Multi-hop Networks with Cooperative Relaying Assisted Links

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***Abstract*—We assess the impact of cooperative relaying assisted hops on a multi-hop network. On the example of the reactive Dynamic Source Routing (DSR) protocol, we utilize cooperative relays to improve the link delivery probabilities of the individual hops allowing to significantly improve the end-to-end delivery ratio for large networks. First, we discuss two types to trigger retransmissions by cooperative relays in case direct transmissions between nodes fail. Second, we show that cooperative relaying assisted links lead to improved end-to-end delivery probabilities for multi-hop networks and determine the associated costs in terms of delay and consumed energy. For multi-hop routes with a large number of hops, cooperative relaying can decrease the costs while improving the end-to-end delivery ratio significantly making reliable communication possible where unassisted multi-hop communication is functionally not feasible.**

***Index Terms*—Cooperative relaying, multi-hop network, reactive routing, ad hoc network**

I. INTRODUCTION AND OBJECTIVES

The task of routing protocols in ad hoc networks is to set up a route between a source node and a destination node utilizing intermediate nodes which propagate packets along the route. Numerous routing protocols have been suggested in recent years [1]. Well known reactive protocols are Ad hoc On-Demand Distance Vector (AODV) routing and Dynamic Source Routing (DSR).

Once a route is established, the source transmits a packet to the first intermediate node which continues to propagate the packet hop by hop towards the destination. For reliable communication each transmission should be immediately acknowledged with an `ACK` packet. This allows that link errors can be detected quickly and reacted upon. In case of a route failure, there are generally three possibilities to resolve the situation:

1) inform the source by propagating the information of the route failure back to the source to rely on an alternate route as in DSR [2] or the DSR extension Multipath Source Routing [3],
2) try to locally repair the route as suggested in AODV [4],
3) try to repair the direct link by means of diversity or other physical layer techniques.

The usage of an alternate route as discussed in [5] is costly in terms of energy and delay. The further down the route a packet has propagated, the more transmissions are required to inform the source of the link failure. Additionally, an alternate route may suffer from the same fading as the previous route or the alternate route data may be outdated. This is especially the case in environments with high fading fluctuations. Locally repairing a route by issuing a new route discovery from an intermediate node, as suggested in AODV, may include flooding at least parts of the network, which is generally costly. Further, route repair may not be applicable in all situations. In AODV, route repair may only be initiated if the distance between an intermediate node with the broken link and the destination does not exceed `MAX_REPAIR_TTL`.

These disadvantages can be mitigated by trying to repair a link by means of diversity, which has been shown to be especially suitable in industrial environments because many of all outages are comparably short [6]. In such cases it can be expected that links can be repaired comparably fast reducing delay by eliminating the need to propagate information about a failed link back to the source.

In this work we apply cooperative relaying [7] to assist multi-hop communications. Cooperative relaying uses space-time diversity by having a cooperative relay retransmit instead of the source. It has been shown to outperform time diversity theoretically [7] and experimentally [8]. Cooperative relays may be used to improve the link delivery ratio of intermediate links increasing the end-to-end delivery ratio of the multi-hop route while decreasing delay and energy consumption per successful transmission. For our analysis we use the concept of *erristors* introduced in [9]. Erristors allow to smartly compute multi-hop networks. Further, using erristors, we determine the expected gain of cooperative relays validated by real world measurements and discuss how to trigger retransmissions in case a direct transmission fails.

II. EXPECTED DELIVERY PROBABILITIES IN RELAY ENHANCED NETWORKS

A. Multi-hop Routes

We assume a noise-limited system with Rayleigh block fading channels [9]. For a discussion on the impact of interference on multi-hop networks, the reader may refer to [10]. The received signal strength in Rayleigh channels is exponentially distributed with a reception probability

$$p := \Pr(\gamma \geq \Theta) = e^{-\frac{\Theta N_0}{P_0 d^{-\alpha}}} \tag{1}$$

where P_0 is the transmission power, N_0 the noise level, d the distance between two communicating nodes, α the path loss coefficient, and Θ the minimum signal-to-noise ratio required by the receiver. An erristor is derived from (1) and defined as $R := \frac{\Theta}{\bar{\gamma}}$ where $\bar{\gamma} = \frac{P_0 d^{-\alpha}}{N_0}$ is the mean received signal-to-noise ratio. Erristors simplify the analysis of wireless networks with diversity and multi-hop communications using rules comparable to those in electronic circuits. Serial circuits correspond to multi-hop communication. The total erristance is computed by the sum of the single hops' erristances (Fig. 1). Diversity transmissions are modeled by parallel circuits. Each transmission increases the delivery ratio, thus decreases the corresponding erristance. The joint erristance of multiple diversity transmissions is computed by the product of the individual transmissions' erristances (Fig. 2). We derive the erristor circuit for a cooperative relaying assisted multi-hop network.

Fig. 1 illustrates the erristor model for a multi-hop transmission between N nodes with $H = N - 1$ hops.

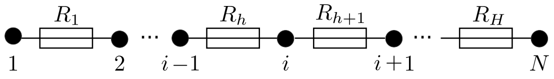


Fig. 1: Erristor circuit of a multi-hop link with H hops.

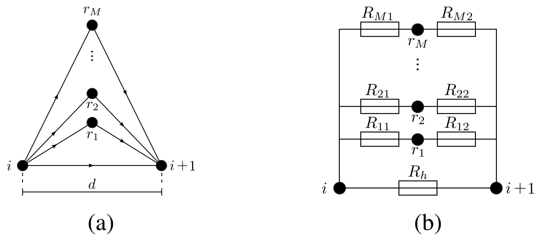
The end-to-end delivery probability p_{EE} is computed by $p_{\text{EE}} = \prod_{h=1}^{H} p_h$ where p_h is the delivery probability of hop $h = 1 \ldots H$. Using erristors, the product can be transformed into a sum of erristances. The relation between probability p and erristance R is given by

$$p = e^{-R} \Leftrightarrow R = -\ln p \,. \tag{2}$$

For our analysis, we assume that neighboring nodes have equal distances d and the delivery probabilities between nodes are statistically independent. In a network of homogeneous nodes, it is assumed that nodes transmit with equal transmission power. It follows from (1) that all hops have the same delivery probability $p_h = \sqrt[H]{p_{\text{EE}}}$. Thus, given an end-to-end delivery probability p_{EE}, the total erristance $R = -\ln p_{\text{EE}}$ is the sum of H erristors with equal erristances: $R = \sum_{h=1}^{H} R_h = H \cdot R_h$.

B. Cooperative Relaying Assisted Links

Cooperative relaying improves the link delivery probability by diversity transmissions. Fig. 2 illustrates a single link which is supported by M cooperative relays which retransmit packets when lost during the direct transmission. A cooperative relaying link consists of two links. Firstly, the relay has to receive the initial transmission from node i successfully. Then, secondly, the relay will forward the packet to node $i+1$. The erristance of the cooperative relay path is the sum of these two links' erristances. According to the rules of erristor circuits, the cumulative erristance $\widehat{R_h}$ of hop h including direct and diversity transmission is



(a) (b)

Fig. 2: (a) Illustration of a single hop with M cooperative relays and (b) the corresponding erristor circuit.

$$\widehat{R_h} = R_h \prod_{m=1}^{M} (R_{m1} + R_{m2}) \,. \tag{3}$$

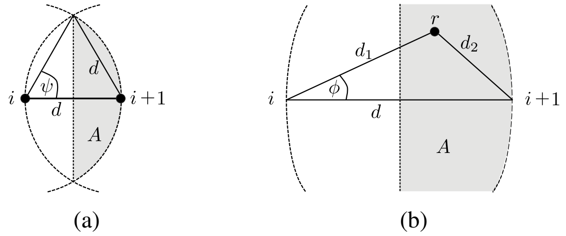
The end-to-end erristance $\widehat{R}$ of the multi-hop network with H assisted hops is computed by $\widehat{R} = \sum_{h=1}^{H} \widehat{R_h}$.

According to (1), the delivery probability between two nodes depends on their distance. We determine the expected erristance of a cooperative relay to circumvent the need to make assumptions about relay node positions.

C. Expected Erristance of Cooperative Relays

We only consider relays which benefit from a multi-hop gain, i.e. the distances between source-relay and relay-destination are smaller than the source-destination distance. Previous measurements have shown that nodes which benefit from a multi-hop gain are more likely to be selected for relaying than others [6]. In dense networks, where nodes generally have a high node degree, it can be assumed that such nodes are available.

Nodes that benefit from the multi-hop gain are only located in the area enclosed by two circles with radii d as illustrated in Fig. 3a. We determine the expected erristance by integrating over all possible locations and normalizing by the area. Due to symmetry it is sufficient to compute the expected gain for the gray area A. The size of A depends on the distance between two nodes i and $i+1$ and can be computed by $A(d) = \frac{1}{4}\left(2\psi d^2 - d^2 \sin(2\psi)\right)$ with $\psi = \arccos(0.5)$.



(a) (b)

Fig. 3: (a) Illustration of possible relay node positions and (b) schematically zoomed in.

Fig. 3b illustrates the integration over A. A relay node r may be positioned with distances d_1 and d_2 to nodes i and $i+1$, respectively. Thus, the erristance of the cooperative path depends on the location of r. Accordingly, considering M cooperative relays, (3) is modified to

$$\widehat{R}_h = R_h \left(\frac{1}{A} \int_{-\psi}^{\psi} \int_{\frac{\frac{d}{2}}{\cos\phi}}^{d} \left(R(d_1(r)) + R(d_2(r,\phi))\right) r \, dr \, d\phi \right)^{M} \tag{4}$$

with $d_1(r) = r$ and $d_2(r,\phi) = \sqrt{d^2 + r^2 - 2 \cdot d \cdot r \cos(\phi)}$.

To model various $p_h = \sqrt[H]{p_{\text{EE}}}$ the distance d between neighboring nodes is modified. With decreasing p_h, the distance d increases and, therefore, the average distance to a relay also increases. This decreases the link delivery probability of the cooperative path as well. Tab. I gives examples of the expected link probabilities for various p_{EE}. The probabilities correspond to erristances according to (4) where $p_h \widehat{=} R_h$, $p_r \widehat{=} R_1 + R_2$, $p_1 \widehat{=} R_1$, and $p_2 \widehat{=} R_2$. $p_{\text{T,I}}$ and $p_{\text{T,II}}$ will be explained below and are included for the sake of completeness. The probabilities reflect experimental results obtained in [8]. Due to symmetry it is assumed that $p_1 = p_2$. $p_r \geq p_h$ can be reached, for example, with an adaptive relay selection scheme as investigated in [8].

TABLE I: Examples of link probabilities corresponding to p_{EE}.

p_{EE}	p_h	p_r	p_1	p_2	$p_{\text{T,I}}$	$p_{\text{T,II}}$
0.009	0.73	0.89	0.94	0.94	0.94	0.89
0.090	0.85	0.97	0.98	0.98	0.98	0.97
0.900	0.99	1.00	1.00	1.00	1.00	1.00

III. HOW TO TRIGGER COOPERATIVE RETRANSMISSIONS

In case of failed direct transmissions, cooperative relays having received the packet successfully are triggered to retransmit. We distinguish two types of triggers:

- For *type I* triggers, a selected relay will forward a packet automatically if it does not receive an `ACK` from the destination (implicit trigger),
- while for *type II* triggers, selected relays are triggered explicitly by the source failing to receive an `ACK`.

Both trigger types may lead to redundant transmissions. A transmission is denoted as redundant if a packet is forwarded to the destination despite having already received the same packet successfully. For type I, redundant transmissions may occur if an `ACK` send out by the destination is not received by a relay. In this case the relay will automatically forward the packet unnecessarily to the destination. Type II triggers lead to redundant transmissions in case the source misses an `ACK` transmitted by the destination. Note, however, that the source is not aware that this retransmission is redundant. Retransmission of the packet is not required, merely the destination needs to be triggered to retransmit the `ACK`. We compute the performance of both trigger types depending on the delivery ratio between nodes.

We determine the probability of redundant transmissions due to falsely triggered relays. Let $p_{\text{T},t}$ model the probability of a successful trigger of type t. For type I relays $p_{\text{T,I}} = p_1$, for type II $p_{\text{T,II}} = p_1^2$. Let the random variable (RV) R_t model the probability of a retransmission for trigger type t. The Bernoulli distributed RV K_h models the direct successful packet delivery at hop h with $\Pr(K_h = 1) = p_h$ and $\Pr(K_h = 0) = 1 - p_h$. The probability of redundant transmissions $\Pr(R_t | K_h = 0)$ is then computed by

$$\Pr(R_{\text{I}} \mid K_h = 1) = \left(1 - (1 - p_1 \cdot (1 - p_2))^M\right) , \tag{5a}$$

$$\Pr(R_{\text{II}} \mid K_h = 1) = (1 - p_h) \cdot \left(1 - \left(1 - (p_1^2)\right)^M\right) , \tag{5b}$$

where M is the number of relay nodes. For type I, relays are triggered if they receive the packet from the source with probability p_1 and do not receive the `ACK` from the destination with $1 - p_2$ given a successful transmission with p_h. For type II triggers, the source does not receive the `ACK` from the destination with probability $1 - p_h$, while relay nodes are triggered when both data and trigger packets are received with probability p_1^2. Fig. 4 illustrates $\Pr(R_t)$ for various M.

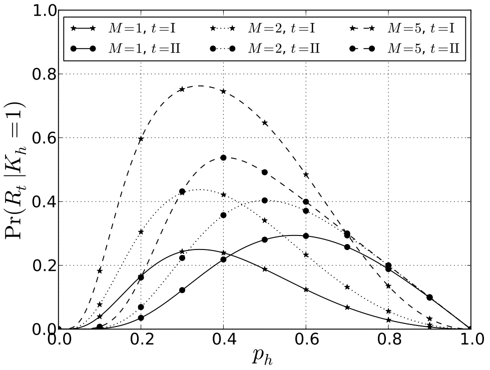


Fig. 4: Probability of a redundant transmission.

Type I triggers benefit from a higher relay-destination delivery probability p_2 than the source-destination probability p_h (see Tab. I). This leads to a decreased probability for redundant transmissions for small M and high p_h. With increasing M, $\Pr(R_{\text{I}})$ increases significantly because relays are triggered independently of each other with probability $1 - p_2$. In comparison, the probability of redundant transmissions by type II triggered relays mainly depends on the source not receiving the `ACK` with $1 - p_h$. Increasing M raises the probability that relays receive the trigger from the source which adds only marginally to $\Pr(R_{\text{II}})$. Also with increasing M, the advantage of higher delivery ratios $p_2 \geq p_h$ for type I triggers is consumed quickly due to increased number of relay-destination links. This shifts the point where type II triggers outperform type I triggers to larger p_h. For a qualitative conclusion, we determine the expected number of redundant transmissions to consider the impact of changing M and the characteristics of both trigger types.

Let the RV M_{T} denote the number of relays which have received the packet from the source and are triggered successfully. M_T is binomially distributed with

$$\Pr(M_{\text{T}} = m) = \binom{M}{m} (1 - p_{\text{T},t})^{M-m} \cdot p_{\text{T},t}^m . \tag{6}$$

The expected number of redundant transmissions $E[M_{\text{T}}] = \sum_{m=1}^{M} m \Pr(M_{\text{T}} = m)$ is illustrated in Fig. 5 for both trigger types. The intersection between both trigger types with equal M is shifted to lower p_h. Type I triggers have a comparably high probability of redundant transmissions for large M, but the number of triggered relays is small. In case type II relays are triggered, the number of triggered relays is high due to a high source-relay delivery probability p_1. While $\Pr(R_{\text{II}}) < \Pr(R_{\text{I}})$, the number of triggered relays M_{T} is expectedly larger for type II triggers than for type I. For $p_h \to 0$, the probability of having a large number M_{T} for

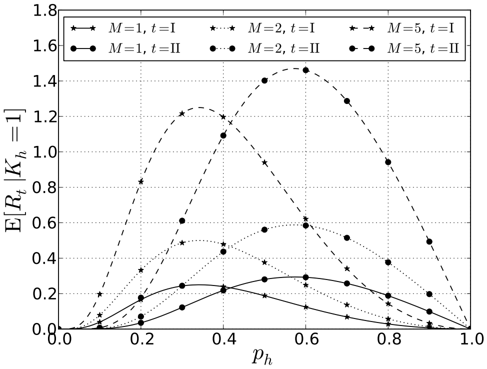


Fig. 5: Number of expected redundant retransmissions for both trigger types.

type II triggers decreases, thusly outperforming type I triggers in terms of redundant transmissions.

Finally, let the RV D_t model successful retransmissions using cooperative relaying for trigger type t. $\Pr(D_t)$ is computed as follows:

$$\Pr(D_{\text{I}} = 1) = \sum_{m=1}^{M_T} \Pr(D_{\text{I}} = 1 | M_{\text{T,I}} = m) \cdot \Pr(M_{\text{T,I}} = m) \tag{7}$$

where $Pr(D_t = 1 \mid M_{\text{T}} = m) = (1 - (1 - p_2)^m)$ for both types t. $\Pr(D_{\text{II}} = 1)$ is computed accordingly. Fig. 6 illustrates the corresponding delivery probabilities with cooperative relaying for various M. The type I trigger automatically forwards a lost transmission and cannot fail because it does not rely on additional transmissions. In comparison, type II triggered relays need to receive the additional request from the source. Relays which do not receive the trigger from the source do not participate in retransmission. This is a problem especially for protocols which only select a small number of relays.

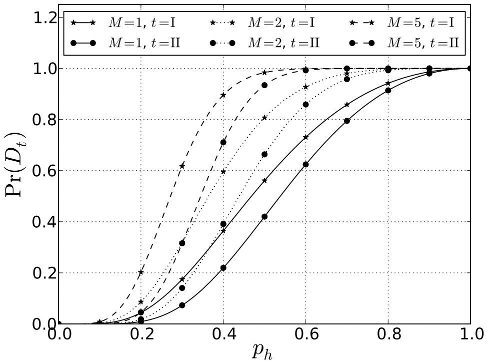


Fig. 6: Probability of a successful retransmission.

Given the assumptions in Tab. I, type I triggers outperform type II triggers in terms of redundant transmissions and delivery probability in the relevant interval of $p_h \gtrapprox 0.75$ [6]. The assumptions comply with results from previous measurements. In the following we only consider type I triggers.

IV. ENERGY AND DELAY COSTS

We determine the costs associated with the transmission of a single frame over a H-hop network and distinguish `DATA` and control packets. `CTRL` packets, such as `ACK` or route maintenance, are assumed to be of half the size of `DATA` packets. IEEE 802.15.4, a standard widely used in ad hoc networks such as ZigBee, or Wireless Sensor Networks (WSNs) such as ISA100.11a and WirelessHART, specifies a single modulation and coding scheme per physical layer [11]. Thus, the transmission time correlates solely to the size of the frame. With equal transmission powers, the used energy depends only on the transmission time. Therefore, we summarize delay and energy under the general term *costs* and symbol C. The costs of a `DATA` packet are normalized to one unit ($C_{\texttt{DATA}} = C_{\text{tx}} + C_{\text{rx}} = \frac{1}{2} + \frac{1}{2} = 1$) while control transmissions `CTRL` cost half a unit ($C_{\texttt{CTRL}} = \frac{1}{2}$) due to reduced size.

A. Direct Transmission Costs

One approach for multi-hop routing networks is to use a route as long as it is reliable such as in DSR, for example. In case a selected route fails at hop h, a route maintenance packet indicating a `ROUTE ERROR` is propagated $h - 1$ hops back to the source which may initiate a new route discovery or select another cached route [2]. The associated costs with a (failed) transmission are as follows:

1) Acknowledged `DATA` packets lead to costs $C_{\text{hop}} = C_{\texttt{DATA}} + C_{\texttt{CTRL}} = \frac{3}{2}$ per hop.
2) In case of failure at hop h, a `ROUTE ERROR` control packet has to be propagated over $h - 1$ hops with a per hop cost of $2 \cdot C_{\text{ctrl}} = 1$ (see Fig. 7, primary route).

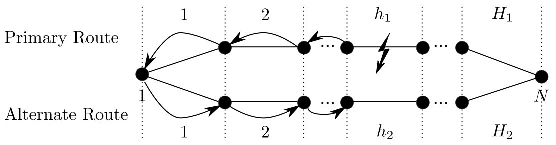


Fig. 7: Overhead in case of failure at hop h.

3) Transmission for at least $h_1 - 1$ hops on an alternate route to reach the same depth assuming the alternate route is of equal or longer length, i.e. $H_2 \geq H_1$ (see Fig. 7, alternate route).

Accordingly, a successful delivery (item 1) leads to costs $C_{\text{succ}} = C_{\text{hop}}$. The costs associated with failing at hop h (items 1-3) are computed by $C_{\text{fail}}(h) = C_{\text{tx}} + (h-1)\,(C_{\text{hop}} + C_{\texttt{CTRL}})$. We further determine the costs of cooperative relaying assisted links.

B. Cooperative Relaying Costs

We assume cooperative relays to constantly receive packets independent of the direct transmission's outcome. In case a relay is triggered it additionally retransmits the packet. The costs are computed as follows

$$C_{\text{relay}}(h) = M(h) \cdot (C_{\text{rx}} + \Pr(R_t) \cdot C_{\text{tx}}) \tag{8}$$

where $M(h)$ is the number of cooperative relays at hop h and $\Pr(R_t) = \sum_{k\in\{0,1\}} \Pr(R_t \mid K_h = k) \Pr(K_h = k)$ the trigger probability of type t. The joint costs of a direct transmission and a cooperative transmission are computed by $\widehat{C}_{\text{succ}}(h) = C_{\text{succ}}(h) + C_{\text{relay}}(h)$ in case of a successful transmission and $\widehat{C}_{\text{fail}}(h) = C_{\text{fail}}(h) + C_{\text{relay}}(h)$ in case of a failed transmission.

C. Number of Cooperative Relays per Hop

We discuss the number of relays assisting each hop. The further down a multi-hop link a packet has propagated, the more expensive is the propagation of the `ROUTE ERROR` to the source. The number of relays is determined to have expectedly the same costs as having to propagate the route maintenance packet, but leading to improved delivery ratios. The number of relays $M(h)$ for hop h is computed by

$$M(h) = \frac{C_{\text{fail}}(h)}{C_{\text{relay}}(h)} \,. \tag{9}$$

For our analysis, we now neglect the fact that M and h can only assume integer values. Fig. 8 shows the number of relays for various p_{EE}. For very high p_{EE} the energy spent on control packets is insufficient to allow for cooperative relays with equal costs. But $p_{\text{EE}} = 0.01$ allows to have cooperative relay assisted hops for $h \geq 9$ at equal costs. With further decreasing p_{EE} relays can also be used earlier along the route, the number of relays can be increased. Further analyses only consider integer values for the number of cooperative relays $M(h)$. Tab. II lists the number of relays obtained from Fig. 8 by rounding off.

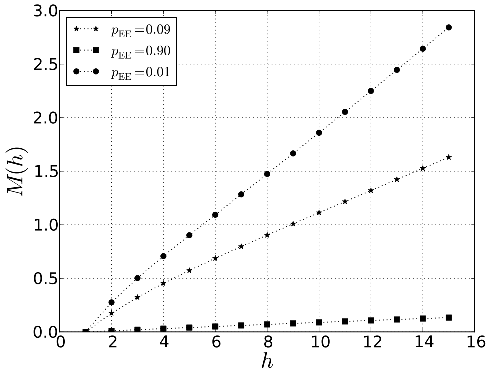


Fig. 8: Number of relays to be selected using equal amount of energy.

Fig. 9 shows the impact of the relays using expected probabilities obtained from the erristance computed by (4). If relays are used (solid lines), the end-to-end delivery ratio does not decrease significantly. The losses at hops without cooperative relaying are, however, too severe to achieve an acceptable end-to-end delivery ratio $\widehat{p_{\text{EE}}}$[1]. Thus, we will further consider networks where each hop is assisted by three relays and consider the costs associated with successful packet deliveries.

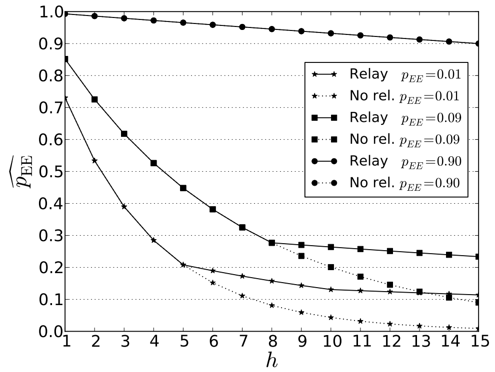


Fig. 9: p_{EE} and resulting $\widehat{p_{\text{EE}}}$ using cost-fair number of cooperative relays.

TABLE II: Number of relays for fair costs.

p_{EE}	p_h	Hop h														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.009	0.73	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2
0.090	0.85	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0.900	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

V. END-TO-END DELIVERY PROBABILITY OF ASSISTED MULTI-HOP NETWORKS

We consider the case of using alternate routes as suggested in DSR and compare cooperative relaying assisted multi-hop transmissions in terms of reachable end-to-end delivery probability and associated costs. We distinguish multi-hop routes 1) *without* (w/o) cooperative relays, 2) with *fair* use of cooperative relays in terms of costs and 3) *fixed* number of relays with $M(h) = 3$, $h = 1 \ldots H$.

Let the Bernoulli distributed RV K_{EE} model the successful reception of a `DATA` packet at the destination with $\Pr(K_{\text{EE}} = 1) = \widehat{p_{\text{EE}}}$ and $\Pr(K_{\text{EE}} = 0) = 1 - \widehat{p_{\text{EE}}}$. The expected costs of a successful transmission for H hops are

$$E[\widehat{C} \mid K_{\text{EE}} = 1] = \sum_{h=1}^{H} \widehat{C}_{\text{succ}}(h) \tag{10}$$

while for failed transmission the costs are

$$E[\widehat{C} \mid K_{\text{EE}} = 0] = \sum_{h=1}^{H} \widehat{C}_{\text{fail}}(h) \cdot \frac{1 - \widehat{p_h}}{1 - \widehat{p_{\text{EE}}}} \,. \tag{11}$$

Note that in absence of cooperative relaying $\widehat{C}_{\text{succ}}(h) = C_{\text{succ}}(h)$ because $C_{\text{relay}} = 0$ for $M_h = 0$. The same applies for $\widehat{C_{\text{fail}}}(h)$.

Once the source transmits a packet to its neighboring intermediate node, the packet is propagated towards the destination. The expected number of transmissions resulting from starting the propagation can be computed by

$$E[\widehat{C}] = E[\widehat{C}|K_{\text{EE}} = 1] \cdot p_{\text{EE}} + E[\widehat{C}|K_{\text{EE}} = 0] \cdot (1 - p_{\text{EE}}) \,. \tag{12}$$

The computation of $E[C]$ is done correspondingly. Finally, we determine the expected efficiency of each scheme by

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[1] In the absence of cooperative relays $\widehat{p_{\text{EE}}} = p_{\text{EE}}$ and $\widehat{p_h} = p_h$.

determining the expected costs per successful transmission:

$$\eta = \frac{E[\widehat{C}]}{\widehat{p_{\mathrm{EE}}}} \tag{13}$$

Tab. III summarizes the costs for the three compared modes for various p_{EE} and resulting $\widehat{p_{\mathrm{EE}}}$ according to (10)-(13).

TABLE III: Expected costs according to (10)-(13). The number of relays are chosen according to Tab. II.

p_{EE}	Mode	$\widehat{p_{\mathrm{EE}}}$	$E[\widehat{C} \mid K_{\mathrm{EE}}]$		Max	$E[\widehat{C}]$	η
			K=1	K=0			
0.009	w/o	0.009	22.50	14.50	35.00	14.57	1619.11
	fair	0.117	32.02	8.32	47.00	11.09	95.02
	fixed	0.895	51.06	16.40	76.00	47.44	52.98
0.090	w/o	0.090	22.50	14.50	35.00	15.22	169.11
	fair	0.220	26.52	9.99	40.00	13.63	61.96
	fixed	0.980	48.34	16.22	76.00	47.68	48.68
0.900	w/o	0.900	22.50	14.50	35.00	21.70	24.11
	fair	0.900	22.50	14.50	34.00	21.70	24.11
	fixed	1.000	45.16	16.01	76.00	45.16	45.16

Cooperative relaying improves the end-to-end delivery probability significantly when applied, especially for low p_{EE} (p_h). This aligns with previous measurements where the link delivery ratio was measured to be increased significantly by cooperative relaying [8]. Naturally, when using diversity schemes the expected costs $E[\widehat{C} \mid K_{\mathrm{EE}}]$ increase with decreasing p_{EE} due to additional diversity transmissions. Though, for the fair scheme, where the number of cooperative relays per hop varies, the expected costs for failed transmissions decrease. This can be explained using Fig. 9. The further `DATA` has propagated from the source, the higher the costs to send a `ROUTE ERROR` allowing to use cooperative relays improving the link delivery probability. Therefore, failures at the beginning of the route, where hops are not assisted, become more likely, thus, reducing expected costs.

The maximum costs per failed transmission increase significantly when using cooperative relaying assisted links. In the worst case, $h-1$ hops are successful requiring $M(h)$ cooperative transmission per hop leading to $\sum_{h=1}^{H-1} M(h)+1$ transmissions while the last hop fails. Though this case becomes very unlikely due to the comparably high delivery probability $\widehat{p_{\mathrm{EE}}}$ achievable through assisted links.

Finally we consider the expected costs per transmission $E[C]$. The fixed scheme increases the costs while also increasing the delivery probability significantly. The fair scheme decreases the costs because route errors are more likely to happen in the beginning of a route while moderately increasing $\widehat{p_{\mathrm{EE}}}$. We consider the expected costs per successful transmission η to set costs and delivery probability in relation.

Cooperative relaying decreases the costs by up to one magnitude for low p_{EE}. The costs for constantly listening are compensated by improving the delivery probability dramatically compared to the scheme without cooperative relaying assistance. With increasing p_{EE}, the delivery probability does not increase as significantly as for low p_{EE}, leading to relatively increased costs for constant reception. For high p_{EE} the costs for constantly listening cannot be compensated by increased delivery probability, the costs per successful transmission exceed those for the case without relays. By reducing the number of relays the costs for high p_{EE} can be reduced leading to less improvement of delivery probability for low p_{EE}.

VI. CONCLUSIONS

In this work we analyzed the impact of cooperative relaying assisted hops in multi-hop networks. Firstly, we identified two types to trigger retransmissions by cooperative relays and discussed their application. Implicit triggering significantly boosts the delivery probability at moderate costs. In the relevant interval of link delivery ratios p_h, redundant retransmissions improve the delivery ratio by triggering on average more relays. Secondly, we applied cooperative relaying to assist transmissions on hop-by-hop basis for multi-hop protocols on the example of DSR. Cooperative relaying can decrease the costs per successful packet delivery in terms of delay and energy significantly, especially for harsh environments where a multi-hop communication without diversity transmissions would not be feasible.

ACKNOWLEDGMENT

This work was performed as part of the project Cooperative Relaying in Wireless Networks (RELAY) of the research cluster Lakeside Labs. It was partly funded by the ERDF, KWF, and the state of Austria under grant 20214/15935/23108. Special thanks to C. Bettstetter for proof reading this paper.

REFERENCES

[1] K. Akkaya and M. Younis, “A survey on routing protocols for wireless sensor networks,” *Ad Hoc Net*, vol. 3, no. 3, pp. 325–349, Nov. 2005.

[2] D. Johnson and D. Maltz, “Dynamic source routing in ad hoc wireless networks,” *Mobile Computing*, vol. 353, pp. 153–181, 1996.

[3] S.-J. Lee and M. Gerla, “Split multipath routing with maximally disjoint paths in ad hoc networks,” in *Proc. Int. Conf. on Communications (ICC)*, Jun. 2001.

[4] C. Perkins, E. Belding-Royer, and S. Das, “Ad hoc On-Demand Distance Vector (AODV) Routing,” RFC 3561 (Experimental), Internet Engineering Task Force, Jul. 2003.

[5] A. Nasipuri, R. Castañeda, and S. Das, “Performance of multipath routing for on-demand protocols in mobile ad hoc networks,” *Mobile Networks and Applications*, vol. 6, no. 4, pp. 339–349, Aug. 2001.

[6] T. Andre, G. Brandner, N. Marchenko, and C. Bettstetter, “Measurement-based analysis of cooperative relaying in an industrial wireless sensor network,” in *Proc. IEEE Globecom*, Dec. 2012.

[7] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, “A simple cooperative diversity method based on network path selection,” *IEEE J. Sel. Areas Commun.*, vol. 24, pp. 659–672, Mar. 2006.

[8] T. Andre, N. Marchenko, G. Brandner, W. Masood, and C. Bettstetter, “Measurement-based analysis of adaptive relay selection in industrial wireless sensor networks,” in *Int. Workshop on Wireless Network Measurements (WiNMee)*, May 2013.

[9] M. Haenggi, “Analysis and design of diversity schemes for ad hoc wireless networks,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 19–27, Jan. 2005.

[10] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, “Impact of interference on multi-hop wireless network performance,” *Wireless Networks*, vol. 11, no. 4, pp. 471–487, Jul. 2005.

[11] *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Computer Society Std., Sep. 2006.