Experimental Evaluation of Multihop-Aware Cooperative Relaying

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***Abstract*—Through real-world measurements we evaluate the impact of multihop-aware cooperative relaying on end-to-end route performance in wireless multi-hop networks. In an experiment with 50 devices in an industrial environment cooperative relaying increases the end-to-end transmission reliability for multi-hop links to nearly 100 % while reducing the average packet delay. We suggest how to include relay selection in the route discovery process of ad hoc routing protocols such as Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) and perform two experiments. In the first experiment we discuss route discovery strategies focusing on small delay benefiting from reliable data link transmissions using cooperative relays. In the second experiment we compare reliability and delay for five different transmission powers with and without cooperative relaying.**

Keywords*—*Cooperative relaying, multihop networks, ad hoc network, ad hoc routing, wireless networks, radio measurements

I. INTRODUCTION AND MOTIVATION

Approaches to improve reliability in ad hoc networks using reactive routing protocols often focus on route selection after route discoveries. Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) may discover multiple routes between a source and a destination. Route selection aims to identify the route yielding best performance with respect to a selected metric [1]. Metrics include hop count, round trip time, or expected transmission count (ETX) [2] often with the goal to improve the reliability of the route. The drawback of these metrics is that they only consider long-term effects and do not consider fading at short periods, such as small-scale fading or shadow fading. Measurements in an industrial environment showed that 45 % of all link failures are of short duration [3]. These short link failures do not require to discover new routes but can be overcome by diversity.

Diversity transmissions have been suggested on data link as well as on network layer. Network layer diversity makes use of alternative routes identified during the route discovery [4]. Data is sent on multiple routes increasing the probability of successful delivery. Link layer diversity transmissions mostly focus on time diversity or cooperative diversity. Cooperative relaying is a suitable form of diversity: a third node, the cooperative relay, overhearing the communication between a source and sink, retransmits an unacknowledged packet instead of the source. Due to a time-correlated channel, immediate retransmissions by the source are less likely to succeed compared to retransmissions by a cooperative relay benefiting from space-time diversity [3], [5].

We analyze the impact of data link layer cooperative relaying on the end-to-end delivery ratio in multi-hop ad hoc networks. The vast majority of papers addresses cooperative relaying theoretically. Only a limited number of experiments has been done of comparably small size focusing on single links. We deploy a network of 50 sensor nodes focusing on multi-hop routes and the impact of data link layer, decode-and-forward cooperative relaying on higher layers.

The delivery ratio is defined as the number of packets received at the destination over the number of packets transmitted at the source. Closely related to the delivery ratio is the end-to-end packet delay. Retransmissions on the link layer slightly increase the end-to-end delay. When repairing broken routes at network layer, however, a new route discovery is required significantly increasing end-to-end delay. The number of route discoveries may be decreased by increasing the reliability at the link layer. Cooperative relaying decreases end-to-end delay and jitter. Additionally, we

1) determine performance of a reliable data link layer on network layer, i.e., high reliability on data link layer makes network layer diversity unnecessary;
2) use different transmission powers to determine their impact on reliability;
3) deploy a network with multi-hop routes to determine performance indicators in real-world deployments.

In Sec. II we discuss related work followed by the description how to include cooperative relaying in multi-hop networks while Sec. III illustrates how to include cooperative relaying in multi-hop networks. We perform two experiments whose setup is described in Sec. IV. In the first experiment, evaluated in Sec. V, properties of route discoveries for ad hoc routing protocols such as AODV and DSR are determined and discussed with respect to route selection metrics. The focus is shifted from selecting routes supposedly increasing reliability to routes decreasing delay. Reliability is handled on link layer by on-demand cooperative diversity. The cooperative relay temporarily extends the route if required, i.e., a packet is rerouted through the cooperative relay. We determine the distribution of route lengths and route arrival times. The second experiment, described in Sec. VI, implements the routing protocol making use of cooperative relaying assisted links and evaluates the end-to-end reliability and packet delay with and without cooperative relaying.

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II. RELATED WORK

Frey and Pind use up to 49 Tmote Sky nodes and compare DSR and Greedy Routing [6] in a static environment with emulated dynamics. They compare reliability and delay with and without acknowledgments. Nassr *et al.* use up to 30 Mica2 nodes to compare several routing protocols [7] with up to 10 hops focusing on packet delivery ratio. Instead of using link layer acknowledgments they use multi-path redundancy to increase end-to-end reliability. Backes and Cordasco present their implementation of AODV for TinyOS 2.0 using TelosB motes [8]. They focus on the implementation of the protocol. Becker *et al.* use eight cricket motes in an indoor environment to compare routing protocols with respect to reliability, route length and, delay [9].

Work on cooperative transmissions in multihop networks has mainly focused so far on computation and simulation. Cooperative transmissions where multiple transmissions are combined at the physical layer help to improve the network reliability [10], [11], [12]. Cooperative relaying on network layer has been implemented in [13]. The authors deploy a small network of commodity hardware in an office environment and determine network throughput.

Experiments were conducted in smaller scale than in this paper, in office environments with less severe fading, or constructed environments. In previous experimental work we analyzed expected gain by cooperative relaying in comparison to time diversity [5], [3] and relay selection strategies [5], [14]. But all experiments focused on single-hop transmissions. Other extensive measurements making use of comparable hardware focus on wireless sensor networks [15], [16].

III. MULTIHOP-AWARE COOPERATIVE RELAYING

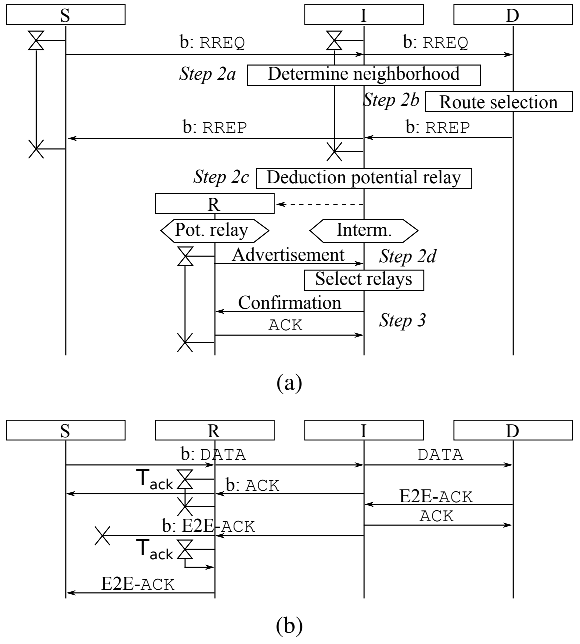
A. Relay Selection

We describe the application of multihop-aware relay selection [17] in the route discovery process illustrated in Fig. 1a. The process starts by flooding the network with a route request `RREQ`. Nodes use these packets to determine the neighborhood required to deduce whether a node is a potential relay (*step 2a*). Upon selection of one or more routes, the destination D responds with a route reply `RREP`. By comparing the route in the `RREP` with their neighborhood, nodes I can deduce their potential to act as relays for specific links.

To complete the relay selection, a potential relay R advertises itself to nodes I for which R may relay. From the list of potential relays, a node I selects one or more nodes if available, confirms the selection of R which in return acknowledges the confirmation. We select the first three nodes as relays that advertise themselves to increase the likelihood of successful delivery [5]. For the sake of analysis, nodes reset themselves when receiving a `RREQ` with a higher ID than before to make sure no previous information is available.

B. Data Transmission

Fig. 1b depicts the transmission protocol. `DATA` is broadcasted by S to the next node I on the route. R overhears the transmission and buffers the packet. A timer $T_{\texttt{ack}}$ is started to assure timely reception of the data link layer (DL) `ACK`. Upon reception of the `ACK` the timer is stopped. Relays are triggered implicitly [18], i.e., if the timer runs out, the relay automatically retransmits the previously buffered packet.



(a)

(b)

Fig. 1: (a) Route discovery protocol and (b) data transmission protocol. Broadcasts are indicated by *b:* in the absence of syntax for broadcasts in message sequence charts.

Once received by D, `DATA` is end-to-end acknowledged. The `E2E-ACK` is also supported by cooperative relays. A uniformly distributed random offset of 10 ms is added to $T_{\texttt{ACK}}$ to reduce the probability of collisions when accessing the channel.

IV. EXPERIMENTAL SETUP AND METHOD

Experiments are conducted using off-the-shelf IEEE 802.15.4 Z1 wireless nodes from Zolertia. Measurements are done in the 2.4 GHz band. We use TinyOS for implementation. We randomly deploy 50 nodes in a production hall for packages made of card board. Fig 2 depicts the environment and the nodes' positions schematically. We run the experiments for a fixed pair of source and destination as depicted in Fig. 2. The selection of source and destination is limited by the availability of power outlets. Both nodes are connected to a laptop running the experiments and displaying status messages. The long running experiments require the laptops to be powered via cable.

Experiments with 20 nodes and different topologies yielded comparable results in a smaller scale. In total, experiments have been done on three days for approximately eight hours each. The nodes are attached at heights between 1.6 m and 2 m at various machines, shelves, and pillars. About a dozen people and three fork lifters move in the environment. The hall includes several machines with unshielded moving parts operated by up to three persons each. We repeat the experiments with output powers of -10, -7, -5, -3, and -1 dBm. Output powers above -1 dBm led to direct connection between

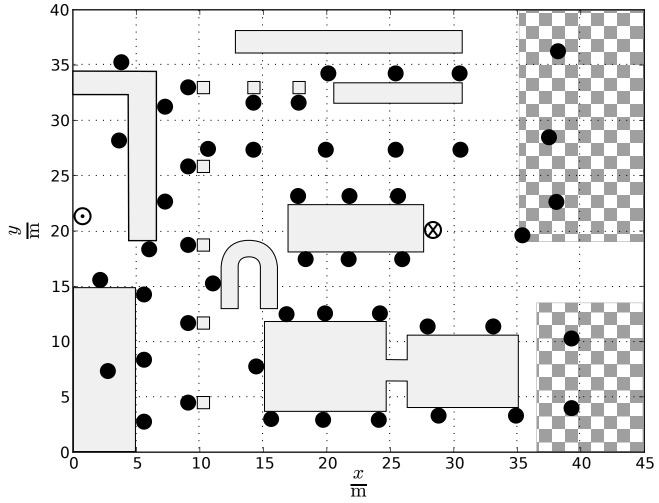


Fig. 2: Layout of the industrial environment. Dots mark node positions. Source and destination are marked with a · and x within a circle, respectively. Gray areas are machines, pillars and walls made of metal or concrete; checkered areas is storage for raw material (mostly paper).

source and sink, powers below -10 dBm did not suffice to connect the network. Changing the transmission power has two effects. Firstly, it allows to analyze the impact of different transmission powers on a given topology. Secondly, with increasing power the node density increases by increasing the transmission range, i.e., the network topology changes yielding results for various topologies. In total we perform 500 consecutive route discoveries in the first experiment and send 3000 data packets for each transmission power in the second experiment. Other experiments with fewer route discoveries and fewer number of packets yielded similar results to the ones presented in the following, i.e., the results are representative for the environment.

V. EXPERIMENT I: ROUTE DISCOVERY

The route discovery follows the standard approach defined by DSR [19] and AODV [20]. In the absence of a route to a destination D, a source S initiates a route discovery by broadcasting a `RREQ` at time t_1. Nodes propagate the `RREQ` after a random offset of 5 ms to reduce the probability of medium access collisions. At $t_2^{(1)}$ the destination receives the first route. Multiple routes i may be received by the destination at times $t_2^{(i)}$ of which one or more are selected. The selection of multiple routes may decrease the overhead caused by route discoveries if a selected route fails [21]. For the route discovery experiment all received routes are logged by the destination. The end of the route collection phase t_3, i.e., the time when no further routes are considered for route selection, ends after three seconds for this experiment. Finally, the first received route is selected and propagated in a `RREP` packet back to S receiving the route at t_4. Note that the selection of the route has no impact on this first experiment. The first route received is returned immediately in a `RREP`. The minimal route discovery duration is determined at the source based on the time difference between `RREQ` sent and `RREP` received.

TABLE I: Arrival times (in ms) of consecutive routes after the first route is received.

	Time route $\Delta t_2^{(i)}$ received					
	i=2	i=3	i=4	i=5	i=6	i=7
5 %	3	6	10	15	17	21
mean	9	15	20	23	26	28
95 %	21	27	30	33	34	36

A. Route Arrival Times

We discuss the arrival times of multiple routes at a destination D. Tab. I shows the arrival times of consecutive routes $\Delta t_2^{(i)} = t_2^{(i)} - t_2^{(1)}$ after the first route has been received. For example, on average the third route is received $\Delta t_2^{(3)} = 15$ ms after the first route. The differences in arrival times for different transmission powers are not significant and are joined.

Upon reception of the first route, the destination may continue to collect additional routes for a time $t_c = t_3 - t_2^{(1)}$. Collecting more routes allows to select the best route from a larger pool according to a specified metric. Depending on the number of received routes, t_c ranges from roughly 5 ms to 35 ms. For comparison, a route discovery where the destination sends back the first route it receives, takes on average $\Delta t = t_4 - t_1 = 59$ ms with 42 and 80 ms for 5- and 95-quantiles. Backes and Cordasco measured similar durations [8]. We continue to investigate the distribution of received routes to determine when to abort the collection phase.

B. Route Lengths

A destination D may abort the collection phase once the probability to find a better route is small. Independent of the transmission power the probability not to receive at least one route is below 0.05. The mean number of routes received varies between three and four routes. Fig. 3 shows the distribution of route lengths, i.e., the number of hops on the route. For example, for transmission power -10 dBm, 12 % of all received routes have a route length of two hops. The distribution is similar for all transmission powers and roughly follows a normal distribution. For the tested environment, the majority of routes has a length of three or four hops. Longer routes mainly occur for transmission powers -7 and -10 dBm. Nodes only propagate the first `RREQ` they receive. Generally, it holds that the shorter the route, the smaller the end-to-end delay of packets due to decreased number of transmissions. Therefore, to minimize the delay we aim to select the shortest route. Cooperative relaying extends the route on-demand in case of link failure. The cooperative relay retransmits instead of the source (temporarily) adding a hop to the route, i.e., the retransmission by the relay. Extensions to consider the link quality indicator (LQI) of intermediate hops or ETX during route discovery can easily be integrated.

When flooding networks, shorter routes are discovered before longer routes. Longer routes require additional broadcasts prolonging the time of discovery. Note, however, that it is possible for longer routes to be discovered first because of the random channel access. In a total of approx. 5500 successful route discoveries, in 93 % the first discovered route is also the shortest route. Once the first route is received, it is selected

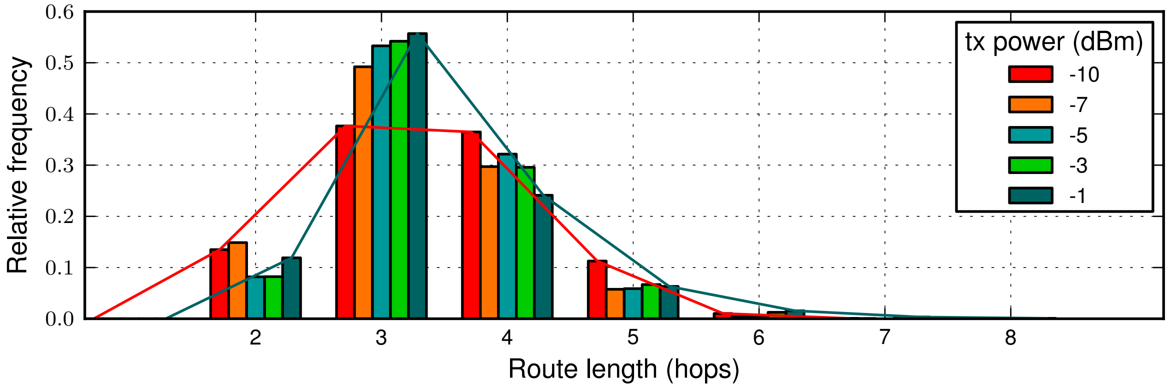


Fig. 3: Distribution of route lengths of received routes at the destination. Bars are connected to improve readability.

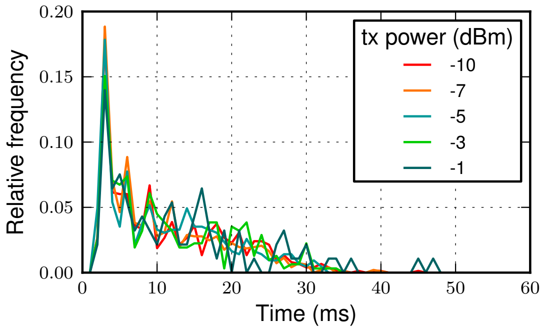


Fig. 4: Arrival times of node disjoint routes after the primary route is received.

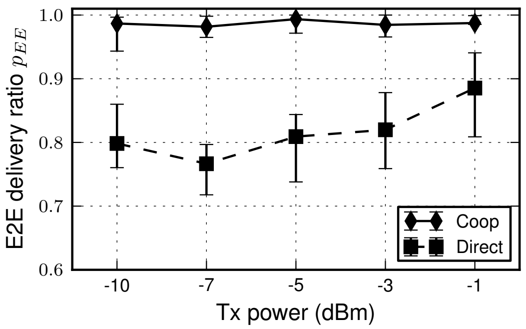


Fig. 5: End-to-end delivery ratio with and without cooperative relaying for various transmission powers. Bars indicate 0.05- and 0.95-quantiles.

as primary route and immediately propagated to S using the `RREP` packet to minimize the duration of route discoveries.

C. Alternative Route

We select an alternative node-disjoint route to reduce the impact of node failure and decrease the number of route discoveries [21]. With increasing transmission power the probability to discover at least one alternative, node disjoint route increases from 38 % to 82 %. Fig. 4 shows the distribution of arrival times for node-disjoint routes $\Delta\widetilde{t}_2^{(i)}$ after the primary route is received. $\Delta\widetilde{t}_2^{(i)}$ is defined according to $\Delta t_2^{(i)}$ though only node disjoint routes are considered. The majority of node-disjoint routes is received within 5 to 15 ms. On average, the node-disjoint route is discovered after 11 ms prolonging the average route discovery duration from 59 ms to 70 ms.

So far we discussed possibilities to reduce the route discovery duration. Based on the distribution of route lengths and arrival times, we select the first route received in favor of short delays. The average route discovery time is approx. 60 ms.

VI. EXPERIMENT II: DELIVERY RATIO AND DELAY

We evaluate the transmission protocol described in Fig. 1b with respect to end-to-end delivery ratio and packet delay. The route selection considers findings from the previous experiment. The first route received by a destination is selected as primary route. The first node-disjoint route received after the primary route is selected as alternative route. For the sake of analysis, no alternative route is selected if no node-disjoint route can be found. The absence of an alternative route has no impact on cooperative relaying because the relays and the alternative route are selected independently.

A route consists of N nodes. $N-2$ intermediate nodes propagate data over $H = N-1$ hops, i.e., the route length, from a source to a destination. Each individual hop h has an associated local delivery ratio p_h, $h = 1 \ldots H$. The data confirms previous results [14] indicating that the delivery ratios of the individual hops are statistically independent. Therefore, the end-to-end delivery ratio p_{EE} is the product of the individual delivery ratios of the individual hops: $p_{\mathrm{EE}} = \prod_{h=1}^{H} p_h$. Node 1 and N are source and destination of the route, respectively.

A. End-to-End Delivery Ratio

Fig. 5 compares the end-to-end delivery ratio p_{EE} for various transmission powers. Cooperative relaying (solid line) achieves delivery ratios p_{EE} of 98 % and above compared to 76 % to 90 % without cooperative relaying. Long routes benefit from increased delivery ratios p_h of the single hops when using

TABLE II: Detailed summary of packet transmissions for transmission power $-3\,\mathrm{dBm}$ including delivery ratios for various measured route lengths H and delivery ratios for hops h for (a) network without cooperative relaying and (b) with cooperative relaying. The end-to-end delivery ratio can be increased significantly using cooperative relaying by improving the individual hops' delivery ratios. Comparable for other transmission powers.

(a)

H	$\Pr(H)$ (%)	h												E2E		
		1			2			3			4					
		5	M	95	5	M	95	5	M	95	5	M	95	5	M	95
2	5	89	93	97	85	87	92		-			-		90	93	97
3	80	95	98	100	89	91	94	89	93	99		-		77	83	89
4	15	98	99	100	80	83	91	88	92	94	93	96	98	66	73	79

(b)

H	$\Pr(H)$ (%)	h												E2E		
		1			2			3			4					
		5	M	95	5	M	95	5	M	95	5	M	95	5	M	95
2	5	97	99	100	97	99	100		-			-		94	99	100
3	80	98	99	100	97	99	100	99	100	100		-		97	99	100
4	15	100	100	100	99	99	100	98	99	100	99	99	100	95	98	100

cooperative relaying. On average, $80\,\%$ of all measured single hop links without cooperative relaying achieve reliabilities of $p_h \geq 90\,\%$. Though the accumulated end-to-end delivery ratio p_{EE} is comparably small. In comparison, using cooperative relays all links achieve a delivery ratio of $p_h \geq 98\,\%$.

Cooperative relaying allows high end-to-end delivery ratios independently of the transmission power. Without cooperative relaying the end-to-end delivery ratio improves with increasing transmission power. When using cooperative relaying, the transmission power may be reduced while maintaining reliable end-to-end communication.

Tab. II compares the delivery ratios a without and b with cooperative relaying for transmission power $-3\,\mathrm{dBm}$. In all route selections performed in the experiment only routes of length $H = 2, 3, 4$ were selected and are listed in each table including their relative frequency $\Pr(H)$ of occurrence. The columns to the right list the delivery ratios h for each hop including their 0.05- and 0.95-qunatiles. The final column lists the end-to-end delivery ratio p_{EE}. For example, $5\,\%$ of all packets are delivered on a route of length $H = 2$. On the first hop ($h = 1$), on average $93\,\%$ of all packets are delivered successfully (Tab. IIa). Using cooperative relaying, the delivery ratio can be improved to $99\,\%$ (Tab. IIb).

The benefit of cooperative relaying in multi-hop networks is twofold. Firstly, while the improvement of cooperative relaying increases the delivery ratio with respect to single links only moderately, the accumulated end-to-end reliability increases significantly. In case of $H = 4$, the end-to-end delivery ratio can be increased from $72\,\%$ to $98\,\%$ in our setting. Secondly, if the delivery ratio of the direct link decreases significantly, cooperative relaying allows reliable transmissions [5]. While significant drops in delivery ratio seldom occur, with increasing route length the probability increases.

In the example of Tab. IIa, the delivery ratio drops approx. by ten percent points per additional hop. Generally, the end-to-end delivery ratio is a monotonically decreasing function with increasing number of hops. Cooperative relaying can cope with such fading [5] allowing high delivery ratios even when the direct link suffers. It repairs the route locally when required. Therefore, especially larger networks can benefit.

B. Delay

We compare the expected packet delay with and without cooperative relaying. In case of a route failure, an intermediate node may optionally try to locally repair the route if the destination is not more than `MAX_REPAIR_TTL` hops away. We consider the general case in which the node will send a route error packet `RERR` to inform the source about the broken route. Consider that the farther down a route a packet has propagated, the longer it will take to inform the source about the broken route increasing packet delay.

We illustrate the computation of the expected delay on the example of 3000 DATA packets that are transmitted using transmission power $-3\,\mathrm{dBm}$. Packets that fail on the primary route are assumed to be delivered successfully using the alternative route. This yields a lower bound for the delay.

Let d be a random variable modeling the distribution of transmission delays. The expected packet delay $\mathrm{E}[d|H]$ for a given route of length H hops is computed by

$$\mathrm{E}[d|H] = (1 - p_{\mathrm{EE}}(H)) \sum_{h=1}^{H} \Pr(\widetilde{h}) \cdot (\tau(h) + \tau(H)) + \tau(H) p_{\mathrm{EE}}(H)\,, \tag{1}$$

where $\tau(h)$ is the round trip time (RTT) for $h = 1 \ldots H$ hops and $\Pr(\widetilde{h})$ is the probability for an error to occur at hop h. Tab. III lists values for $\Pr(\widetilde{h})$. For example, for $H = 3$, $11\,\%$ of all packets failed to be transmitted on the first hop ($h = 1$).

The RTT is the time measured between sending a data packet at the source and receiving the corresponding `ACK` from the destination not including route discoveries. The mean RTT for a successful delivery for one, two, three, and four hops are 20, 36, 53, and $71\,\mathrm{ms}$, respectively. The mean RTT per additional hop is $20\,\mathrm{ms}$ with $5\,\%$ and $95\,\%$-percentile of 17

TABLE III: Probability $\Pr(\widetilde{h})$ of an error to occur at hop h (in percent).

H	h 1	2	3	4
3	11	52	36	-
4	2	61	24	11

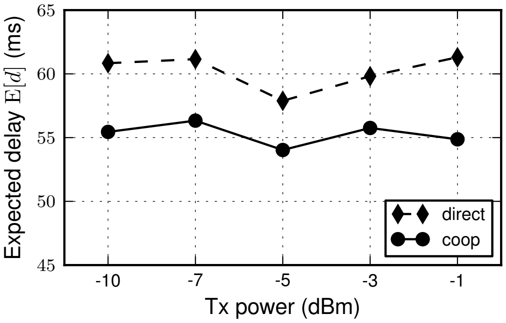


Fig. 6: Expected mean delay for a successful packet transmission. Cooperative relaying decreases mean packet delay on average by 5 ms due to increased delivery ratios.

and 24 ms. The expected delay $\mathrm{E}[d]$ can then be computed by $\mathrm{E}[d] = \sum_{\forall H} \mathrm{E}(d|H) \cdot \Pr(H)$.

Fig. 6 illustrates the expected delay per successfully delivered packet based on measured RTTs for various transmission powers. The expected delay per packet varies over the transmission powers due to delivery ratios varying with transmission power. On average, the delay per successfully delivered packet can be decreased from 60 to 55 ms. Additionally, the variance of the delay can be decreased which is significant for applications requiring small jitter. Longer route discoveries and more frequent discoveries increase delay and jitter for non-cooperative networks.

VII. CONCLUSIONS

We have experimentally investigated the performance of ad hoc routing protocols supported by multihop-aware cooperative relaying with respect to delivery ratio and packet delay. We deployed a 50 node network in an industrial environment. Firstly, we determined properties of route discoveries to decide when to abort the route collection phase. Using AODV, we measured that in 93 % of all cases the shortest route is delivered first. The rationality is that shorter routes reduce delay. If a short route fails, it will be repaired temporarily on demand by the cooperative relay. Secondly, we analyzed the performance with and without cooperative relaying. The network using cooperative relays increases the mean end-to-end delivery ratio while decreasing the mean packet delay independently of the transmission power. The gain increases with increasing number of hops, i.e., especially networks with a large diameter profit from cooperative relaying.

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