Energy-Efficient Multiple-Metric Data Delivery for Wireless Sensor Networks

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ABSTRACT: *.Due to limited resources of individual senor nodes, there is usually a trade-off between energy spending for packets transmissions and the appropriate level of reliability. Since link failures and packet losses are unavoidable, sensor networks may tolerate a certain level of reliability without significantly affecting packets delivery performance and data aggregation accuracy in favor of efficient energy consumption. However a certain degree of reliability is needed, especially when hop count increases between source sensor nodes and the base station as a single lost packet may result in loss of a large amount of aggregated data along longer hops. An effective solution is to trade off between energy and reliability while improving packet delivery and minimizing unnecessary packet transmissions in favor of high success reception rates of representative data packets. Based on this approach, the proposed scheme achieves moderate energy consumption and high packet delivery ratio. The proposed scheme was experimentally investigated on a testbed of TelosB motes and proven to be more robust and energy efficient than the current implementation of TinyOS2.x MultihopLQI.*

Keywords: Network Reliability, Wireless Sensor Networks, Energy Efficient Networks, Packet transmission

Received: 1 March 2012, Revised 18 April 2012, Accepted 24 April 2012

1. Introduction

Wireless sensor networks (WSNs) are in many aspects quite similar to Mobile Ad Hoc Networks (MANETs) and Wireless Mesh Networks (WMNs); however, two distinct characteristics call for a different approach. First, the need for energy-efficient operation severely constrains the capabilities of individual sensor nodes such as processing, memory, and communication are limited resources. Second, deployment scenarios of WSN highly structure the communication topology between sensor nodes in the network; in particular, communication between two arbitrary sensor nodes in the network, being part of many ad hoc and mesh scenarios, does not occur in WSNs where most information is relayed either between neighbours or to/from the base station. The proposed solution will consider both characteristics of resource limitations and communication patterns in favour of reliable load balancing routing energyefficient data dissemination. In the literature, several reliability-oriented collection protocols have been proposed for WSNs [1][2][3][11]. However, such protocols have some disadvantages. The main drawbacks of the existing reliability-oriented routing protocols based on link quality are that they are unaware of the energy status of relay sensor nodes and do not explicitly pursue load balancing in their routing schemes; thereby diverting load to sensor nodes with low energy capacity. This leads these overloaded relay sensor nodes deplete their residual powers faster that their peer nodes. This significantly reduces the lifetime of nodes.This paper focuses on developing a reliable load-balancing routing (RLBR) protocol for network lifetime maximisation based on reliability-oriented protocols [1][2][3] and traditional energy-aware routing protocols [6].

The remainder of the paper is organized as follows. In section II, the related work is introduced. Section III describes the proposed routing protocol. Section IV briefly presents the experimental methodology in terms of implementation platform, testing setup and the performance metrics used to evaluate the routing efficiency. The empirical observations are illustrated in section V. Finally, Section VI concludes the paper and discusses future work.

2. Related Work

In mote-dominated wireless sensor networks, MintRoute [1], MultihopLQI [2] and Collect Tree Protocol (CTP) [3] are multihop reliability-oriented routing protocols. These protocols are successive evolution of TinyOS-based collection tree routing layers [4]. MultihopLQI and CTP are developed as a variant of MintRoute. The major difference in each of these protocols lie in how the route cost is calculated.

While in MultihopLQI the reliability cost is a function of the hardware-based link quality indicator (LQI) provided by IEEE802.15.4-compliant RF transceivers in TelosB motes [9], MintRoute and CTP use EXT [5] as a reliability metric of the single-hop sender and (WMEWMA) [1] as an average filter. However, the aforementioned collection protocols do not explicitly employ any form of energy and/or load balancing. Another collection protocol called Arbutus [11] falls in this group of collection protocols, but has been proposed for achieving load balancing as its primary motivation. It only achieves load balancing by using the traffic load on the immediate links of a relay sensor node as an input to the cost computation algorithm.

However, none of the recent studies reviewed above combines link reliability and energy-wise metrics into account with load balancing. In addition, the link cost computation approaches followed by the abovementioned collection protocols are not always optimal routes are as good as its lowest quality hop and the child sensor node cannot either deduce the dynamics of link qualities between predecessor parents or the base station base on immediate link estimations as the link quality is time-varying.

Another important challenge in battery-powered WSNs deals with balanced energy usage for packets transmissions. It has been shown in [6], [7] and [8] that the network lifetime is extended if the rate of energy across the network is uniformly dissipated. For example, if a selected route is the preferred path and all routed data packets consistently relayed through relay sensor nodes along this selected route, these relay sensor nodes will deplete their batteries faster and eventually die off earlier than their peer nodes on other routes. RLBR appropriately adapts such situation and does its best effort to be aware of energy levels of the relay sensor nodes. This dynamic adaptation strategy can alleviate the energy-hole problem as stated in [7] and [8]. It also aims for load balancing between relay sensor nodes in terms of balanced energy usage, and minimising energy dissipation for packet transmissions by means of adaptive beaconing and in-network aggregation of data packets.

Finally, since MultihopLQI routing layer is a well-tested collection tree protocol recent WSNs deployments [14] and [15], benchmarking the RLBR with such protocol is considered a reasonable evaluation.

3. Routing Protocol Description

The work in this paper is built on our existing work stated in [12], [13], and [17] which focuses on TinyOS-based indoor WSNs, but it also aim to improve the performance of the RLBR protocol by extending the experiments for outdoor TinyOS-based WSN testbed that experiencing interferenceprone channels. RLBR employs Channel State Information (CSI) e.g., RSSI and LQI, link estimation base on packet transmissions e.g., success reception ratio (*PRR*) and packet error ratio (*PER*), and residual energy capacity including other parameters, e.g., source id, CRC, hop count, aggregation load, and latency to form a cost function for selecting the most reliable and energy-efficient route towards the base station. In other words, RLBR reduces energy consumed for packets transmissions by embedding routing information in the overheard packets and minimising control traffic. As a result, it maintains low packet error ratio and improves packet delivery while minimizing redundant packet transmission and/or retransmissions throughout the network.

3.1 Data Delivery Patterns

The construction of the routing tree is performed in three overlapped phases: *Network startup*, *Data transmission*, and *Route maintenance*. Delivery of delay-sensitive aggregated packets is considered in *Data transmission phase* in order to maintain agile data delivery and avoid misplacing deadlines for data packets. Hence, each sensor node must decide when to stop waiting for more data to be aggregated based on a preset maximum waiting time. For example, at time 0, an aggregating parent sensor node starts aggregating data from its own packets, if any, and from its children that have participated in aggregation. Later, at time *t* this aggregator sensor node will forward the so far aggregated data up to time *t* to its parent. The amount of aggregated data is a function increasing in participating sensor nodes and decreasing in waiting time *t*. Sensor node within vicinity can exploit unavoidable overhearing neighboring nodes' traffic to improve the selection of parent nodes and uncongested data aggregators.

For example, figure 1 shows the communication range for a sensor node A. While node A is sending its packets to its current valid parent B, it can overhear the packets sent from C to D and from F to G; thereby using the overheard information sensor node A can change its current parent from B to D or to G based on parent selection parameters in order to reduce aggregation load on B; thereby preventing time-sensitive aggregated date, if any, from being dropped at the overloaded sensor node B. If node D has less aggregation load, better link quality with A, higher residual energy and larger id, and also node C sends its packets to D within its vicinity, which relays the forwarded packets to E.

Consequently, in terms of reducing energy dissipated for transmissions, it is more efficient for sensor node A to send its data packets to D, where its data packets can be aggregated with C and D's data packets. However, aggregating sensor node A's data packets with C's and D's is based on aggregation queue state information maintained in sensor node D; while it is not overloaded with aggregated data packets to keep RLBR stringent to time-sensitive deadlines of the forwarded data packets. Due to various deployments could cause different data patterns, this feature of data aggregation is kept optional as it is applicationspecific and it can be enabled or disabled based on the application. Since this distributed parent selection process is performed dynamically whenever there is a packet to send, this approach can adaptively change the topology of aggregation according to different situations based on the aggregation or relaying load.

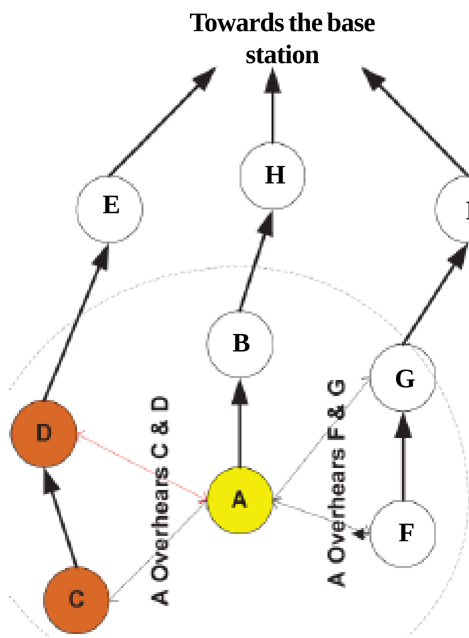


Figure 1. Cooperative Routing based on Overhearing

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, RLBR does minimize this number of transmissions to be *energy-efficient* and *cost-effective* for the 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 packet transmissions and improve energy savings. However, in real-time applications, these encapsulated data packets vary in their deadlines and sensitivity to the end-to-end delivery delay and need to be delivered before a given deadline to the base station according to the importance of the sensing measurements. The packet delivery deadline depends on the real-time application and is associated with every originated data packets at the source sensor nodes. As shown in figure 2, the average *end-to-end delay* is the sum of all *one-hop* delays along the selected route r_j. Due to on-flight aggregation, encapsulated data packets tend to be delayed at each intended relaying sensor node waiting being encapsulated with other arriving or locally generated data packets for a given holding time Δt_{enc} which called a *per-relay encapsulating delay*. In this case, the *average* (*ni-to-b*) *endto- end delay* $\Delta t_{ni,rj,b}$ is estimated on-flight on route r_j between sensor node n_i at the data packet are being encapsulated and the base station *b* by adding one-hop delays along the route r_j between n_i and *b* 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 further until the associated real-time deadline $t_{deadline}$ at the base station. 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 not be longer than it should be to dispatch the encapsulated packet at a appropriate dispatch time $t_{dispatch}$. Consequently, this dispatched encapsulated packet might also be reencapsulated again at next hops relays and Δt_{enc} must comply with packets delivery deadlines. In case $\Delta t_{enc} \leq 0$, $\Delta t_{ni,rj,b}$ will be negative and the arriving packet must be relayed without encapsulating delay; otherwise, the arriving packet can be delayed for Δt_{enc} as expressed in equation 1. Since packet encapsulating is being done for more than one packet over route of *N-i* relay sensor nodes, the encapsulated packet at relay sensor 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 appropriate dispatch time with $min(t_{dispatch})$ that satisfies the accumulated condition in equation 2 over route of *N-i* sensor nodes.

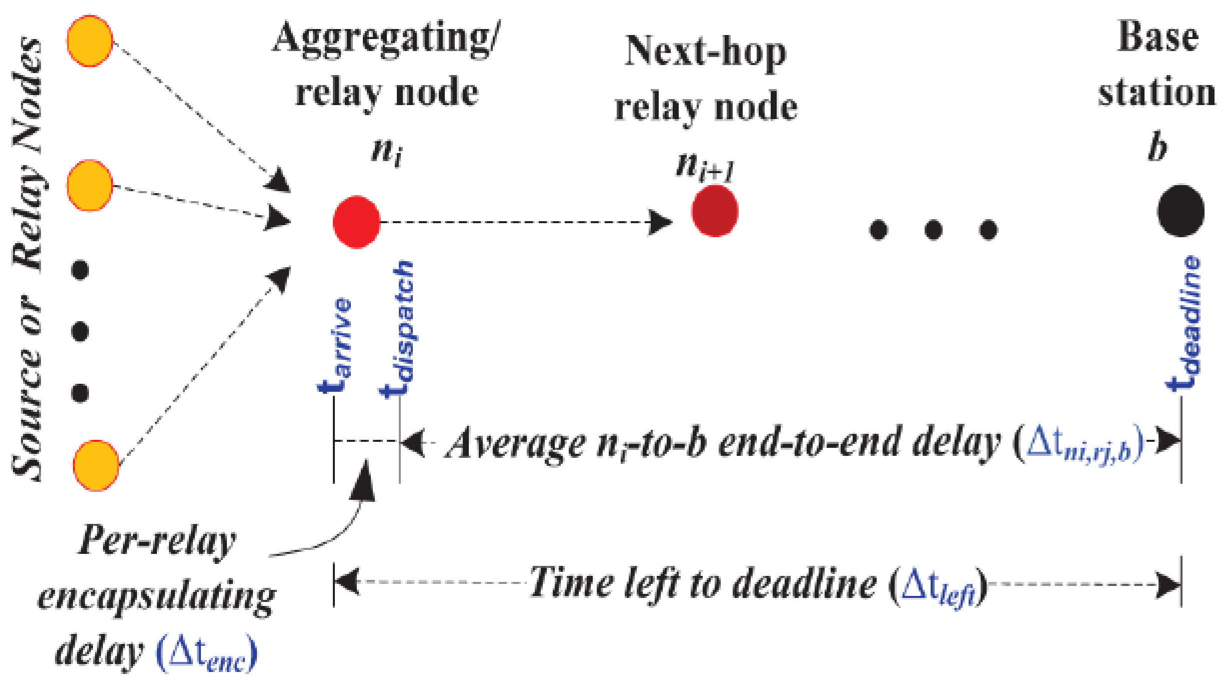


Figure 2. Aggregation Delay Calculated per Hop

$$\Delta t_{enc} = \Delta t_{left} - \Delta t_{ni,rj,b} \qquad (1)$$

$$\sum_{k=i}^{N} min(t_{dispatch_k}) - t_{arriving_k}) \leq \sum_{k=i}^{N} \Delta t_{enc_k} \qquad (2)$$

To gauge the benefit of this approach of minimising packet transmissions throughout the network, *data packet delivery efficiency* (η) accounts for the ratio of the total number of data packets received at the base station to the total number all control and data packets in the network. The η is used as a benefit metric to gauge end-to-end packet delivery performance of the routing scheme in terms of route messages transmissions. Conversely, the reciprocal of data packet delivery efficiency, namely, data packet delivery cost ($1/\eta$ used as a routing overhead metric to give an overall estimation of the energy consumed by relay sensor nodes for delivering a data packet towards the base station.

3.2 Energy Cost Estimation

From energy usage viewpoint, the sensor nodes closer to the base station are the most critical nodes in the network as the load on them is significantly higher than their peers that are distant. Without appropriate countermeasures to ensure network lifetime maximisation by balancing the energy load, these nodes will deplete their residual energy faster; thereby making the network worthless. In figure 3, it supposed that the most energy efficient selected multihop route r is constructed by N adjacent sensor nodes transmitting with transmission power level of Pow^{tx} to relay a data packet over the route r with similar link reliabilities from source senor node n_1 towards the base station b. The total average dissipated energy E_r required to forward one packet from each of the senor nodes *ni* at level (N+1-i) to the base station along the routing path r can be calculated based on the number of hops or hop count (*hc*), and the average amount of energy consumed $E_{n\,i}$ by node n_i at each hop; where $t_{n\,i,r,b}$ is the time spent for relaying a packet from source sensor node n_1 towards the base station b over route r. Equations 3 to 5 express E_r as a function of the *hop count* "hc=(N+1-i)" from the sensor node n_i at which the packet is generated along the route r towards the base station b. $E_{n\,i}$ is the average consumed energy by a sensor node n_i. However, E_{n_i} is increasing as the sensor node n_i becomes closer to the base station as it forwards more packets from its downstream nodes. For example, the most critical sensor node is node n_N, which is the closest sensor node to the base station and always consumes the maximum amount of energy as a result of relaying packets from (N-1) nodes, e.g., n_1, n_2… n_{N-1}, along the route r towards the base station.

$$E_r = (N\,(Pow^{tx}_{n_1} \times t_{n_1,r,b}) + N - 1\,(Pow^{tx}_{n_2} \times t_{n_2,r,b}) + ... + 2\,(Pow^{tx}_{n_{N-1}} \times t_{n_{N-1},r,b}) + 1(\,Pow^{tx}_{n_N} \times t_{n_N,r,b})) \quad (3)$$

$$E_r = (N \times E_{n_1} + (N - 1) \times E_{n_2} + ... + 2 \times E_{n_{N-1}} + 1 \times E_{n_N} \quad (4)$$

$$E_r = \sum_{i=1}^{N} [(N + 1 - i) \times E_{n_i}] = \sum_{i=1}^{N} [\,hc \times E_{n_i}] \quad (5)$$

4. Experimental Methodology

This section briefly investigates the implementation challenges in the tiny wireless sensors platform and describes the experimental testbed including performance metrics used to benchmark the RLBR protocol against the TinyOS-2.x [4] implementation of MultihopLQI [2] on TelosB 2.4GHz lowpower wireless platform developed by Crossbow Inc. [9].

4.1 Implementation Platform

Crossbow's TelosB mote (TPR2420CA) [9] is an open source radio platform fully compatible with the TinyOS [4] and designed to enable WSNs experimentations. TelosB bundles IEEE 802.15.4–compliant CC2420 RF transceiver chip [9] that offers up to 250kbps data rate, integrated antenna, and low-power 8MHz MCU with 10kbytes RAM. TelosB operates within 2.4GHz ISM band and employs the OQPSK modulation scheme. The interested reader should consult [9] and [16] for an exhaustive details of TelosB platform that was targeted for low-power WSNs.

4.2 Experimental Testbed

The proposed RLBR protocol was evaluated on TinyOSbased outdoor testbed comprising of 30 arbitrarily organised TelosB wireless sensor motes, and link layer provided by Chipcon's CC2420 [18] radios in noisy outdoor environment with interference-prone 2.4GHz channels. Longer routes were stimulated by picking routing tree root at the perimeter or the corner of the deployed testbed to be the base station.

4.3 Observed Entities and Performance Metrics

The real WSN is evaluated considering different performance metrics that are observed and, relayed to the attached laptop, and

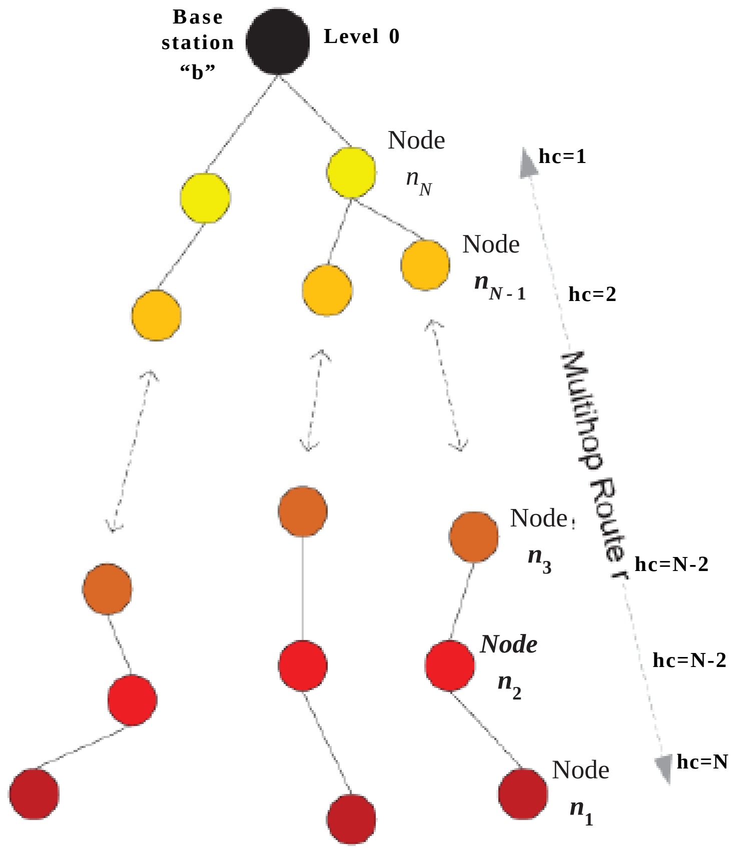


Figure 3. Calculating Average Dissipated Energy

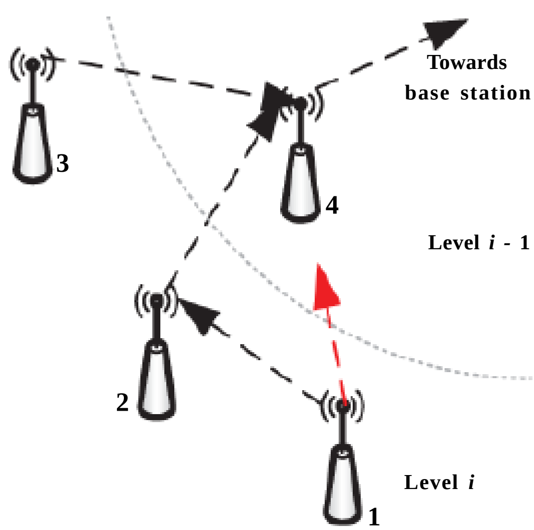


Figure 4. Asymmetric Links

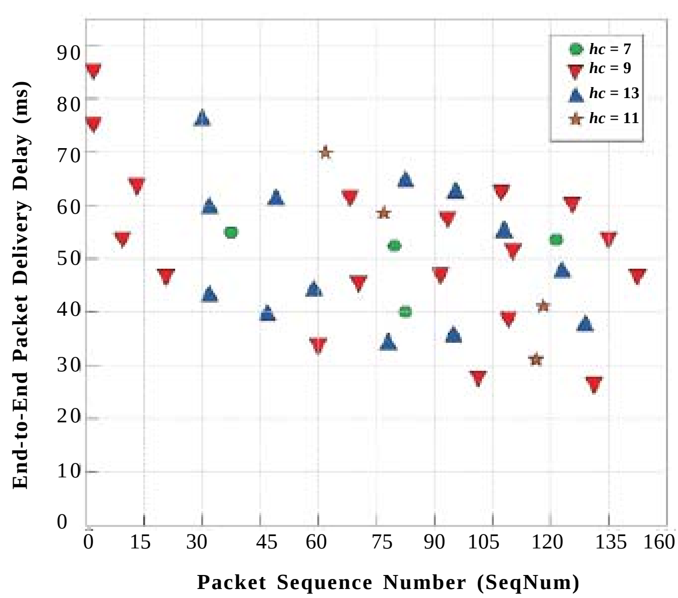


Figure 5. End-to-End Delay

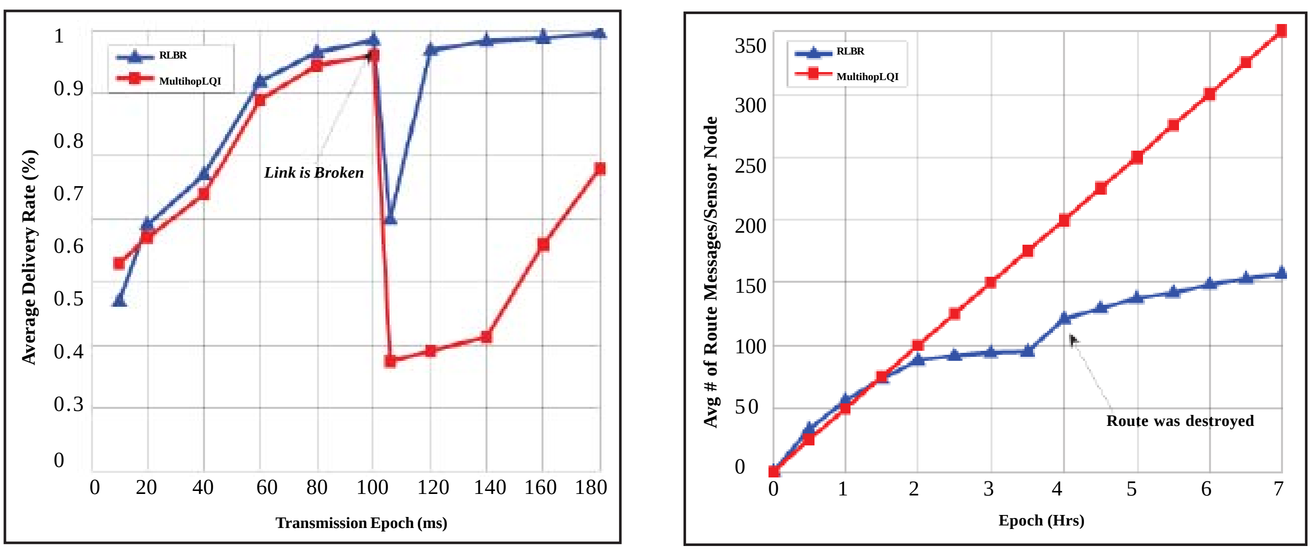
saved in log files for intensive analysis using Matlab scripts. The log files record the observed metric such as Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), and radio packet record that contains packet sequence number, timestamps, node level, node id, and CRC. These metrics will be used to evaluate the routing efficiency in the deployed scenarios and also how the sensor network behaviour is characterized in terms of: *packet delivery performance* to assess the significance of wireless link reliability on packet loss probability; *average end-to-end delay* to evaluate the multihop data aggregation and hop count effect on data delivery time; and *average dissipated energy* to figure out how sensor nodes deplete their energy to achieve multihop communication.

5. Experimental Results

5.1 Link Dynamics

TinyOS-2.x MultihopLQI uses only link quality information at 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 typical feature of low-power WSNs. As illustrated in figure 4, with MultihopLQI protocol, sensor node 1 chooses sensor node 4 as its parent, but it never gets its sent packets acknowledged back from node 1 as a result of asymmetric link between 1 and 4 that makes node 4 unreachable for node 1's packets. To solve this problem based on averaged link quality values, sensor node 1 will switch to other neighbour reachable node, e.g., node 2 at its level, to be its new valid parent after maximum transmission failures due to link asymmetry and transmission range between nodes 1 and 4.

Figure 5 shows how the proposed routing protocol builds its multihop route in the deployed topology in terms of endto- end delivery delay and hop count (*hc*) by means of a snapshot of transmitted packets' sequence numbers. During the beginning of the transmission epoch, the proposed routing protocol has a bit higher delivery delay due to route configuration. However, it immediately improves its delivery performance with low retransmissions and much lower control packet rate. As a result, the end-to-end packet delivery delay decreases gradually.

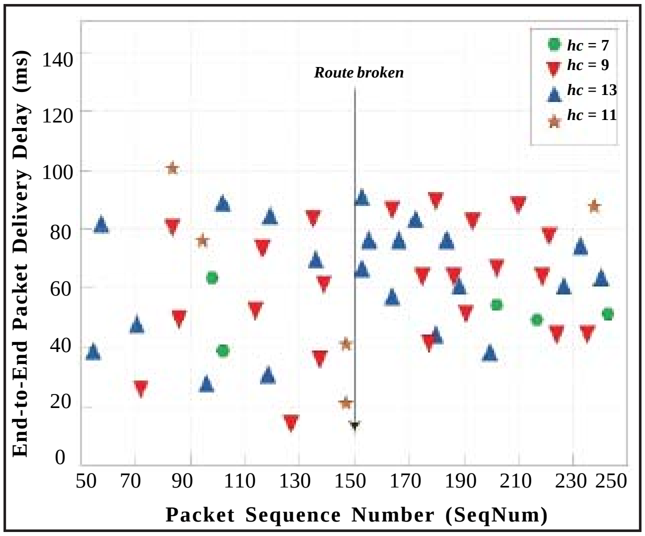


(a) Average Delivery Rate (b) Route Messages per Node

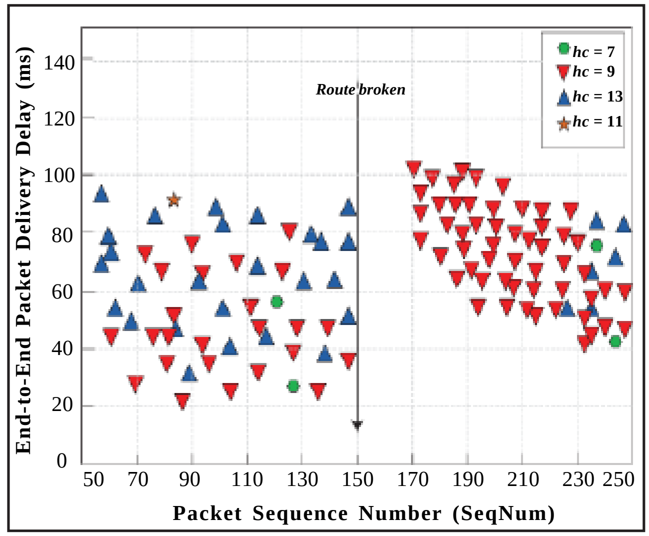
Figure 6. Delivery Performance vs. Link Failure

5.2 End-to-End Packet Delivery Performance

The proposed routing protocol provides a faster recovery from the broken links thanks to the hybrid approach of looking up in backup neighbouring routing tables as it can be seen in figure 6 (a) when the a link is broken at 100ms of the transmission epoch. Once an alternative energy-efficient and reliable route is established using consecutive repair phases, the average end-to-end delay decreases considerably, thereby the average throughput is improved even though the number of hops is a bit higher. This chosen reliable route requires only smaller amount 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. Increasingly, the proposed routing protocol achieves a



a. The proposed scheme



b. MultihopLQI

Figure 7. Route Recovery

higher delivery rate. Conversely, MultihopLQI begins with a higher delivery rate and initially achieves a lower average end-toend delivery delay. This is because the route configuration start-up time required by the proposed routing protocol for updating routing tables and parent selection process is a bit longer while MultihopLQI maintains only a state for one parent node at a time and neither routing tables nor blacklisting is used but at the additional energy cost of significantly increased packets retransmissions to successfully deliver a data packet.

In the view of the cost of beaconing route messages, e.g., control packets, over long epochs of few hours, the beaconing rate per sensor node is adaptive as it starts with a slightly high rate in the proposed routing protocol at the beginning due to the rapid establishment of the routing tree then begins to decrease and becomes stable at lower rates. Figure 6 (b) showcases on hourly basis the average number of route messages (control packets) that were transmitted per sensor node in order to build and maintain the routing tree. Also it can be seen the message beaconing pattern in the proposed routing protocol is slightly raised at the fourth hour due to intentional link failure, this is with the aim of rapidly reconstructing the routes on an alternative route with more number of hops and more sensor node participating in the new route. However, once again it adaptively embarks on a steady rate pattern in order to become stable eventually. On the other hand, since 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; thereby the beaconing of control packets is considerably kept at a higher rate in MultihopLQI and linearly increases over long epoch in terms of few hours.

To jointly evaluate reliability and delivery performances of the routing scheme, a number of intermediate wireless sensor nodes were switched-off or removed to allow the occurrence of broken routes between source sensor nodes and the base station. Figure 7 (a) and (b) illustrates the endto- end delivery performance of RLBR and MultihopLQI respectively in terms of the end-to-end delay and hop count (*hc*) when a route is broken after a packet with sequence number 150. As a result of the presence of other neighbouring wireless motes able to forward relayed packets, RLBR reacts efficiently and responds swiftly to recover from a broken route due to the removal of wireless sensor mote along the preselected path. It maintains an alternative energyefficient and reliable route to recover and compensate the failed one within route reconfiguration time of about 66.40ms; this new constructed route is used temporarily as a backup route to deliver source-originated data packets in timely manner towards the base station. However, the alternative route might be a slightly longer and constructed with additional number of hops, e.g., 9 hops as an average. Therefore, the average end-to-end packet delivery delay is slightly increased to almost 81.32ms using the alternative route. In contrast, MultihopLQI is incapable of rapidly recovering from broken routes if a wireless mote on a preselected route is removed. Even though it needs shorter average end-to-end delay for packet delivery of about 78.43ms due to using route with shorter hops, it slowly recovers from the broken route after a much longer time as it requires about 98.52ms to fix the broken route due to the removal of the mote. Overall, MultihopLQI has an unstable routing tree topology as a result of the frequent restructure of its routing tree according to the pure dependency on LQI as a hardware-based reliability metric.

Although MultihopLQI could recover from link failure, its delivery ratio is noticeably reduced after shorter time. This leads to a lower average packet delivery rate for MultihopLQI compared to the proposed routing protocol which achieves a higher average packet delivery rate, which validates the aforesaid results in figure 6(a).

5.3 Average Dissipation Energy

Compared to MultihopLQI, RLBR makes trade-offs between routes based jointly on both link reliability and energy efficiency in favour of consistently distributing the weight of forwarded packets among the relaying sensor nodes. In addition, RLBR broadcasts fewer route messages over the long run of network's operating time. As a result, RLBR consumes smaller amount of energy of about 35% for route messages transmissions required for delivering data packets through the routing tree towards the base station. To estimate the average amount of energy consumed by relay sensor nodes for delivering a data packet towards the base station, the reciprocal of data packet delivery efficiency (η) is used as a packet delivery cost ($1/\eta$) metric or routing overhead metric to give an overall estimation of the energy consumed by relay sensor nodes for delivering a data packet towards the base station. This efficiency metric (η) accounts for the ratio of the total number of data packets received at the base station to the total number all control and data packets. As an average, RLBR achieves higher delivery efficiency while incurs a significantly lower control overhead than that of MultihopLQI. Figure 8 showcases how the packet delivery cost ($1/\eta$) for RLBR and MultihopLQI changes over long run and gives an average estimation of the energy cost spent for delivering packet transmission throughout the network. RLBR transmits a smaller amount of route messages or control packets than MultihopLQI. The decrease in route messages transmissions of RLBR is a result of avoiding unnecessary route message transmissions using data aggregation, adaptive beaconing, and reliable and efficient route selection. This results in lower beaconing rates and lower control cost while network topology stabilizing; thereby achieving a much lower energy consumption in RLBR.

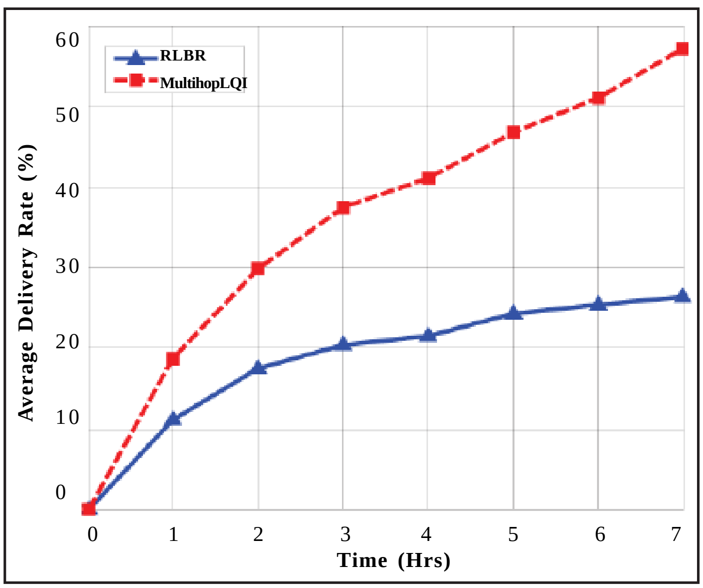


Figure 8. Average Packet Delivery Cost ($1/\eta$)

6. Conclusion and Future Work

In this paper, a reliable load-balancing routing (RLBR) protocol was proposed based on a per-hop load balancing mechanism of the routing layer. It leverages recent advancements over the standard network layer components provided by the TinyOS2.x implementation of MultihopLQI. RLBR consumes less energy while reducing topology repair latency and supports various aggregation weights by redistributing packets relaying loads. It also allows for adapting the amount of traffic to the fluctuations in network connectivity and energy expenditure. Overall, RLBR performs well as it shows a high success rate of packet delivery and moderate energy consumption. While the experiments conducted here have highlighted the substantial performance gains of RLBR, the ongoing work aims to improve the performance of RLBR by extending the experiments to simulations on large-scale WSN.

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