Trusted Routing for Resource-Constrained Wireless Sensor Networks

Khaled Daabaj, Mike Dixon, Terry Koziniec, Kevin Lee
School of Information Technology, Murdoch University, Perth, WA 6150, Australia
{k.daabaj, m.dixon, t.koziniec, kevin.lee}@murdoch.edu.au

Abstract—**Designing a reliable and trusted routing scheme for resource-constrained Wireless Sensor Networks (WSNs) is a challenging task due to the lack of infrastructure and the highly dynamic network topology. To ensure trustworthy end-to-end communications between wirelessly connected sensor nodes, a considerable amount of bidirectional traffic must be relayed either between neighboring sensor nodes or between source sensor nodes and the base station. Such scenarios may lead to an added routing overhead, higher energy depletion rate and network life time minimization. The existing trusted routing protocols focus on trusted data dissemination while lacking the consideration of the restricted resources of sensor nodes and low-power radio link failures. To solve this problem, we propose a reliability-oriented routing scheme that takes into account the link reliability and residual energy of sensor nodes, thus allowing for better trustworthy data exchange, traffic balancing and network lifetime extension. Based on real testbed experiments and large-scale simulations, the attained results show the benefits stemming from the adoption of our scheme to be a reliable and energy efficient data delivery platform for potential trusted data exchange models. Our results show that the scheme is able to reduce energy consumption without affecting the connectivity of the network.**

Keywords-wireless sensor networks; reliable routing; energy awareness; real-time packet encapsulating.

I. INTRODUCTION

Sensor nodes in Wireless Sensor Networks (WSNs) are mainly battery operated and have limited energy and processing capabilities. In order for large deployments to be cost-effective, sensor nodes are resource-constrained in terms of energy capacity, radio transmissions, processing capabilities, and memory storage [18]. A reliable data delivery and energy efficiency play a key role in WSN research. Many protocols have been proposed to provide energy efficiency and reliable data transfer of packets in WSNs [19]. However, the main drawbacks of the existing trusted routing protocols for WSNs are that they are unaware of the communication patterns and the energy status of relay sensor nodes and they do not explicitly pursue balanced energy usage in their routing schemes. This results in the arbitrary routing of traffic to sensor nodes with potentially low energy capacity. This significantly reduces the life time of these sensor nodes and can adversely affect the entire WSN. This paper focuses on a reliable delivery of data that can be ensured through the careful selection of error free links, rapid recovery from packet loss and the avoidance of overloaded relay sensor nodes. Since link failure and packet loss are unavoidable, sensor networks must tolerate a certain lack of reliability without a significant effect on packet delivery performance, data aggregation accuracy or energy consumption. In this paper we present an effective hybrid approach that minimizes the tradeoff between energy, reliability, cost and agility. Our scheme adaptively reduces control traffic in favor of a metric that measures the reception success ratio of representative data packets. Based on this approach, the proposed routing scheme can achieve moderate energy consumption and high packet delivery ratio even in environments featuring high link failure rates.

II. RELIABILITY AND ENERGY EFFICIENCY

Densely deployed WSNs consist of a large number of sensor nodes in the areas of interest. Once the data of interest is detected, sensor nodes generate packets and forward them to the base station based on multihop routing through neighboring nodes. This clearly shows the need for a reliable data transport in error prone nature of WSNs. In the literature, enormous number of routing protocols has been proposed to provide reliable data delivery [1,2,19]. Although the majority of these proposed protocols achieve a higher packet delivery ratio in the network, performance of such protocols has not been investigated under interference-prune network scenarios [3]. In addition, they do not support end-to-end reliable data delivery [4,17]. On the other hand, as nodes in WSNs are battery operated, it is not practically feasible to frequently replace the batteries. Energy consumption needs to be minimized in order to prolong the network lifetime. There have been many protocols proposed for energy efficiency [5,6,19,20]. However, these protocols still suffer from high energy consumption due to continuous polling and require extra transmission and retransmission to cope with the frequent link failures [19].

Although the authors of the aforementioned protocols claim to achieve reliable data delivery and energy efficiency, large-scale simulations results were not provided to validate their experimental results or vice versa. Also such protocols were not well investigated in the real-time context [19].

III. TRUSTWORTHY ENERGY EFFICIENT ROUTING

The proposed solution considers both characteristics of resource limitations and communication patterns in favour of reliable and energy-efficient data dissemination. The work here is built on our existing reliable load-balancing routing (RLBR) scheme stated in [7,8,9], and extending the experiments to include an outdoor sensor network testbed comprising interference-prone channels, and large-scale simulations to validate these experiments.

A. *Minimizing Packets Transmissions*

Since all sensor nodes in the sensor network have the chance to participate in relaying data packets in a multihop fashion, this routing participation requires a given number of transmissions. Hence, the routing scheme should minimize these transmissions to improve the *energy-efficiency* and *cost-effectiveness* of low-power, duty-cycled WSNs. Therefore, aggregating smaller, relayed, data packets into larger encapsulated packets bounded by the maximum packet data unit could significantly minimize the number of packet transmissions and improve energy savings. However, in real-time applications, these encapsulated data packets vary in their deadlines and sensitivity to end-to-end delay. These deadlines are governed by the importance of the sensing measurements. The average *end-to-end delay* is the sum of all *single-hop* delays along the selected route r_j. Due to in-flight aggregation, encapsulated data packets tend to be delayed at each intended relaying sensor node waiting to be encapsulated with other arriving or locally generated data packets for a given holding time Δt_{enc} . This time is known as the *per-relay encapsulating delay*. In this case, the *average* (n_i*-to-b*) *end-to-end delay* $\Delta t_{ni,rj,b}$ is estimated in-flight on route r_j between sensor node n_i at the point of data encapsulation and the base station *b* by summing the individual delays as stated in [10]. However, the total accumulated *per-relay encapsulating delay* including propagation on route r_j must not exceed the remaining time Δt_{left} which is the time left before the associated real-time deadline $t_{deadline}$ expires. In other words, *per-relay encapsulating delay* Δt_{enc} needs to be bounded in order to avoid missing the application-specific packet delivery deadlines. If a data packet arrives at relay sensor node n_i at a time t_{arrive} to be aggregated with other data packets, Δt_{enc} must be bounded and the encapsulated packet sent at an appropriate release time $t_{release}$. Subsequently, this dispatched, encapsulated, data packet might also be re-encapsulated on further hops and Δt_{enc} must permit receipt withinthe packets delivery deadlines. In the case where $\Delta t_{enc} \leq 0$, $\Delta t_{ni,rj,b}$ is negative and the arriving packet must be relayed immediately without encapsulating delay. In other cases the arriving packet can be delayed for Δt_{enc} as expressed in equation 1. Since the packet encapsulates more than one data element over the route of *N-i* relay sensor nodes, the encapsulated packet at relay node n_i must be dispatched once either sensor node n_i reaches its memory limit or one of these packets reaches the end of its minimum dispatch time *min*($t_{release}$). This time must satisfy the accumulated condition in equation 2 over a route of *N-i* sensor nodes.

$$\Delta t_{enc} = \Delta t_{left} - \Delta t_{n_i, r_j, b} \tag{1}$$

$$\sum_{k=i}^{N} [\min(t_{release_k}) - t_{arriving_k}] \leq \sum_{k=i}^{N} \Delta t_{enc_k} \tag{2}$$

B. *Estimating Energy Depletion Rate*

To consider the benefit of energy balancing of the proposed routing scheme, it is instructive to allow gauging of the energy discharge behavior in terms of energy depletion rate $R(e_{ni})$ of sensor node n_i. The total residual energy capacity of a sensor node's battery e_{ni} is divided into *energy levels*, and at the beginning it is assumed that the initial energy capacity "*init_e*$_{ni}$" of all sensor nodes are identical. If sensor node n_i transmits, receives or overhears packets, its energy capacity decreases to lower levels according to the current consumption model of the mote system. The energy depletion rate $R(e_{ni})$ at which the residual energy capacity e_{ni} of node n_i is reduced can be expressed in equation 3 which is only valid for $t_{ni,r,ni+1} > 0$. Where $t_{ni,r,ni+1}$ is the time spent for sensor node n_i for transmitting or forwarding this packet to node n_{i+1} over route *r*. Assuming that transmitting time equals receiving time for packets of the same size, $t_{ni,r,ni+1}$ is also identical to the time spent for node n_i for receiving or aggregating a packet from node n_{i-1}. $R(e_{ni})$ is measured in *energy unit per second*.

$$R(e_{n_i}) = \frac{\left((P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_{i-1},r,n_i} \times e_{n_i})_{rx}\right)}{t_{n_i,r,n_{i+1}}} \tag{3}$$

Consequently, from an energy efficiency point of view, the *functional lifetime* T_{ni} of an individual sensor node n_i, in which sensor node n_i can participate in constructing the route *r* with sufficient energy, is obtained by dividing the initial energy capacity level (*init_e*$_{ni}$) by *energy depletion rate* $R(e_{ni})$ as in equation 4.

$$T_{n_i} = \frac{Initial\ energy\ capacity\ level}{Energy\ depletion\ rate} = \frac{init\_e_{n_i}}{R(e_{n_i})} \tag{4}$$

Given these assumptions, the maximum relay sensor node's lifetime T_{ni} is achieved by minimising $(1/T_{ni})$ given in equation 5. Logically the maximum lifetime of a given route *r* is determined by the weakest intermediate or relaying sensor node, which is that with the highest cost. While $P_{ni,r,ni+1}$ is the probability of forwarding a packet to the next hop n_{i+1} through the route *r*, $P_{ni,r,ni-1}$ is the probability of receiving a packet from node n_{i-1} through the route *r*. Hence, $R(e_{ni})$ is a *bidirectional function* of the energy expenditure for relaying the projected network traffic by receiving and transmitting packets at a given energy depletion or dissipation rate of $(P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx}$ and $(P_{n_i,b,n_{i-1}} \times e_{n_i})_{rx}$ respectively.

$$\frac{1}{T_{n_i}} = \frac{R(e_{n_i})}{init\_e_{n_i}} = \frac{\left((P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_i,b,n_{i-1}} \times e_{n_i})_{rx}\right)}{init\_e_{n_i} \times t_{n_i,r,n_{i+1}}} \tag{5}$$

Similarly, for a wireless sensor network of *m* sensor nodes, where every sensor node has *k* available routes towards the base station, the entire network's functional lifetime T_{WSN} can be maximized by minimising the reciprocal of the *functional lifetime* of the entire network which is given in equation 6.

$$\frac{1}{T_{WSN}} = \frac{1}{init\_e_{n_i}} \sum_{j=1}^{k} \sum_{i=1}^{m} \left(\frac{(P_{n_i,r_j,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_i,r_j,n_{i-1}} \times e_{n_i})_{rx}}{t_{n_i,r_j,n_{i+1}}} \right) \tag{6}$$

C. Minimizing the Variance in Energy Levels

In the initial stages of parent selection process, sensor nodes with the best *link reliability probability* $P_{ni,r,ni+1}$ are considered first based on link quality estimated values, whereas sensor nodes with the highest residual energy capacity levels are considered afterwards. Thus, a parent is selected if it offers a reliable route, but when the traffic load, e.g., aggregated or relayed load, increases, the remaining battery capacity of each sensor node is also accounted as the second prime metric in the parent selection process to construct routes along which all sensor nodes have the actual available battery capacity levels exceeding a given threshold. The cost function selects the route that requires the lowest energy per bit. If there is no such route, then it picks that route which maximizes the minimum battery level by utilizing the principle of max-min cost function of the *Conditional Max-Min Battery Capacity Routing* (CMMBCR) stated in [11]. To ensure a longer network lifetime, the strategy of minimizing the variance in energy capacity levels is employed to dissipate up all batteries powers uniformly to avoid some nodes suddenly running out of energy and disrupting the network. Hence, routes should be chosen such that the variance in battery levels between different routes is reduced. However, few energy levels leads to a low performance in energy balance, for instance, if there is only one energy level, then all routes will use this only energy level for all times and the most reliable route will be used frequently until it is exhausted. From energy cost point of view, the residual energy capacity level e_{ni} sensor node n_i defines the refusal or readiness of this node to respond to route requests and forward data traffic. The maximum lifetime of a given route is determined by the weakest intermediate sensor node, which is that with the highest cost.

D. Link Reliability

In *route maintenance phase*, the value of routing metric is to be used first from the routing table, and then to select a valid parent on a route r_j from multiple available routes according to the metric values. Based on link reliability as a primary cost metric, it can be assumed that a given number of sensor nodes are distributed arbitrarily and each node n_i sends a packet at a given transmitting power $P^{tx}_{n_i,r_j,n_{i+1}}$ and has a multihop route r_j of $hc_{ni,rj,b}$ hops to the base station *b*. $hc_{ni,rj,b}$ is the hop count of the route r_j between n_i and *b*, which is greater than or equal *zero*. If sensor node n_i can't reach the base station *b*, $hc_{ni,rj,b}$ is set to *infinity*. In view of that, the likelihood of relaying a packet originated at node n_i is expressed in equation 7, which is the *probability* $P_{ni,rj,b}$ of relaying a data packet towards the base station *b* through the selected route r_j. Where $lq_{ni,r,ni+1}$ is the link quality between sensor node n_i and its current parent (upstream neighbor node) n_{i+1} along route r_j. In other words, $P_{ni,r,b}$ counts for the readiness of node n_i of forwarding a packet based on its residual energy capacity level e_{ni} and link quality $lq_{ni,r,ni+1}$ to its intended upstream neighbor node n_{i+1} that receives the packet and relay it towards the base station *b*.

$$P_{n_i,r_j,b} = \begin{cases} \prod_{hc_{n_i,r_j,b}} P_{n_i,r_j,n_{i+1}}(lq_{n_i,r_j,n_{i+1}}, P^{tx}_{n_i,r_j,n_{i+1}}), & 0 < hc_{n_i,r_j,b} < \infty \\ 0, & hc_{hc_{n_i,r_j,b}} = \infty \\ 1, & hc_{hc_{n_i,r_j,b}} = 0 \end{cases} \tag{7}$$

In case the base station is unreachable, $P_{ni,rj,b}$ is approaching zero as the cost or route r_j in terms of hop count $hc_{ni,rj,b}$ is perpetuating to infinity. Otherwise, $P_{ni,rj,b}$ is normalized to one and the cost $hc_{ni,rj,b}$ is zero; this means that no packets are being sent or relayed by sensor node n_i.

IV. EVALUATION SETTINGS

In this section we evaluate our protocol, using testbed experiments as well as simulation. The experiments were conducted using 30 Crossbow TelosB motes (TPR2420CA) [12] running the TinyOS-2.x [13]. The TelosB combines a low-power 8MHz MCU with 10kbytes RAM, integrated antenna and an IEEE 802.15.4–compliant CC2420 RF transceiver chip [21]. The CC2420 provides the data link layer and offers a data rate of up to 250kbps. The TelosB operates within the 2.4GHz ISM band and employs the OQPSK modulation scheme. The interested reader should consult [12,14] for more details about TelosB-2.4 GHz platform which is designed for low-power WSNs. The TelosB motes are deployed randomly and commence transmitting with the same residual power capacity using fresh AA batteries. The only exception is the base station which is powered via a USB port on a laptop running Linux. This acts as a bridging device that has IEEE802.15.4 coordinator functionality [21].

The simulated network is composed of a 100 static sensor nodes uniformly deployed and arranged in a square sensor field of 10x10 grid with uniform 10m spacing between motes and a single stationary base station deployed at one corner to ensure a deep routing tree. IEEE 802.15.4 is used as the MAC and physical layer protocol with bandwidth of 250Kbps, consistent with our experimental parameters. The wireless medium is simulated in ns-2 using the multipath shadowing propagation model [15] as it characterizes the realistic propagation behavior of an outdoor environment. The energy consumed for communications are measured by implementing the ns-2 radio energy model configured with power parameters matching those of the Chipcon 2.4GHz CC2420 [21]. At the beginning of each simulation, each sensor node is assigned with the same initial energy level. The base station features a persistent energy supply as is usually the case in real WSN applications. Our routing scheme is evaluated experimentally and using large-scale simulations and compared to TinyOS-2.x MultihopLQI protocol [13,16]. As the simulation part is still in progress, few simulation results are presented here in terms of different numbers of source nodes between 30 and 70. Evaluation metrics include network connectivity, to assess the significance of wireless link reliability on packet loss probability; average end-to-end delay in terms of delivery rate; average dissipated energy and network lifetime.

V. PERFORMANCE EVALUATION RESULTS

A. Experimental Testbed Results

1) Network Connectivity: Packet loss in WSNs typically depends on complex set of parameters, including the location of each sensor nodes in relation to the base station, spacing between sensor nodes, gain of mote's antenna, the environmental conditions that affect the quality of the channel, and the number of hops traversed that the packet must travel along to be delivered successfully towards the base station. Figure 1 shows that selected relay nodes along the routing path that can send directly to the base station have different packet loss readings, which depend on their distances and locations in relation to the base station. To keep the results independent of the transmitting power, the results are averaged for many runs with the lowest transmitting power output of -20dBm and various distances, i.e., 1, 2, 3, 4, 5 meters, between the base station and the last hop sensor nodes that can send directly to the base station. It can be observed that our scheme can choose the most reliable relay sensor node with the lowest packet loss ratio. However, the effective relay selection approach used by our routing scheme could lead to additional computation overhead. Conversely, MultihopLQI depends only on individual link quality values that are provided by physical layer of the RF transceiver. This could yield parent sensor nodes with higher packet reception loss of more than half of the transmitted packets towards the base station due to asymmetric links problem and poor connectivity. This higher per-hop packet loss causes MultihopLQI to increase packet retransmissions to deliver the packet successfully towards the base station; thereby resulting in larger amount of energy expenditure.

TinyOS-2.x MultihopLQI uses only link quality information at the physical layer of each beacon individually. This pure reliance on one form of channel state information (CSI) leads MultihopLQI to inappropriately react with the asymmetric links which is a typical feature of low-power WSNs [17]. The proposed solution (RLBR) solves the asymmetric link problem by taking the average of the link quality values to provide better packet delivery ratio estimations. It also uses bidirectional link estimations based on required retransmissions for active bidirectional monitoring of link status. This allows the proposed solution to properly switch to alternate parents when exceeding a threshold of maximum transmission failures. As illustrated in figure 2, with the MultihopLQI protocol, sensor node 1 chooses sensor node 4 as its parent, but it never recieves acknowledgement packets back from node 1. This is a result of an asymmetric link between 1 and 4 that makes node 4 unreachable for node 1's packets. To solve this problem using averaged link quality values, sensor node 1 will switch to an alternate neighboring node. For example, node 2 becomes a valid parent after the maximum transmission failure threshhold is exceeded due to link asymmetry and transmission range. The proposed routing protocol builds its multihop route in the deployed topology in terms of end-to-end delivery delay and hop count (*hc*). During the beginning of the transmission or epoch, the proposed routing protocol has a slightly higher delivery delay due to the overheads of route configuration. However, it immediately improves the packet delivery performance with lower retransmissions and much lower control packet rate. As a result, the end-to-end packet delay decreases gradually despite traversing a longer route.

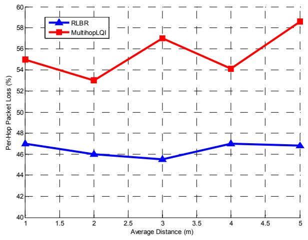


Figure 1. Network Connectivity

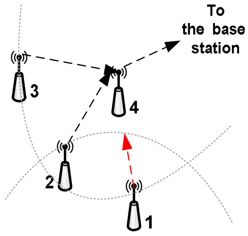
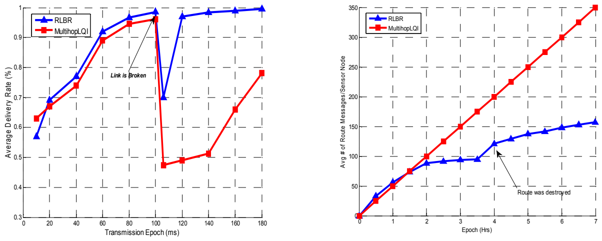


Figure 2. Asymmetric Links

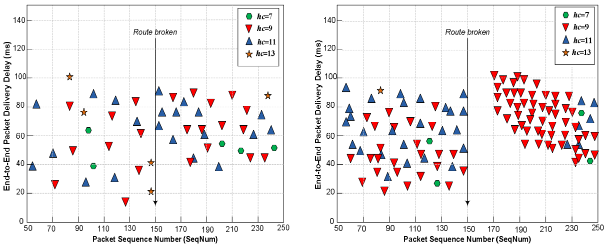
2) Average End-to-End Packet Delivery Performance: The proposed routing protocol provides a faster recovery from the broken links due to the hybrid approach utilizing backup neighboring routing tables. This can be seen in figure 3 (a) when a link is broken at 100ms after the transmission time. Once an alternative energy-efficient and reliable route is established, using consecutive repair phases, the average end-to-end delay decreases considerably. Consequently, the average throughput is improved even though the number of hops has increased, which may affect the timeliness of data packets. This chosen, reliable, route requires a lesser number of retransmissions to successfully deliver a data packet at an average delivery rate of 99.6% after 40ms from the time at which the route was broken compared to the benchmark, MultihopLQI which provides an average delivery rate less than 78% after the same epoch. Progressively, the RLBR achieves a higher delivery rate. Conversely, MultihopLQI begins with a higher delivery rate and initially achieves a lower average end-to-end delivery delay. This is because the route configuration start-up time required by the RLBR for updating routing tables and the parent selection process takes some time. As MultihopLQI maintains only a state for one parent node at a time , neither routing tables nor blacklisting are used. However, this results in the additional energy cost associated with the significantly increased packets retransmissions required to successfully deliver a data packet. In view of the cost of beaconing route messages, e.g., control packets, over long run of few hours, the beaconing rate is adaptive on a per sensor basis. It starts with a slightly high rate in the RLBR at the beginning due to the rapid establishment of the routing tree then begins to decrease and stabilizes at a lower rate. Figure 3 (b) illustrates, on hourly basis, the average number of route messages that were transmitted per sensor node in order to build and maintain the routing tree. The message beaconing pattern in the RLBR is slightly raised at the fourth hour due to an intentional link failure This failure was introduced to demonstrate the rapid reconstruction of an alternative, but longer, route.. Once again it adaptively embarks on a steady rate pattern in order to become stable eventually. By comparison, MultihopLQI avoids routing tables by only maintaining a state for the best parent sensor node at a given time It keeps transmitting control beacons at a constant rate of 30 beacons per second, considerably higher than RLBR. This rate increases linearly over long periods.



a. Delivery Rate vs. Link Failure b. Control Overhead

Figure 3. Packet Delivery Performance

In order to jointly evaluate the reliability and delivery performance of the routing scheme, a number of intermediate wireless sensor nodes were switched-off or removed to create broken routes between source sensor nodes and the base station. Figures 4 (a) and (b) illustrates the end-to-end delivery performance of RLBR and MultihopLQI respectively in terms of end-to-end delay and hop count when a route is broken after packet number 150. The RLBR reacts efficiently and responds swiftly to recover from a broken link along the preselected path. It maintains an alternative, energy-efficient and reliable route to recover. This route reconfiguration time is 66.40ms. This newly constructed route is used temporarily as a backup route to deliver source-originated data packets in a timely manner towards the base station. However, the alternative route may require additional hops, leading to an increase in the average end-to-end packet delivery delay. In this case it is slightly increased to 81.32ms. In contrast, MultihopLQI is incapable of rapidly recovering from broken routes if a wireless mote on a preselected route is removed. Even though MultihopLQI results in a shorter average end-to-end delay for packet delivery of about 78.43ms, recovering from the broken route takes a much longer time (98.52ms). Overall, MultihopLQI lacks stability, frequently restructuring its routing tree in response to changes in its LQI, hardware-based, reliability metric. Although MultihopLQI did recover from link failure, its delivery ratio was noticeably reduced after a shorter time. This leads to a lower average packet delivery rate for MultihopLQI as compared to the RLBR, validating the earlier results shown in figure 3 (a).



a. Proposed Scheme b. TinyOS Collection Layer

Figure 4. Recovery from Broken Links

3) Packet Delivery Cost: Using the MultihopLQI protocol, sensor nodes broadcast control packets at a constant rate. In terms of energy, non-adaptive high rate beaconing expends more energy for unnecessary transmissions in conditions requiring infrequent topological changes. In addition most relayed packets are routed through optimal routes based mainly on link quality. As a result, the selected route will be used frequently and the sensor nodes along this route will be exhausted quickly. This leads to an imbalance in the energy utilization throughout the entire network. Compared to MultihopLQI, RLBR makes trade-offs between routes based on link reliability and energy efficiency in favour of a more even distribution of forwarded packets among the relaying sensor nodes. In addition, RLBR broadcasts fewer route messages over the life of the network. As a result, RLBR consumes only about 35% of the energy required for route message transmissions as compared to MultihopLQI. To estimate the average amount of energy consumed by relay sensor nodes for delivering a data packet towards the base station, the packet delivery cost is used as a routing overhead metric. This cost metric accounts for the ratio of the total number of control and data packets to the total number of data packets received at the base station. On average, RLBR achieves higher delivery efficiency while incurring a significantly lower control overhead than that of MultihopLQI.

B. Latger-Scale Simulations Results

1) Functional Network lifetime: Using simulations of a larger network featuring 100 sensor nodes with a range of source nodes between 30 and 70 in number, our proposed scheme balances the energy consumption and keeps updating energy efficient routes. In general, figure 5 shows that the network lifetime declines as the number of deployed sensor nodes increases, due to the high volume of control and data packets that are retransmitted throughout the sensor network. Compared with MultihopLQI, the use of RLBR results in a slower and a more graceful linear degradation of the network lifetime. This leads to a substantial improvement in the expected life of a WSN when implemented using RLBR. Despite, MultihopLQI's occassional ability to balance the traffic load based on link quality estimates, the large numbers of redundant packet copies that are retransmitted between different sensor nodes depletes the available energy more rapidly. To this end, the simulation results agree with the assertion made earlier that the proposed scheme can reduce the energy consumed for transmissions and maximise the network lifetime.

2) Average Dissipated Energy: Figure 6 illustrates the relationship between the average dissipated energy during network operation and the number of source nodes at which data traffic is generated. As an overall trend it can be seen that the averaged dissipated energy by the sensor nodes in all routing schemes has an increases with the number of source nodes. Compared with MultihopLQI, the proposed routing scheme performs favourably with energy consumption increasing linearly with the number of source nodes. In contrast, MultihopLQI dissipates more energy for the same number of source nodes and the energy dissipation increases considerably as the number of generating nodes grows. This suggests that RLBR is capable of supporting larger WSN's than MultihopLQI.

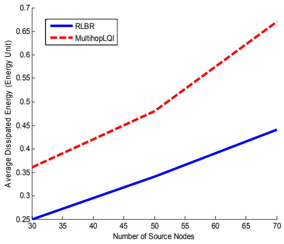


Figure 5. Energy Depletion

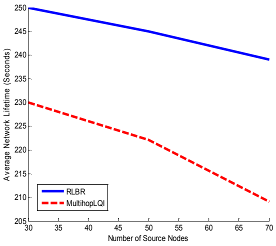


Figure 6. Network Lifetime

VI. Conclusion and Future work

In this work, a reliability-oriented routing scheme is proposed based on per-hop energy balancing and probability network connectivity. The results show that it leverages recent advancements over the standard network layer components provided by the TinyOS2.x. The proposed routing scheme consumes less energy while reducing topology repair latency and supports various aggregation weights by redistributing packet relaying loads. It also provides an adaptive control protocol rate that responds to fluctuations in network connectivity and energy expenditure. From a reliability viewpoint, it creates a routing tree using estimated numbers of transmissions and retransmission to the base station and link quality estimations based on numbers of successfully received packets. Our routing scheme performs well with a high success rate of packet delivery and moderate energy consumption. While the experiments conducted here have highlighted the substantial performance gains of the proposed solution, our ongoing work aims to further validate the performance of our routing scheme through the inclusion of other routing metrics in favor of trustworthy data delivery.

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