Packet Delivery Performance of Simple Cooperative Relaying in Real-World Car-to-Car Communications

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***Abstract*—We evaluate the packet delivery performance of low-complex cooperative relaying in car-to-car communications by real-world measurements. The ratio and temporal correlation of packet delivery are evaluated for suburban and highway environments using three cars equipped with programmable radios and serving as sender, relay, and destination. We compare the relaying performance to that of pure time diversity and show how temporal autocorrelation of packet delivery is a key factor in whether or not relaying exhibits benefits. Results are relevant in the design of relay selection protocols, as they give guidelines for the affordable selection delay.**

***Index Terms*—Cooperative relaying, vehicular communications, time diversity, measurements, testbed, VANET**

I. Introduction and Motivation

Cooperative diversity techniques have been developed to mitigate the negative effects of small-scale fading caused by multipath propagation [1]. They apply relay nodes that overhear transmissions from a sender to a destination and forward the overheard data to the destination. Such cooperative relaying exploits the broadcast nature of the channel and employs the concept of space-time diversity.

A huge amount of research has been done in the past ten years to assess the benefits and drawbacks of cooperative relaying by simulations and analytical means (see [2]–[5] and references therein). Given the great body of publications in this domain, it is surprising that only few studies assessing cooperative relaying with *real-world measurements* in *realistic environments* were published so far [6]–[9]. In particular, the authors of this letter are not aware of any publication investigating cooperative relaying in a real environment for vehicular ad hoc networks. This lack of practical results is partly due to the fact that implementations of cooperative relaying require changes in the data link layer and/or physical layer of the protocol stack. Programmable hardware platforms enabling such implementations have been commercially available for reasonable prices for just a few years.

The goal of our work is to contribute toward closing this research gap. Based on an implementation of a low-complex cooperative relaying protocol on the programmable platform WARP [10], we measure and evaluate the packet delivery performance in an outdoor car-to-car communications scenario. Measurements are made for suburban and highway environments with three cars serving as sender, relay, and destination, respectively. In particular, we analyze the dynamics of packet reception in terms of its temporal correlation and show the impact of these dynamics on whether or not relaying is beneficial compared to time diversity with respect to packet delivery success. We also determine the practically important maximum relaying delay that still leads to gains compared to time diversity. To the best of our knowledge, such experiments have not been published beforehand by other authors. This letter extends our preliminary work in [11].

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II. Related Work

There are few papers on measurement-based assessment of cooperative relaying schemes. Bradford *et al.* [6] measure and evaluate decode-and-forward relaying schemes in the lab. Measurements are performed with fixed distances between nodes with very low mobility and RF shields influencing radio channels. Kyritsi *et al.* [7] measure the performance of cooperative relaying in an indoor office scenario with two access points and two devices moving on predefined paths. Valentin *et al.* [8] propose and implement a medium access control (MAC) protocol for mobile cooperative WLANs. Measurements are carried out in a railroad scenario, where devices move on an oval shaped railroad with low mobility. Gonzales *et al.* [9] compare the achievable data ratios of relaying schemes in a scenario, where indoor mobile stations communicate to an outdoor base station. In summary, none of these papers analyzes cooperative relaying in a realistic outdoor scenario with high speed vehicles.

III. Evaluation Methodology

Measurements are performed in a car-to-car communications scenario, where three cars are equipped with WARP boards serving as sender S, destination D, and relay R, respectively. The antennas are placed on the roofs of the cars. Each board is connected via Ethernet to a notebook to collect status packets and to track the positions of the cars with GPS sensors. Wireless communications is performed using the WARP orthogonal frequency-division multiplexing (OFDM) reference design (version 12). A relaying protocol and a retransmission protocol are implemented by the authors at the MAC layer. Table I shows the transmission parameters. Three scenarios for the positions of S, D, R are studied:

TABLE I: Transmission parameters

Parameter	Value
Frequency	2.4 GHz
Bandwidth	10 MHz
Header length	24 bytes
Payload length	1024 bytes
Modulation	OFDM with QPSK
Average TX power of packet	14 / 11 dBm (full / half power)
Peak transmission (TX) power	22.2 / 19.6 dBm (full / half power)
Antenna gain	7 dBi

- *Relay middle* (RM): R is driving between S and D.
- *Relay last* (RL): R is driving behind S and D.
- *Relay and destination in same car* (RD): Two cars are used, one car acts as S, the other as both R and D, i.e., one car is equipped with two WARP boards; the distance between the antennas is 1.8 m.

The cars are used in two environments:

- *Suburban*: driving speed 50–70 km/h, medium traffic density, average distance $30\,\mathrm{m}$ between consecutive cars.
- *Highway*: driving speed 130 km/h, low traffic density, average distance 60 m between consecutive cars.

We assess the packet delivery from S to D with help of a relay R and compare this performance to that of a single direct transmission from S to D and to that of a time diversity scheme in which S sends the same packet twice to D. For a fair comparison, the single transmission scheme uses a full-power packet; the other two schemes employ half-power packets (see Table I). As shown in Fig. 1, the MAC layer has been programmed to subsequently transmit

- a full-power packet S_f sent by S,
- three half-power packets S_h, S_h^*, S_h^{**} sent by S,
- a half-power packet R_h sent by R.

The time period between two subsequent packet transmissions is $\delta = 30\,\mathrm{ms}$.

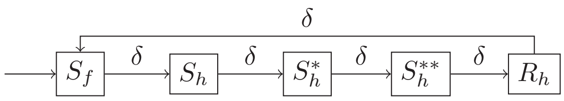
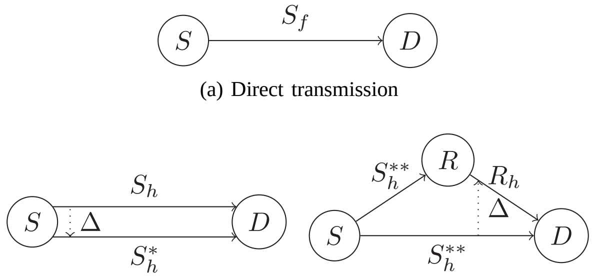


Fig. 1: Transmission cycle

A packet is delivered, if it is received by the communication partner and the cyclic redundancy checks (CRCs) of both header and payload are valid. As shown in Fig. 2, a packet is delivered (a) by direct transmission if S_f is delivered to D, (b) with time diversity if at least one of the half-power packets S_h or S_h^* is delivered to D, and (c) using cooperative relaying if S_h^{**} is delivered to D, or S_h^{**} is delivered to R and R_h is delivered to D. No packet combining is employed.

The performance of time diversity and cooperative relaying depends on the time period between the first and the second packet of the given scheme. This time is denoted by Δ in the following. To assess time diversity, we consider two packets S_h and S_h^* separated by Δ. For cooperative relaying, we consider S_h^{**} and R_h separated by Δ. Packet delivery is evaluated as a function of Δ ranging from $30\,\mathrm{ms}$ to $30\,\mathrm{s}$, which means that $\Delta \in \mathcal{T}$, $\mathcal{T} := \{(5i+1)\,\delta \mid i = 0, 1, \ldots, 199\}$.



(a) Direct transmission

(b) Time diversity

(c) Cooperative relaying

Fig. 2: Transmission scenarios

Note that the time diversity scheme also benefits from spatial diversity due to movements of the cars.

In each environment about $100\,000$ packets are transmitted. To assess the statistical significance of the measurements, we uniformly and randomly select $2\,000$ transmission cycles from the data set into a subset $\mathcal{B}$ and evaluate this set. This procedure is repeated ten times. We show the mean of these ten values and the $10\,\%$ and $90\,\%$-quantiles.

IV. Temporal Correlation of Packet Reception

The temporal correlation of packet reception of a given link is a key factor for the performance of both time diversity and cooperative relaying (which is space-time diversity). The idea behind time diversity is that a retransmission may be successful if a first transmission failed due to changes of the channel. Informally speaking, a large positive correlation means that little changes of the channel can be expected, which in turn makes it unlikely that the second transmission succeeds if the first one failed. High correlation will lower the performance of time diversity. Therefore, temporal correlation can be used as an indicator for the probability of successful transmission in time diversity and enables us to choose a suitable interval Δ between the diversity packets.

We analyze the correlation of half-power packets for intervals $\Delta \in \mathcal{T}$. Let $T := \{t_i \mid i = 1, \ldots, \kappa\}$ denote the set of κ time instants of $\mathcal{B}$ when S sends half-power packets. We introduce the binary variable

$$R_{t_i} := \begin{cases} 1 & \text{if half-power packet sent at } t_i \text{ is delivered to } R, \\ 0 & \text{else.} \end{cases}$$

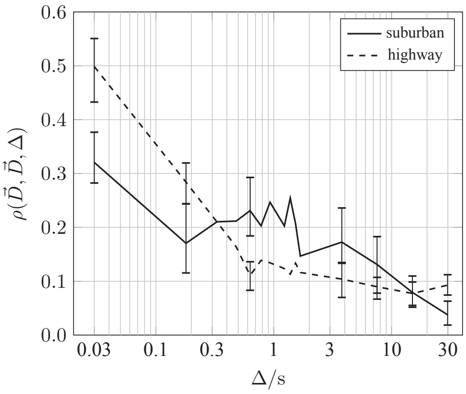
Analogously, we define D_{t_i}.

We evaluate the sample correlation $\rho(\vec{D}, \vec{R}, \Delta)$ with $\vec{D} := (D_{t_1}, D_{t_2}, \ldots, D_{t_\kappa})$ and $\vec{R} := (R_{t_1}, R_{t_2}, \ldots, R_{t_\kappa})$ as

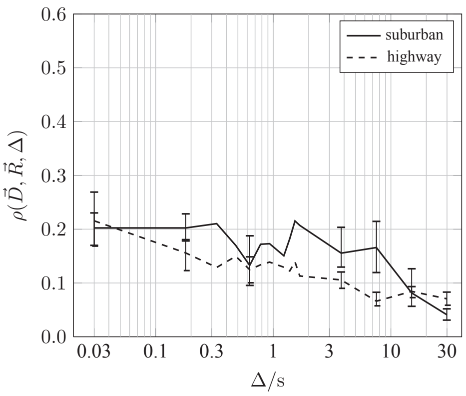
$$\rho\left(\vec{D}, \vec{R}, \Delta\right) := \frac{1}{(|T'|-1)\; s_D\, s_R} \sum_{t \in T'} (D_t - \bar{D})\,(R_{t+\Delta} - \bar{R}),$$

where $\bar{R}$ and $\bar{D}$ are the arithmetic means, s_R^2 and s_D^2 the sample variances, and T' the subset of T containing all time instants when S sends half-power packets S_h at times $t \in T'$ for which $t \leq t_\kappa - \Delta$ holds.

Fig. 3 shows correlations for both suburban and highway environments. The autocorrelation $\rho(\vec{D}, \vec{D}, \Delta)$ shown in (a) is highly positive if the time span Δ between packets is short; it attenuates for increasing Δ. A highway exhibits a



(a) Autocorrelation of $\vec{D}$



(b) Correlation between $\vec{D}$ and $\vec{R}$

Fig. 3: Temporal correlation. Results are for the RD case, but the correlations are similar for the RM and RL cases.

significantly higher correlation for small Δ; for $\Delta \geq 0.15\,$s, the correlations of highway and suburban environments are similar. For both environments, such positive correlation will reduce the performance of time diversity.

Fig. 3 (b) shows the correlation between the links $S-D$ and $S-R$. The correlation between these links is small, even for very small values of Δ. In particular, for $\Delta = 0$ (not shown) the mean correlation is 0.31 (suburban) and 0.21 (highway), compared to 1.0 for the autocorrelation of half-power packets.

V. End-to-End Packet Delivery Ratio

Fig. 4 shows the percentage of packets delivered successfully from S to D as a function of Δ for all transmission schemes, environments, and relay positions. The delivery ratio of direct transmission is not a function of Δ. As expected, the delivery ratio of time diversity improves for increasing Δ due to decreasing correlation. For all environments and relay positions the packet delivery ratios of time diversity and cooperative relaying are higher than that of direct transmission.

For RM, cooperative relaying outperforms time diversity for both environments (a) and (b), mainly due to the multihop gain. For RL, cooperative relaying is worse than time diversity for the suburban environment (c) and for medium to large Δ on the highway (d). It is better, however, for small Δ on highway ($\Delta < 0.1$ s). The reason for this behavior is the autocorrelation shown in Fig. 3 (a). The autocorrelation on a highway is significantly higher than for a suburban environment. Thus, cooperative relaying improves the packet delivery ratios due to the lower correlation between the links $S-D$ and $S-R$ (Fig. 3 (b)). Finally, for RD, cooperative relaying excels time diversity on highways (f) for $\Delta < 0.1$ s. In the suburban environment (e), however, time diversity is better with respect to packet delivery for $\Delta \geq\ 30$ ms. This behavior can again be explained by the correlation.

If Δ is very small, both packets of time diversity are highly correlated. In the extreme case $\Delta = 0$, the correlation between these packets is one. For cooperative relaying, however, the correlation between the links $S-D$ and $R-D$ is around 0.2 to 0.3. The packet delivery ratios for time diversity ($\Delta = 0$, RD) are $89\,\%$ (highway) and $93\,\%$ (suburban); for cooperative relaying they are $96\,\%$ (highway) and $95\,\%$ (suburban). Thus, for small Δ, cooperative relaying outperforms re-transmission in both environments in terms of packet delivery ratio.

VI. Conclusions and Further Work

Measurements conducted for vehicular communications analyzed the packet delivery performance of a simple protocol for cooperative relaying in comparison to conventional transmission schemes. Results show that cooperative relaying without diversity combining can outperform conventional schemes with respect to packet error rate if the relay is located between sender and destination and/or the time elapsed between the two diversity packets is short. If relaying does not benefit from a multihop gain and the delay is larger than about 150 ms, pure time diversity outperforms relaying in the observed scenarios in terms of packet delivery ratio. This behavior can be explained by the temporal correlation of packet reception, which decreases for increasing delay and thus improves packet delivery for time diversity. These insights are useful for the design of relaying protocols. They indicate how fast relay selection has to become to yield benefits.

Note that we studied reliability gains of cooperative relaying using the packet delivery ratio. Clearly, other performance metrics must be considered as well, such as data rate and energy consumption. They have been studied theoretically, but experiments for vehicular networks are subject to future work.

Acknowledgments

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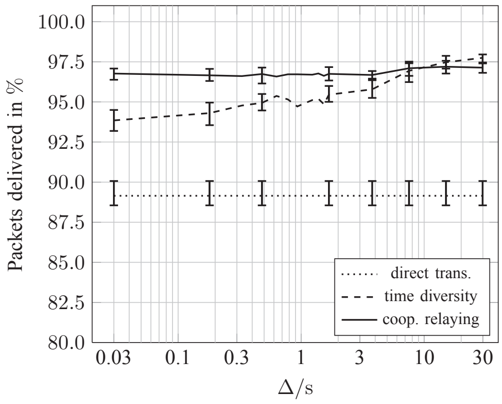
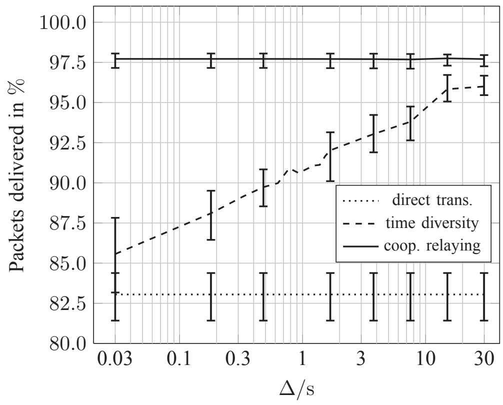
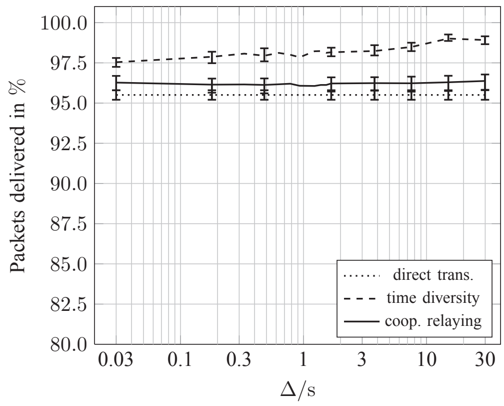


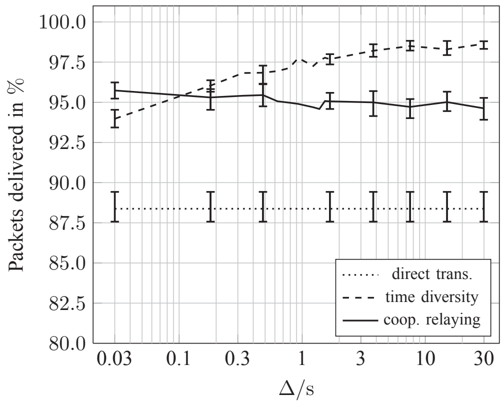
(a) RM (suburban)



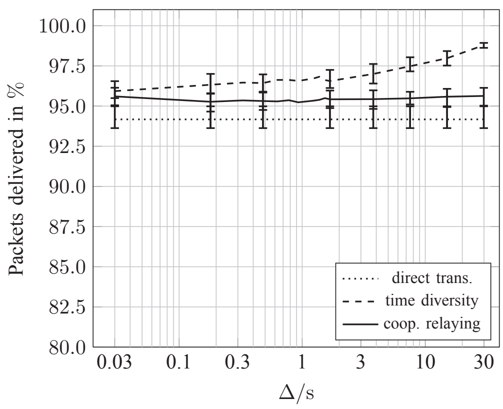
(b) RM (highway)



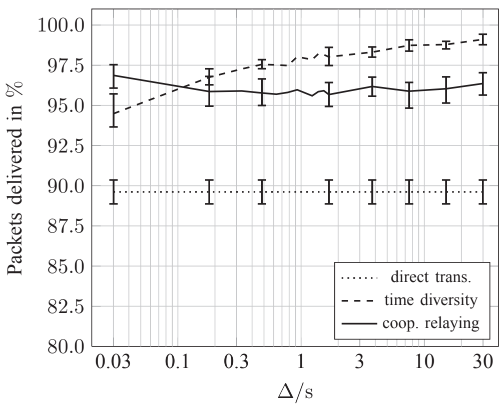
(c) RL (suburban)



(d) RL (highway)



(e) RD (suburban)



(f) RD (highway)

Fig. 4: Packet delivery ratios

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