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An Energy-Efficient Forwarding Scheme for Wireless Sensor Networks

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An Energy-Efficient Forwarding Scheme for Wireless Sensor Networks

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Abstract— **Energy-efficient forwarding becomes important if resources and battery lifetime are limited such as in Wireless Sensor Networks. Although widely used, simple hop-based forwarding along a path from one node towards a sink can be very inefficient in terms of delivery rate as well as energy efficiency, especially in lossy environments. We will show that just minimizing the expected number of transmissions within the network is not always the most efficient forwarding strategy. Using a realistic link loss model, we derive two new forwarding schemes named *Single-Link* and *Multi-Link Energy-Efficient Forwarding* that trade off delivery rate and energy costs best by maximizing energy efficiency. Multi-Link Forwarding further benefits from addressing multiple receivers during packet forwarding, instead of a single one. By mathematical analyses, extensive simulations, and experimental experiments we contrast the performance of our approaches against a comprehensive framework of different forwarding strategies.**

I. INTRODUCTION

Many recent experimental studies have shown that, especially in the field of Sensor Networks where low-power radios are employed, wireless communication is far away from perfect packet reception within the communication range [1], [2], [3], [4]. That is, communication models widely used in simulations that correspond to binary links experiencing either no or full loss are not realistic. Instead of modeling only a connected and disconnected region, more realistic link loss models introduce a transitional region with widely varying degrees of packet loss [5], [6], [7]: Although for a sender-receiver pair the packet reception tends to decrease with distance, there might be some cases where more distant nodes may have smaller loss than nearby nodes.

The existence of a transitional region is critical for packet forwarding strategies since it determines how much energy has to be spent for successful packet delivery. In terms of energy, it might be more efficient to establish longer paths experiencing low loss instead of shorter ones with poor link qualities where many retransmissions might occur [8], [9], [6]. In this way, overall packet transmissions can be kept to a minimum even if the forwarding path is longer.

For one-to-many communication where sensor nodes report data to one single sink node, many routing algorithms use distance-based forwarding, where the number of hops serves as a distance metric [10], [11], [12], [13], [14]. However, since connectivity between nodes depends on link quality, it is not clear which neighbor should forward packets towards the sink to achieve optimal energy efficiency. If each node simply selects the node with the lowest hop counter, it is likely that the end-to-end path will exhibit high packet losses leading to poor efficiency due to many retransmissions.

Several experimental studies have explored this problem with different routing schemes [8], [9], [6], [3]. However, most work focuses on minimizing the expected number of transmissions or tries to maximize end-to-end delivery. In this paper, we will focus more on *energy efficiency* to find the best trade-off between delivery rate and required energy. By mathematical analyses and extensive simulations, we investigate a broad framework of distance-vector-based forwarding strategies. Furthermore, we propose two new forwarding schemes namely *Single-Link Energy-Efficient Forwarding* and *Multi-Link Energy-Efficient Forwarding*.

The paper is organized as follows. In Section II, we first outline related work. Section III describes the link loss model that is used for simulations. It also gives information about assumptions made in this paper and performance metrics we focus on. Section IV provides an analysis of two simple forwarding schemes that we will call *Hop-based* and *PRR-based Forwarding*. By blacklisting bad nodes, we will explore to what degree such strategies can be improved. In Section V, we present Single-Link and Multi-Link Energy-Efficient Forwarding. We will give a comprehensive mathematical analysis for packet forwarding with infinite and finite retransmissions. In that way, we will derive a forwarding strategy that trades off delivery rate and energy costs best by maximizing energy efficiency. Using extensive simulations, we will compare the performance of all forwarding strategies in Section VI. Real-world experiments are presented in Section VII. Finally, Section VIII gives conclusions and describes future directions.

II. RELATED WORK

Several routing protocols for sensor networks concentrate on energy-related issues - since it is surely most challenging and important [15], [16]. For many-to-one communication with multiple data-reporting nodes and one sink node, protocols like Directed Diffusion [10] use distance-vector based routing. First, the sink node propagates an 'interest' or 'advertisement' throughout the network. By assigning each node a hop counter, reverse paths are established that are later used for data reporting towards the sink. Such an initialization phase of establishing reverse-paths is also used in many other protocols [17], [11], [12], [14]. In order to not burn out a nodes' energy along the shortest path, many approaches attempt to improve energy balancing among all forwarding nodes [18], [13], [19]. GBR [13] improves Directed Diffusion by uniformly balancing traffic throughout the network using data aggregation and traffic spreading. Shah *et al.* [19] propose an energy aware routing scheme that employs a probability function based on energy consumption of different routing paths. Other energy aware routing schemes are analyzed by Gan *et al.* in [18].

However, experimental studies have shown that packet loss is not uniformly distributed over distance; losses also occur for nearby nodes, and a significant amount of links are asymmetric [1], [6], [4], [20], [7]. Due to this, simulation results of many routing protocols could not be verified in reality. In this paper, we will analyze the initialization phase of establishing reverse paths for many-to-one communication in consideration of delivery rate and energy efficiency for such lossy environments. Techniques for energy balancing throughout the network are orthogonal and beyond the scope of our work.

There are many attempts to improve fault tolerance through robustness by multipath routing [21], [14]. Ganesan *et al.* [21] propose partially disjoint multipath routing schemes, they call them "braided multipath". For this, they study the energy-robustness tradeoff compared to complete disjoint multipath routing schemes. Ye *et al.* propose Gradient Broadcast (GRAB) [14] where packets travel towards the sink by descending a cost path. Costs are defined as the minimum energy overhead to forward packets to the sink along a previously established path. Nodes close to the sink have smaller costs than far away ones. All nodes receiving a packet with smaller cost will participate in packet forwarding. Since multiple paths with decreasing costs exist, GRAB is quite robust and reliable with respect to data delivery. However, multipath forwarding comes at the expense of high energy consumption. We will tackle robustness by *multi-link forwarding*. Unlike addressing a specific node for forwarding, packets are broadcast to many potential forwarders (which we will call a *forwarder set*). This way, it is more likely that one of these nodes will receive the packet correctly, thus avoiding unnecessary retransmissions. However, in order to conserve energy, only one node among all potential nodes will eventually forward the packet.

In [9], Seada *et al.* propose energy-efficient forwarding strategies for geographic routing by studying the effects of lossy environments. They focus on greedy forwarding where each node tries to forward packets to nodes that are closest to the sink with respect to geographic distance. Such maximum-distance greedy forwarding techniques work well under ideal conditions but poorly in realistic environments. It turns out that many packets are transmitted on lossy links leading to bad end-to-end delivery rates with high energy costs. Seada *et al.* therefore suggest a packet reception rate times distance metric that achieves optimal results by balancing longer, lossy links and shorter, high quality links. In contrast, our work studies energy-efficient forwarding for non-geographic routing without requiring nodes to be location-aware.

Yarvis *et al.* [3] have performed real-world experiments for large scale sensor networks and evaluated the performance of Destination-Sequenced Distance Vector Routing (DSDV) in reality. They also propose quality-based routing, a forwarding scheme that attempts to maximize end-to-end delivery rates by measuring the reception rates on each link. As a result, links experiencing poor reception quality are avoided; thus packet loss decreases. However, since maximizing end-to-end delivery tends to prefer shorter but high-quality links, the path lengths counted in hops increase significantly.

In [2], De Couto *et al.* analyze the throughput of minimum hop count distance-vector based routing protocols and observe significant losses in overall end-to-end packet delivery. Since minimizing hop counters maximizes traveled distance per hop and in the same way minimizes delivery rate, traditional routing protocols like Dynamic Source Routing (DSR) and DSDV perform poorly. In [8], the authors extend their previous work and propose a minimum transmission metric that is approximated by $\frac{1}{forward\ link\ quality} \times \frac{1}{backward\ link\ quality}$, incorporating packet reception rates and link asymmetry.

Like De Couto *et al.*, Woo *et al.* focus on the Minimum Transmission (MT) metric [6]. They present experimental studies for forwarding schemes like Shortest Path Forwarding, MT Forwarding, and techniques used in DSR and DSDV. However, as we will show in Section V, minimizing the expected number of total transmissions might not result in the most energy-efficient forwarding strategy. Unlike minimizing the expected number of transmissions, we will concentrate on maximizing energy efficiency as the ratio of delivery rate and energy costs. Furthermore, we will extend packet forwarding by taking multiple forwarding links into account, i.e., a packet is not sent to one single but to multiple forwarders at the same time. In this way, delivery rate as well as energy efficiency are further improved.

III. MODEL, ASSUMPTIONS, AND METRICS

The model that is used both in our analyses and simulations captures the packet reception rate (PRR) on a link between two nodes as follows. Below a distance D_1, nodes exhibit full connectivity, i.e., PRR is equal to 1. Nodes are disconnected if they are at least distance D_2 away from each other. In the transitional region between D_1 and D_2, the expected reception rate decreases smoothly with some variation. We model this behavior as

$$PRR(d) = \begin{cases} 1 & d < D_1 \\ \left[\frac{d-D_1}{D_2-D_1} + X\right]_0^1 & D_1 \leq d \leq D_2 \\ 0 & d > D_2 \end{cases} \qquad (1)$$

with $[\cdot]_a^b = \max\{a, \min\{b, \cdot\}\}$ and $X \sim N(0, \sigma)$ be a Gaussian variable with variance σ^2. Samples of this link loss model are shown in Figure 1 for parameters $D_1 = 10$, $D_2 = 30$, and $\sigma = 0.3$.

The existence of a connected, transitional, and disconnected region could be verified in reality [1], [6], [4], [7]. While the reception rates within the connected resp. disconnected region exhibit no variation, the variation might be quite high in the transitional region. Although it is likely that the reception rate decreases smoothly with increasing distance between a pair of neighbor nodes, there might be nearby nodes in the network which experience bad links whereas some distant nodes have good links.

For both our analyses and simulations we assume that nodes are uniformly distributed over a 200×200 m field with a maximum radio range of 30 m. The network is stationary without mobility. We consider two nodes to be neighbors if the packet reception rate is at least 1%. Furthermore, we assume that each node already knows the reception rate of all its neighbors, e.g., through packet reception measurements. Link estimators, as analyzed in [6], could be used to provide this information.

We will consider many-to-one communication with one sink and several sensor nodes reporting data to the sink.

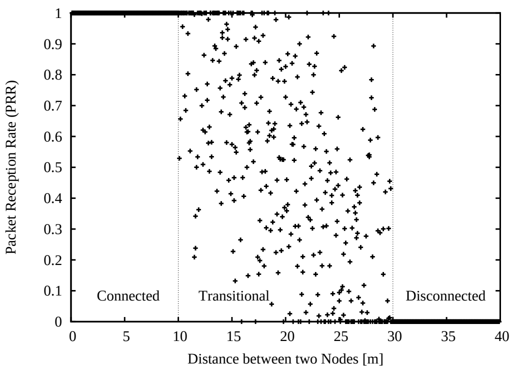


Fig. 1. Samples of the Link Loss Model used in both Analyses and Simulation ($\mu = 0$, $\sigma = 0.3$)

MAC related issues are beyond the scope if this paper, but nodes not participating in packet reception should be able to turn their communication radio off to save energy. For each packet transmission, the required energy could then be calculated as

$$e = e_{tx} + n \cdot e_{rx} + (N - n) \cdot e_{rx}^h \qquad (2)$$

where e_{tx} and e_{rx} are the amount of energy for packet transmission resp. receiving, n the number of addressed receivers, and N the number of neighbors in communication range. e_{rx}^h quantifies the amount of energy required only for decoding the packet header. We assume that nodes who are not receivers of a packet will turn their radios off as soon as they have heard the header. According to the sensor board hardware, we set $e_{rx} = 0.375$ and $e_{tx} = 1$ (see Table I in Section VII-A).

In the following, we are interested in two metrics, namely *delivery rate* and *energy efficiency*. The delivery rate E_r quantifies the fraction of packets that originate at a source node and are properly received at the sink. Since each forwarding node consumes a certain amount of energy for packet reception and transmission, the energy efficiency E_{eff} quantifies the ratio between delivery rate E_r and consumed network energy E_e. That is, the energy efficiency of a single node regarding packet forwarding towards the sink can be calculated by

$$E_{eff} = \frac{E_r}{E_e} = \frac{E_r}{t \cdot e} \qquad (3)$$

where t denotes the average number of packet transmissions required to finally reach the sink and e is the corresponding energy.

IV. ANALYSIS OF HOP- AND PRR-BASED FORWARDING STRATEGIES

A. Hop-based Forwarding

In order to find a path from a source node to a destination node, a widely used method is establishing the reverse path using a hop counter as the distance metric. Afterwards, all packets are forwarded along the path with decreasing hop counters. However, especially in the field of Sensor Networks where low-power radios are used, nodes might have many neighbors with lossy links. Traditional hop-based forwarding algorithms select the node with minimal hop counter as the forwarder, neglecting link qualities. Since it is likely that the node with the minimum hop counter is far away, many retransmissions might be necessary, consuming much energy. Thus, the energy efficiency will be low.

One possibility to overcome this problem is to blacklist bad nodes with respect to the packet reception rate from becoming forwarders. In this way, nodes experiencing high packet losses are no longer considered neighbors. However, finding the best blacklisting threshold might be difficult since it depends on environmental conditions, node density, link qualities, network congestion, etc. How the delivery rate and energy efficiency behave vs. different blacklisting thresholds is depicted in Figure 2.

For different node densities (number of nodes per radio range) we performed 100 simulation runs using the link loss model described in Section III. Among a node's neighbors, i.e., nodes with a reception rate that is equal to the blacklisting threshold or greater, the node with the best hop counter is selected as the forwarder. In case of equal hop counters, the one with the highest reception rate is selected.

Figure 2(a) shows the delivery rate vs. different blacklisting thresholds averaged over all nodes in the network. It is assumed that at most three retransmissions ($R = 3$) may be used to finally deliver a packet. Without blacklisting nodes, the delivery rate is quite low and independent of the node density. Many nodes select forwarders that have poor links, leading to bad packet delivery. By blacklisting such nodes, the delivery rate increases up to a point where blacklisting becomes no longer favorable. Especially for low node densities, blacklisting too many nodes might finally lead to disconnections since no potential forwarding node remains.

Energy efficiency is influenced in the same way. As depicted in Figure 2(b), high delivery rates do not always lead to a high energy efficiency. For example, in case of high node densities, even blacklisting 95% of adjacent nodes causes few disconnections achieving high delivery rates at the same time. However, in terms of energy efficiency, blacklisting fewer nodes would achieve better results. By increasing the blacklisting threshold, forwarding paths are getting longer, and more energy is needed to deliver packets to the sink. Thus, the efficiency of these paths degrades.

B. *PRR-based Forwarding*

In PRR-based forwarding, nodes select forwarders according to their distance (hop counter) and link quality which is expressed by the Packet Reception Rate (PRR). By minimizing $\frac{hops}{PRR}$, the best forwarding node is selected. The idea behind this metric is to downgrade neighbors with low hop counters and poor links. Thus we hope to minimize the influence of blacklisting on the forwarding performance since nodes having poor links are only considered last but are not blocked. Thus, disconnections caused by blacklisting too many nodes might be prevented. However, it could nevertheless help to improve the delivery rate since very bad links are avoided independent of assigned hop counters.

The effects of neighbor blacklisting on the delivery rate and energy efficiency are shown in Figure 3. For low node densities, blacklisting leads to worse results as compared to not doing so due to more network disconnections. For higher densities, delivery rates can be improved slightly. However, the improvements are marginal. Regarding energy efficiency, blacklisting shows no significant improvements at all (see Figure 3(b)). As stated before, in most cases it just produces network partitions.

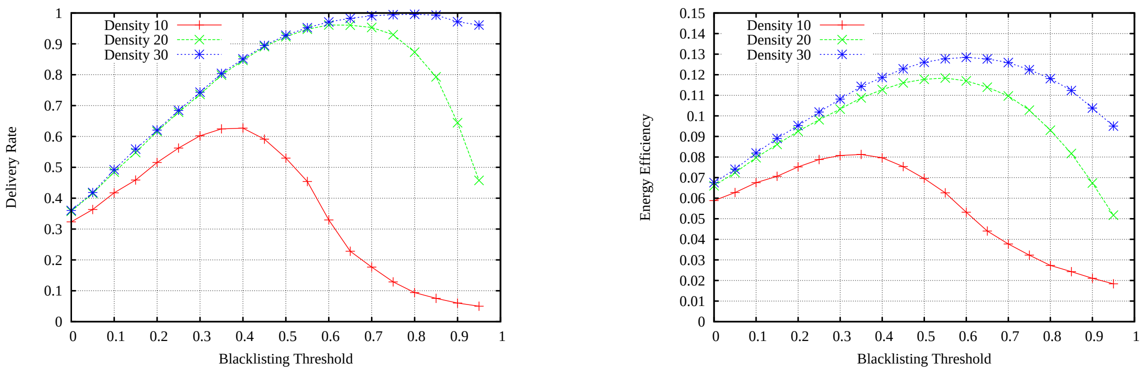
Comparing Hop-based Forwarding and PRR-based Forwarding shows that both strategies could nearly achieve the same results, except for the low density case where PRR-based Forwarding performs better. However, the fact that PRR-based Forwarding does not significantly benefit from blacklisting nodes turns it into a very practical alternative since the main problem of Hop-based Forwarding is the right choice of the blacklisting threshold.

V. ENERGY-EFFICIENT FORWARDING

Energy Efficient Forwarding (EEF) aims at finding the most energy-efficient forwarding path in the network. By examining each of a node's neighbors, the node that maximizes E_{eff} is selected as the forwarder. In contrast to the previous proposed forwarding strategies, we will now take end-to-end reception rate and energy into account.

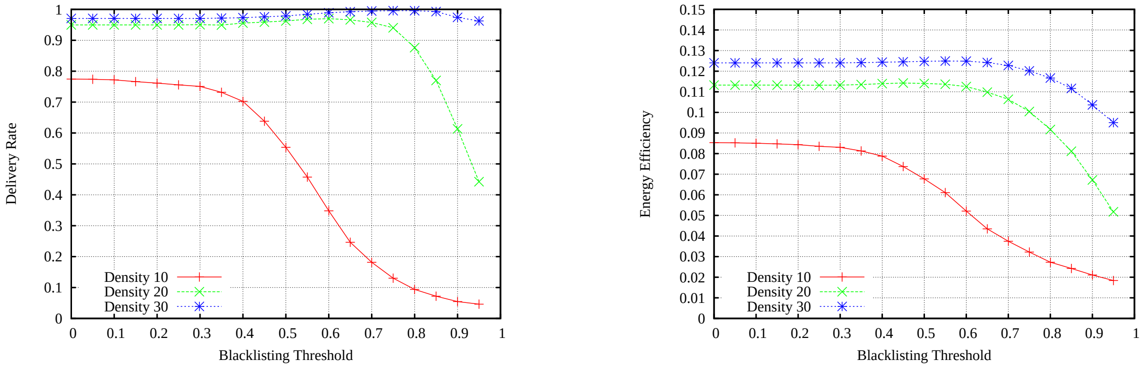
Moreover, we consider *multi-link* forwarding in contrast to *single-link* forwarding where packets are always transmitted to only one forwarder. In multi-link forwarding, the idea is to exploit the broadcast characteristics of the wireless communication channel. That is, a node first determines a set of potential forwarders, the *forwarding set*. It then broadcasts its data packet to the entire forwarding set. Among all nodes that received the packet correctly, the best forwarder is selected.

Sending data packets to more than one forwarding node will surely increase delivery rate, but will also consume more network energy since more nodes must receive a



(a) Delivery Rate (b) Energy Efficiency

Fig. 2. Hop-based Forwarding with Different Blacklisting Thresholds ($R = 3$)



(a) Delivery Rate (b) Energy Efficiency

Fig. 3. PRR-based Forwarding with Different Blacklisting Thresholds ($R = 3$)

packet. Deciding which node should participate in the forwarding set is the task of the forwarding strategy. In the following section we will analyze both forwarding strategies concerning two cases: Sending packets with infinite retransmissions which will finally deliver all packets to the sink (assuming both nodes are connected), and sending packets with at most R retransmissions.

A. Analysis of the Infinite Retransmission Case

Although not realistic, we first analyze the infinite retransmission case, i.e., a node repeats sending a data packet to its forwarding node (or forwarding set) until the forwarder's acknowledgement is received. The acknowledgement can either be sent explicitly or implicitly by piggy-backing with the next forwarder's data packet.

Since infinite retransmissions are used, the delivery rate is finally 100%. That is, maximizing E_{eff} is equal to minimizing the energy consumed E_e, i.e., $E_{eff} = E_e^{-1}$. For the single-link forwarding case, the required energy is calculated as

$$\begin{aligned} E_e &= (1-a_i)(E_e^i + b) + a_i(b + E_e) \\ \Rightarrow E_e &= E_e^i + \frac{b}{1-a_i} \end{aligned} \tag{4}$$

with $a_i = 1 - prr_i$, $b = e_{tx} + e_{rx}$, E_e^i being the required energy of forwarding node i to reach the sink and prr_i being the packet reception rate on node i's link.

Extending this calculation to multi-link forwarding with a forwarding set of size n and a potential forwarding node i leads to

$$\begin{aligned} E_e &= \sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n(b + E_e) \\ &= \frac{\sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n b}{1 - a_n} \end{aligned} \tag{5}$$

with $a_i = \prod_{j=1}^{i}(1 - prr_j)$ and $b = e_{tx} + n e_{rx}$.

It is now interesting to analyze for which link qualities selecting more than one forwarding node would be most efficient. Let us assume there are n nodes with reception rate p in the neighborhood. Furthermore, all nodes require the same amount of energy for packet delivery, i.e., without loss of generality, $E_e^i = 0$. Normalizing e_{rx} to e_{tx}, i.e., $e_{tx} = 1$, leads to $E_e = \frac{e_{tx} + n e_{rx}}{1-(1-p)^n}$.

Figure 4 plots E_e vs. PRR and the number of potential forwarding nodes for $e_{rx} = 0.375$. With decreasing link quality, selecting more forwarding nodes becomes more

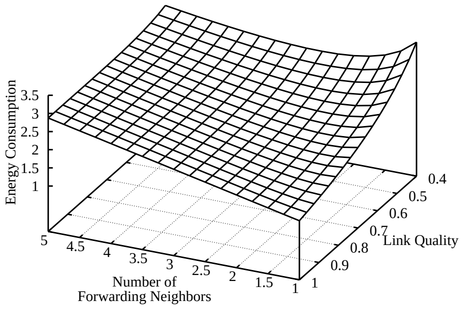


Fig. 4. Energy Consumption for Different Link Qualities and Numbers of Forwarding Neighbors ($e_{rx} = 0.375$)

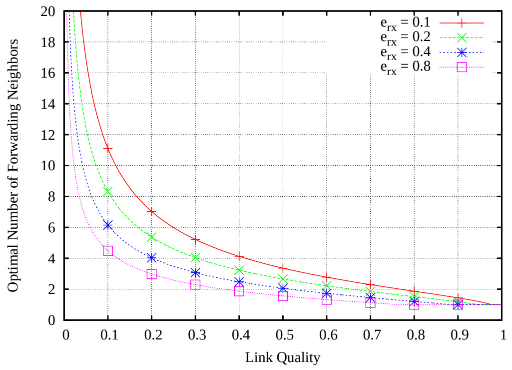


Fig. 5. Optimal Number of Forwarding Neighbors w.r.t. Energy Efficiency vs. Link Quality

efficient in spite of additional receiving costs. The optimal number of forwarding nodes n^* is calculated by solving

$$\frac{\partial E_e(p,n)}{\partial n} = 0. \tag{6}$$

It is shown in Figure 5 for different reception rates and reception costs. While for optimal link qualities with $p = 1$ just one forwarder is selected, more nodes become forwarders for decreasing link qualities and reception costs e_{rx}. Thus, multi-link forwarding might be advantageous in situations where nodes are poorly linked, even in case of high reception costs.

B. Analysis of the Finite Retransmission Case

In the finite retransmission case, each node is allowed to use up to R retransmissions to successfully deliver a data packet to its forwarding node. In the single-link case without retransmissions, the end-to-end delivery rate from a source node to the sink is

$$E_r = \prod_{\substack{k \in \phi, \\ k \neq \text{sink}}} prr_{k,k+1} \tag{7}$$

where ϕ is the path from source to sink and $prr_{k,k+1}$ is the packet reception rate between node k and its forwarder $k+1$.

Allowing up to R retransmissions, the deliver rate changes to

$$E_r = \prod_{\substack{k \in \phi, \\ k \neq \text{sink}}} \left(1 - (1 - prr_{k,k+1})^{R+1}\right). \tag{8}$$

The required energy can be calculated from

$$\begin{aligned} \hat{E}_e^1 &= prr_i(E_e^i + b) + a(b + \hat{E}_e^2) \\ &\vdots \\ \hat{E}_e^{R+1} &= prr_i(E_e^i + b) + ab \\ \Rightarrow E_e &= \hat{E}_e^{R+1} = \frac{\left(prr_i(E_e^i + b) + ab\right)\left(1 - a^{R+1}\right)}{1 - a} \end{aligned} \tag{9}$$

with $a = (1 - prr_i)$, $b = e_{tx} + e_{rx}$, prr_i the packet reception rate of forwarder i and E_e^i its energy costs.

In the same way, Equation 8 can be expressed with E_r^i being the delivery rate of forwarder i:

$$E_r = \frac{prr_i E_r^i (1 - a^{R+1})}{1 - a}. \tag{10}$$

Thus, the energy efficiency for the R-retransmission case is

$$E_{eff} = \frac{prr_i E_r^i}{prr_i(E_e^i + b) + ab} \tag{11}$$

For $b = 1$, minimizing E_e in Equation 9 yields the Minimizing Transmission (MT) forwarding scheme. As we can see, maximizing E_{eff} need not lead to the same forwarding path as minimizing E_e. We will show this fact in the next section also by means of simulations.

Analog to the analysis done so far, we can extend our calculations to the multi-link case. Again, assume a forwarding set of size n. Then, the required energy is

$$\begin{aligned} \hat{E}_e^1 &= \sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n (b + \hat{E}_e^2) \\ &\vdots \\ \hat{E}_e^{R+1} &= \sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n b \\ \Rightarrow E_e &= \frac{\left(\sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n b\right)\left(1 - a_n^{R+1}\right)}{1 - a_n} \end{aligned} \tag{12}$$

with $a_i = \prod_{j=1}^{i} (1 - prr_j)$ and $b = e_{tx} + n e_{rx}$.

In the same way, we get

$$E_r = \frac{\left(\sum_{i=1}^{n} a_{i-1} prr_i E_r^i\right)\left(1 - a_n^{R+1}\right)}{1 - a_n} \tag{13}$$

which leads to

$$E_{eff} = \frac{\sum_{i=1}^{n} a_{i-1} prr_i E_r^i}{\sum_{i=1}^{n} a_{i-1} prr_i (E_e^i + b) + a_n b}. \tag{14}$$

VI. SIMULATION RESULTS

With the mathematical analyses done in the previous section, we are now able to investigate how the different forwarding schemes. We have implemented a comprehensive framework of forwarding strategies consisting of the following algorithms:

- **Multi-Link EEF** Multi-Link Energy-Efficient Forwarding attempts to maximize the energy efficiency E_{eff} by examining more than one potential forwarding neighbor. Unlike the following forwarding strategies, it computes a forwarding set of potential forwarders. Even if only one node will forward a packet later, Multi-Link EEF exploits the broadcast characteristics of the wireless medium. Taking more than one forwarding node into account might increase delivery rates since more nodes take part in packet forwarding but might also consume more energy. However, by maximizing energy efficiency, this trade-off will be considered appropriately.
- **Single-Link EEF** Single-Link Energy-Efficient Forwarding is similar to Multi-Link EEF except the fact that just one forwarding node and not a set of potential forwarders is considered.
- **MT** Minimizing Transmissions attempts to minimize the overall packet transmissions along the source-to-sink path. Minimizing the number of transmissions is equal to minimizing E_e with constant e_{tx} and e_{rx} and $R = \infty$. However, since it does not consider the deliver rate explicitly, it might not be the most energy-efficient forwarding strategy for $R \neq \infty$.
- **PRR-based Forwarding** tries to minimize $\frac{hops}{prr}$ as a trade-off between link quality and distance. Since blacklisting neighbors has just a slight impact on the delivery rate and energy efficiency, we will only show the results for the optimal case.
- **E_r-based Forwarding** focuses on the end-to-end delivery rate and attempts to maximize E_r. It is therefore expected to achieve the best delivery rates among all single-link forwarding strategies.
- **Hop-based Forwarding** This forwarding strategy is primary just hop-based, i.e., the node with the lowest hop counter becomes forwarder. In the case of equal hop counters, the node with the best reception rate is selected.
- **Optimal Hop-based Forwarding** works like simple Hop-based Forwarding but it does blacklist nodes. The blacklisting threshold is optimized such that energy efficiency is maximized. Thus, it gives a theoretically upper bound for simple Hop-based Forwarding.

For both performance metrics delivery rate E_r and energy efficiency E_{eff}, we will explore the influence of *node density*, *network congestion*, *number of retransmissions*, and *receiving energy costs* in the following sections. All points in the graphs were averaged over 100 simulation runs.

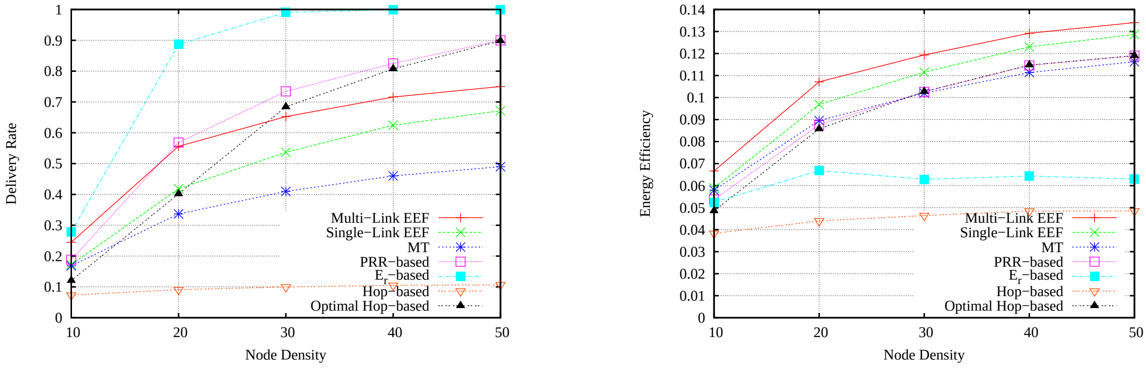
A. Node Density

First we will investigate different node densities varying from 10 to 50 nodes per communication range. Figure 6 depicts the impact of node density on the *delivery rate*. As expected, among all single-link forwarding strategies, E_r-based Forwarding performs best and gives an upper bound for achievable delivery rate in spite of possible disconnections. Simple Hop-based Forwarding shows poor performance because no blacklisting is applied. Thus, many lossy links are used leading to bad delivery rates, as we have seen in Section IV-A. Improving Hop-based Forwarding by blacklisting achieves significantly better results but is still outperformed by PRR-based Forwarding. Although it does not consider end-to-end delivery, it better trades off link quality and number of hops. PRR-based Forwarding also performs better than MT, Single-Link and Multi-Link EEF that rather concentrate on transmission costs and efficiency than just on delivery rate.

However, Single-Link and Multi-Link EEF show promising results. Both perform better than MT. That is, both forwarding strategies are still able to find sufficient paths to the sink although they fully concentrate on energy efficiency. Since Multi-Link EEF exploits broadcasting data packets to an entire forwarding set (instead of a single forwarder), it could further improve the delivery rates achieved by Single-Link EEF.

Concerning *energy efficiency* as shown in Figure 6(b), Multi-Link EEF shows the best results, followed by Single-Link EEF and MT. Again, we can observe that selecting more than one forwarding node might be beneficial even if more energy is spent for packet reception. Furthermore, Figure 6(b) shows that just minimizing the number of transmissions in the network does not lead to the most energy-efficient forwarding strategy even if only single-link forwarders are taken into account.

Simple Hop-based Forwarding performs worst again. Also E_r-based Forwarding shows energy inefficiency, although it achieves the highest delivery rates. Thus, forwarding paths in simple Hop-based Forwarding and E_r-based Forwarding are very expensive in terms of energy and the number of transmissions. The performance of PRR-based and Optimal Hop-based Forwarding with respect to energy efficiency is quite the same. However,



(a) Delivery Rate

(b) Energy Efficiency

Fig. 6. Influence of Node Density on Delivery Rate and Energy Efficiency ($R = 0$)

PRR-based Forwarding could achieve better delivery rates and does not require an optimal blacklisting threshold as Hop-based Forwarding.

Altogether, increasing node density enables better links achieving higher delivery rates and energy efficiency. Only for simple Hop-based Forwarding, higher densities show little effects. Since link qualities are not considered until two forwarders have the same hop counter, in most cases the best forwarder in terms of hops exhibits the poorest link quality independent of node density.

B. *Network Congestion*

In this section, we will perform simulations focusing on network congestion. Since most of the Link Loss Models received from practical measurements [5], [7] capture just the link loss within a non-congested network (as our model in Section III), i.e., without interfering transmissions from other nodes, we extend our model by introducing a *contention probability* ρ. Given probability ρ, the probability of receiving a packet correctly over a link i is then $prr_i(1-\rho)$ where prr_i is the link's packet reception rate obtained from the Link Loss Model.

Since in reality, nodes measuring reception rates on links will not distinguish between losses due to congestion or poor link conditions, they will estimate the overall probability of reception [6]. Thus, for our simulations we assume that ρ and consequently $prr_i(1-\rho)$ is known to all nodes. Since we are mainly interested in the impact of congestion on forwarding performance, we again neglect measurement errors as in the last sections.

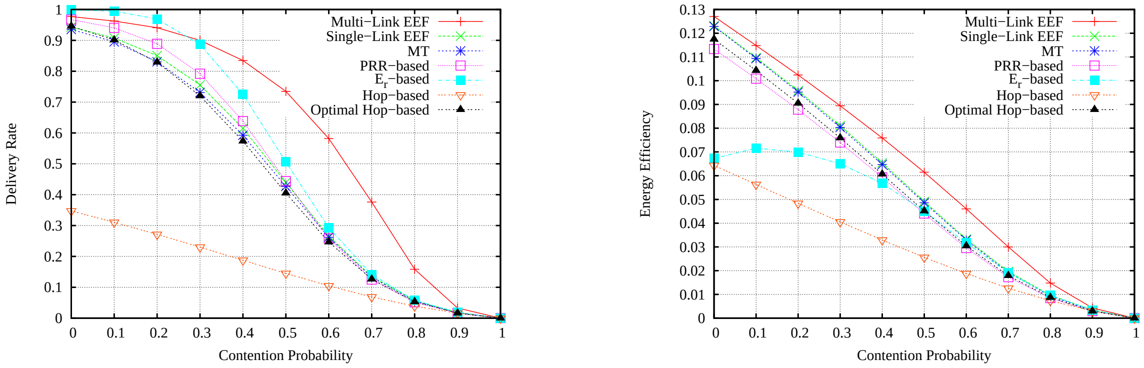
We use a node density of 20 neighbors with three retransmissions that are employed to compensate increasing network congestion. Varying the contention probability from 0 to 1, Figure 7(a) depicts the impact on delivery rate. While E_r-based Forwarding performs best for low congested networks, it is outperformed by Multi-Link EEF for moderately and heavily congested networks. That is due to the fact that with increasing congestion, overall reception rates decreases such that sending packets to more than one forwarder becomes more efficient. Thus, higher end-to-end delivery rates are possible with multi-link forwarding rather than single-link strategies. However, in both cases the overall delivery rate decreases if the network becomes more congested.

Concerning energy efficiency, Multi-Link EEF again achieves the best results among all forwarding strategies (see Figure 7(b)), followed by Single-Link EEF, MT, Optimal Hop-based Forwarding, and PRR-based Forwarding. Due to retransmissions, the energy efficiency for $\rho = 0$ is higher than in Figure 6(b). We will see in the next section how the number of retransmissions influences the delivery rate and energy efficiency.

C. *Packet Retransmissions*

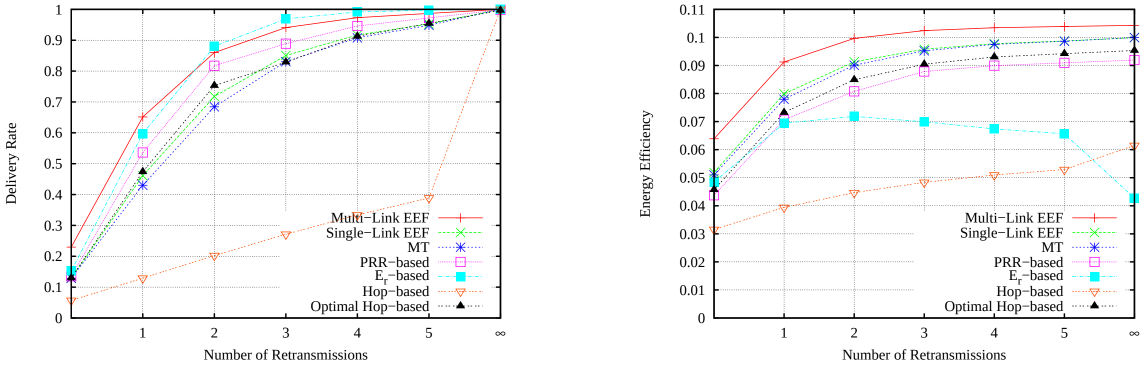
With increasing retransmissions, the packet reception rate on links increases, too. That is, for $R \to \infty$, we get $E_r \to \infty$. If we take a look at the energy costs, E_e converges against the ∞-retransmission case analyzed in Section V-A. However, the energy efficiency as the ratio of delivery rate and energy costs seems to be independent from R, i.e., Equation 11 resp. 14 show no direct dependency on R. Therefore, we would expect that with increasing R, the delivery rate for all forwarding strategies increases whereas the energy efficiency remains unaffected.

In Figure 8(a), the delivery rate vs. number of retransmissions is plotted. We simulated retransmissions ranging from 0 to 5, and in addition the ∞-retransmission case. Furthermore, we set a network congestion factor of $\rho = 0.2$ so that we can better observe the performance increase for different retransmissions and forwarding strategies. As expected, increasing the number of retransmissions improves the delivery rate considerably. Except for simple Hop-based Forwarding, all forwarding strategies



(a) Delivery Rate (b) Energy Efficiency

Fig. 7. Influence of Different Contention Probabilities on Delivery Rate and Energy Efficiency ($Density = 20$, $R = 3$)



(a) Delivery Rate (b) Energy Efficiency

Fig. 8. Influence of Retransmissions on Delivery Rate and Energy Efficiency ($Density = 20$, $\rho = 0.2$)

achieve delivery rates above 80% for at most three retransmissions. Moreover, we can conclude that more than five retransmissions only slightly improves the delivery rate.

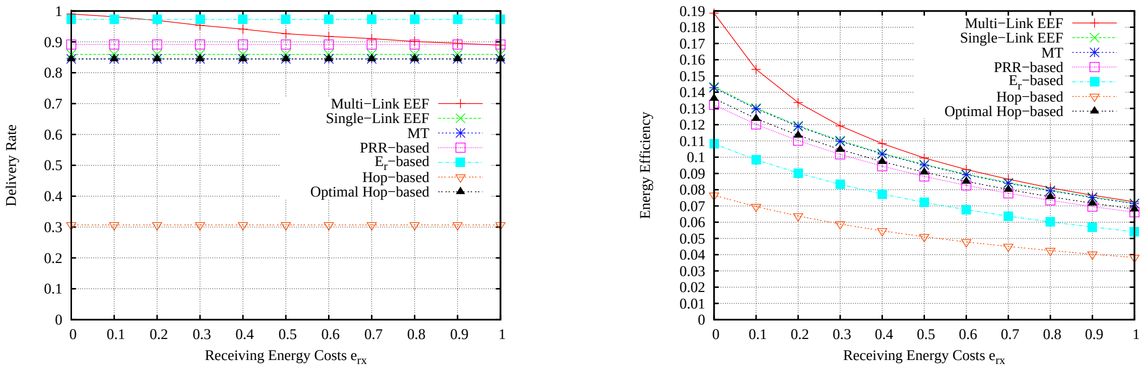
Figure 8(b) depicts the energy efficiency vs. number of retransmissions and shows that the energy efficiency remains not constant with increasing R. That is, E_{eff} is apparently not independent of R. Equations 11 and 14 show how the delivery rate E_r^i and energy costs E_e^i of forwarding node i influence the energy efficiency. Since both E_r^i and E_e^i depend on R (see Equations 10+13 resp. 9+12), E_{eff} is effected by it indirectly, too. Thus, the energy efficiency changes with increasing R.

Except for E_r-based Forwarding, the energy efficiency improves with increasing R because of significant increases in the deliver rate. However, more than five retransmissions could only improve the energy efficiency of simple Hop-based Forwarding significantly. That is due to the fact that for all other forwarding strategies, the delivery rate already reaches almost 100%. Thus, a higher upper bound does not further affect forwarding paths since more retransmissions are not required in the majority of cases. In contrast to this behavior, the energy efficiency for E_r-based Forwarding decreases. Since this strategy always selects nodes with the best delivery rates, increasing the number of retransmissions also increases the number of potential forwarders. Thus, due to better delivery rates, longer paths are taken into account, too. Because of these paths the number of required transmissions increases disproportionately, maximizing E_r achieves the worst energy efficiency.

D. Receiving Energy Costs

Receiving energy costs e_{rx} only affects Multi-Link EEF since it exploits the broadcast characteristics of the wireless medium in such a way that it sends data packets to more than one neighbor, among which one forwarder is selected afterwards. Thus, energy costs for receiving a packet influences the efficiency of the forwarding strategy and also the number of potential forwarders. But even for quite high receiving costs, sending data packets to more than one node might be advantageous because of higher delivery rates, as we have seen in Section V-A.

It is therefore interesting how Single-Link and Multi-Link EEF compete against each other for different receiving costs. Figure 9(a) shows the delivery rate vs. receiving energy costs e_{rx} (as a fraction of sending costs e_{tx}).



(a) Delivery Rate

(b) Energy Efficiency

Fig. 9. Influence of Receiving Energy Costs on Delivery Rate and Energy Efficiency ($Density = 20$, $\rho = 0.2$, $R = 3$)

Of course, all single-link forwarding strategies are not affected since forwarding paths are not changed. However, with decreasing e_{rx} it becomes more efficient to exploit the possibility of more potential forwarders. Thus, Multi-Link EEF could increases the end-to-end delivery. On the other hand, for high e_{rx} values, the delivery rate decreases almost to the rate achieved by Single-Link EEF which is always a lower bound. So in this case, Multi-Link EEF mostly reduces its forwarding set to only one forwarder. However, some cases remain in which nodes exhibit very poor links, such that the delivery rate could be improved by using a multi-link forwarding strategy.

Inspecting the energy efficiency that is depicted in Figure 9(b) leads to the same conclusion. Low energy costs for receiving packets prefer forwarding strategies that broadcast to a potential forwarder set instead of a single forwarder. While the delivery rate could be improved in any case, the energy efficiency will also increase due to better packet delivery and fewer retransmissions.

VII. EXPERIMENTAL EVALUATION

A. The Embedded Sensor Board

For our experimental evaluation we used the Embedded Sensor Board (ESB) developed by the Free University Berlin [22]. The ESB runs at 8MHz and contains 64kB of memory. Most of the 64kB are implemented as flash memory which will contain the software and all constant data. The RAM occupies only 2kB, which is a fairly limited amount of space for dynamic data.

Table I shows typical energy consumptions for an ESB sensor node. When a node operates in its basic mode (processor and all sensors switched on), it consumes about 1500 times more energy than in sleep mode. Sending can again double the amount of energy while receiving increases it only by 1/3. So in order to save most of the available energy, all nodes should switch to the sleep mode whenever possible.[1] According to Table I, the receiving costs can then be expressed by $e_{rx} = 0.375$, normalized with respect to $e_{tx} = 1$.

P_{CL}	12.0mA	basic energy consumption
P_{TX}	12.0mA	energy consumed for sending
P_{RX}	4.5mA	energy consumed for receiving
P_{SL}	0.008mA	total energy needed in sleep mode

TABLE I

TYPICAL ENERGY CONSUMPTIONS FOR THE ESB SENSOR NODES

For wireless communication, a TR1001 radio transceiver is used. It sends at about 1mW in the best case but can be powered down to zero in 100 steps. The range depends heavily on the environment and can range from several 100 meters outdoors to less than 100 meters. The data rate is 19,200 baud/s. However, since each bit will be Manchester encoded, the effective data rate is 9,600 bit/s only.

B. Experimental Setup

Figure 10 shows our testbed consisting of 20 sensor nodes that were used for real-world experiments. While one node acts as a sink (indicated by a green circle in Figure 10), all other nodes send data packets to this sink according to the selected forwarding strategy. The transmission power was set to 12to limit the range of communication. With that setup, perfect as well as lossy links exist in the network, while being fully connected.

In order to establish link loss estimates, each node first sends out 100 ping packets while all other nodes are listening and log the number of properly received packets. To provide a fair comparison among the different forwarding

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[1] It should be kept in mind that the ratio between energy consumption for sending and receiving can differ on other platforms. However, the sleeping mode always requires the least amount of energy.

Fig. 10. Experimental Testbed Consisting of 19 Data Gathering Nodes and one Sink Node (indicated by the green circle)

strategies, the same set of loss estimates is used for all strategies.

The forwarding tables are built up by a beaconing process that continues until all forwarding paths are stable. Beacons contain a node's neighbortable (node identifier and directed link quality) and the currently best forwarding settings, e.g., E_{eff} for Multi-Link EEF or the hop counter for Hop-based Forwarding. As an example, Figure 11 shows the forwarding paths for the Multi-Link EEF strategy.

Once the beaconing process is finished, each node sends 25 data packets with a size of 64 bytes every three seconds to the sink node. The number of retransmissions was set to three. The forwarding is done according to the strategy that should be evaluated. In order to compute the node's energy efficiency, all nodes being involved in packet forwarding will log the number of received and sent packets.

C. *Results*

Table II gives an overview of all experimental results. For each forwarding strategy, a node's average end-to-end delivery rate E_r, the required end-to-end energy E_e, its energy efficiency E_{eff}, and the average number of received and sent data packets required (rx and tx) are given. Each experiment was repeated three times.

With an energy efficiency of 0.0056, Multi-Link EEF achieves the best result, followed by the Single-Link EEF and MT forwarding strategy. Even if the network was limited in size, this gives us a proof-of-concept for our energy-efficient forwarding schemes.

If we take a closer look at the number of sent and received data packets, we can see how Single-Link EEF and Multi-Link EEF differs from each other. As in Single-Link EEF packets are addressed to just one forwarder, the average number of received packets rx is lower than in Multi-Link EEF. Concerning the number of sent packets tx, Multi-Link EEF can benefit from its multi-link concept and forward packets faster than Single-Link EEF. However, in some cases this led to longer forwarding paths, increasing the probability that packets get lost.

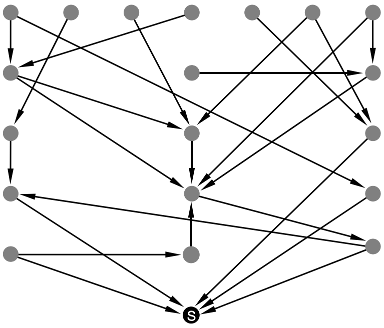

Fig. 11. Example of Forwarding Paths used in the Multi-Link EEF Scheme

Strategy	E_r	E_e	E_{eff}	tx	rx
Multi-Link EEF	0.58	116.18	0.0056	97.73	49.20
Sinlg-Link EEF	0.60	118.37	0.0054	103.40	39.93
MT	0.57	125.58	0.0048	114.33	34.00
PRR-based	0.58	143.51	0.0046	122.93	54.87
E_r-based	0.41	167.66	0.0026	145.73	58.47
Hop-based	0.26	105.75	0.0027	98.78	18.57
Simple Hop-based	0.18	114.43	0.0016	109.33	13.60

TABLE II

EVALUATION RESULTS OF DIFFERENT FORWARDING STRATEGIES

Actually, E_r-based Forwarding should achieve the best end-to-end delivery rates. However, although theoretically optimal, it suffers from longer forwarding paths in practice. Since data packets are issued every three seconds, it is possible that packets sometimes collide or forwarding nodes get congested due to retransmissions and rivaling packets. That is also expressed by the node's overall energy E_e required for packets to reach the sink, which is the highest for E_r-based Forwarding.

As expected, simple Hop-based Forwarding performs worst since forwarders are selected independently to their link quality and we did not implement any blacklisting techniques.

VIII. CONCLUSION AND FUTURE WORK

This paper describes different forwarding strategies for many-to-one communication with several sensor nodes reporting data to one sink node. Considering two performance metrics, delivery rate and energy efficiency, we have analyzed the influence of the node density, the network congestion, the number of provided retransmissions, and the amount of energy required for packet receiving. Focusing on energy efficiency, we have developed two forwarding strategies that perform best among a variety of other forwarding schemes, especially the widely proposed strategy of using a minimizing transmission metric. We summarize the main contributions of the paper as follows:

- Proposal of two forwarding strategies that aim at maximizing energy efficiency: Single-Link and Multi-Link Energy-Efficient Forwarding.
- A mathematical derivation of optimal energy costs and efficiency for both strategies.
- The concept of multi-link packet forwarding that further improve the energy efficiency as compared to the single-link scheme.
- Simulations that show the impact of different network settings on delivery rate and energy efficiency for a comprehensive framework of forwarding schemes.
- Real-world experiments that provide a proof-of-concept and indicate how forwarding schemes work in practice.

For future work, we plan to extend Single-Link and Multi-Link Energy-Efficient Forwarding by considering the network lifetime, too. By taking the amount of remaining energy into account, that would prevent nodes from using the same path permanently and increase the lifetime of frequently used nodes.

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