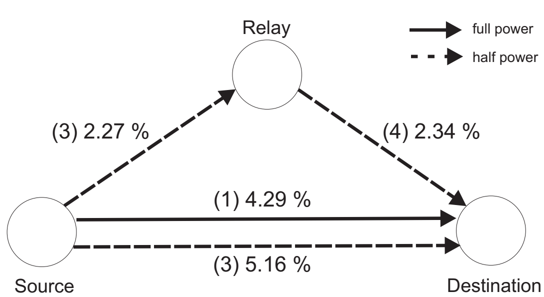

Fig. 2. Percentage of lost packets

About 4.3% of all full-power transmissions (1) have been lost, while 5.2% of all half-power transmissions (3) have been lost. The source-relay and relay-destination links exhibit smaller packet losses (2.3%), which is due to the smaller communication distances.

The packet delivery rate gives information on how many packets have been delivered at the destination, no matter how many bit errors have occurred. For time diversity, a packet is regarded to be delivered, if at least one of the transmissions (2) or (3) is received by the destination. For cooperative relaying, there are two possible paths for a packet to be delivered: the direct source-destination path and the source-relay-destination path; the packet is considered to be delivered if it is delivered over at least one of these paths.

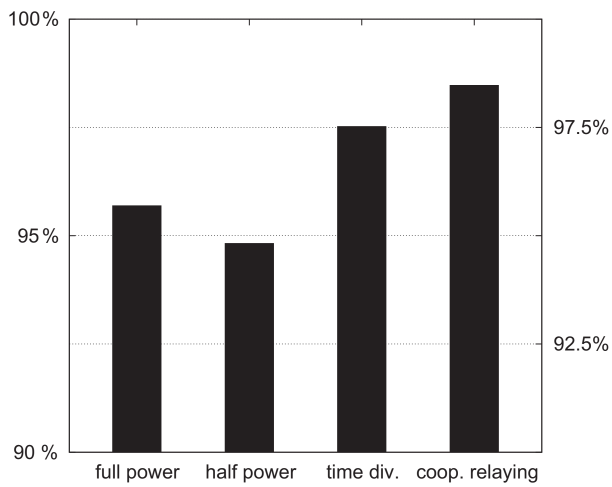

Fig. 3. Packet delivery rate from source to destination

Figure 3 shows the measurement results. Direct transmission with full power reaches a packet delivery rate of about 95.7%. Direct transmission with half power reduces the packet delivery rate to 94.8%. Exploiting time diversity, 97.5% of all sent packets are delivered. Exploiting cooperative relaying, the packet delivery rate is increased further to almost 98.5%.

B. Bit Error Rate and Packet Error Rate

The bit errors of all packets received by the destination or the relay are considered, and the bit error rate (BER) is analyzed for the different transmission strategies. For time diversity, we calculate the minimum bit errors of the packets (2) and (3) in each cycle. For cooperative relaying, we calculate the minimum number of bit errors of the packet over the direct link (half transmission power) and, if existent, the packet over the relay link.

Figure 4 shows the measurement results of the BER. The direct transmission exhibits a BER of 0.49% if we send with full power and 0.75% using half power. Time diversity yields a BER of 0.51%, which is almost as good as direct transmission with full power. Cooperative relaying, however, improves the performance to BER $= 0.37\%$.

Finally, we investigate the packet error rate (PER). For direct communication, a packet will be considered to be erroneous if

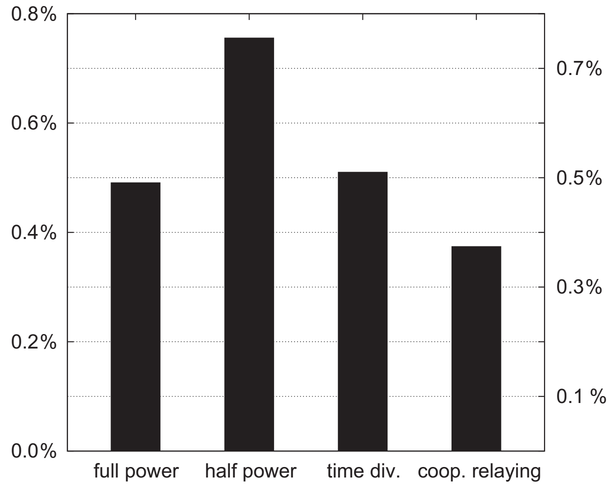

Fig. 4. Bit error rates

at least one bit error occurs in this packet. For time diversity, a packet will be erroneous if each of the two half power transmissions contains at least one bit error. For cooperative relaying, we consider a packet as erroneous if both packets (the packet over the direct source-destination path and the packet over the source-relay-destination path) contain at least one bit error.

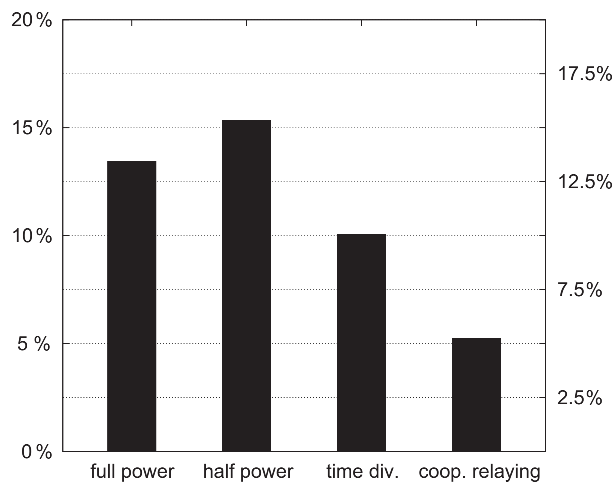

Fig. 5. Packet error rates

The PERs are shown in Figure 5. If direct transmission with full power is used, about 13% of all packets have at least one bit error. Using direct transmission with half power, about 15% of all packets have at least one bit error. For time diversity, the packet-error rate is 10%. Cooperative relaying further reduces the PER to about 5%.

Time diversity is better than direct transmission in terms of PER, although the BER is a little bit higher. The reason for this behavior is that not necessarily both half power messages arrive at the destination. Further, if one of these messages is lost, e.g., due to bad channel conditions, the probability that the other packet contains (many) bit errors is quite high. For the PER it does not matter whether a packet has only one or many bit errors. However, for the BER the exact number of bit errors is important.

IV. Implementation Issues

A. Changes to the WARP Reference Design

Some modifications to the OFDM reference design (version 12) are necessary to conduct the measurements. First, it is essential to modify the FPGA implementation of the reference design in such a way that payloads of packets are still received even if there are bit errors in the header. The second modification addresses the implementation of a custom bit error calculation procedure, which is also located on the FPGA, to calculate bit errors of the header and payload.

B. Identification of Packets

Information sent over the wireless link without any protection cannot be used to identify or classify packets. The reason is that bit errors may be introduced by the wireless link, which then may lead to misclassifications. However, for the evaluation of measurements an unambiguous way of classifying and identifying packets is necessary. Our solution to this problem is to use a program that captures events from the WARP boards, such as the sending or receiving of a packet. A time stamp is attached to each event, which makes it possible to identify each event accurately.

The following improvement is planned here: Figure 1 illustrates the sequence of transmissions. The time interval between transmissions (1), (2), (3) and (4) is $9\,\text{ms}$. The reason behind these long intervals lies in the identification of packets. Currently, we are concatenating the time stamp on the computer that is capturing the events from the WARP board. Due to the fact that, when using Windows, this time has only an accuracy of approximately $5\,\text{ms}$ we have to keep the time intervals long enough to allow for an accurate identification of packets. For future measurements we plan to add the time stamps directly on the WARP boards, which should allow us to increase the number of packets sent per second considerably. We have already implemented a prototype, which is currently getting tested.

V. Related Work

A. Testbeds for Cooperative Relaying Communications

Challenges faced during the implementation of cooperative diversity antenna arrays on off-the-shelf hardware is discussed in [17]. In particular, the authors address synergies needed between the physical, link and routing layers to reduce transceiver complexity and to facilitate the use of existing commodity radio hardware. In [18] the authors describe the implementation of cooperative wireless networking employing two testbeds. Further, the authors show the benefits of cooperation by using the WARPLAB software that allows for an experimental evaluation of physical layer algorithms. The authors of [19] implement two decode-and-forward schemes on programmable radio. Additionally, they evaluate and discuss spatial diversity benefits of cooperative diversity techniques.

B. Measurements for Car-to-Car Communications

Paper [20] presents radio channel measurements of a car-to-car scenario, where the cars drive on a highway in opposite directions. The measurements are used to evaluate the path loss, the power-delay profile and the delay-Doppler spectrum. The authors of [21] present an experimental study of Doppler spread coherence time properties of vehicle-to-vehicle wireless channels. The measurements are performed in rural and highway environments. In [22], results of vehicle-to-vehicle measurements in the 5 GHz frequency band are presented. The measurements are performed in three different environments: large cities, highways and small cities.

VI. Conclusions

The major goal of this paper was to study the benefits of cooperative relaying by conducting real-world experiments. Using a vehicular setup with car-to-car communications, we demonstrated that cooperative relaying exhibits advantages over conventional direct transmission and time diversity transmission in terms of packet delivery rate, bit error rate, and packet error rate. We accounted for fairness in terms of energy consumption by letting cooperative relaying and time diversity take place with half transmission power. Further measurements are needed to confirm the results in different setups and to generalize them.

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