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Energy-Aware Reliability-Oriented Scheme to Deliver Time-Sensitive Data in Sensor Networks

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Abstract—**Reliable data delivery in distributed sensor networks can be achieved by selecting error free links, prompt recovery from packet losses, and avoidance of congested gateways. Since link failures and packet losses are unavoidable in resource-constrained sensor networks, it might be necessary to tolerate a certain level of reliability without significantly affecting packets delivery performance in favor of real-time packet delivery and efficient energy consumption. This paper presents an effective cross-layer approach that improves packet delivery, maintains low packet error ratio, minimizes computation overhead, and adaptively reduces control traffic in favor of high success reception ratios of representative data packets. Based on this approach, the proposed routing scheme achieves a moderate energy consumption and high packet delivery ratio even in environments featuring high link failure rates. The effectiveness of the proposed routing scheme is experimentally investigated using a mote-based testbed as well as simulation. It is shown to be more robust and energy efficient than the network layer of TinyOS2.x. The results show that the scheme maintains higher than 95% connectivity in interference-prone channels while achieving an average of over 35% energy savings.**

***Keywords-wireless sensor networks; reliability; computation overhead; energy efficiency*.**

I. INTRODUCTION

Pervasive computing and communications have evolved into an active area of research and development, due to the tremendous advances in a broad spectrum of technologies and topics including wireless sensor networks (WSNs). Furthermore, WSNs are increasingly being used in areas such as transportation, healthcare and disaster control; and this fact is making ubiquitous Cyber-Physical Systems (CPS) a challenging area for the Service-Oriented Computing (SOC) research community. However, the requirement for energy-aware operation severely constrains the capabilities of individual sensor nodes in areas such as processing, memory, and communication. In addition, the deployment scenarios of WSN highly structure the communication topology of sensor nodes in the network. In particular, most information is relayed either between neighbors or via a base station. This results in the need of energy-efficient and reliability-oriented routing schemes. The main drawbacks of the existing reliability-oriented routing protocols for WSNs are that they are merely based on link quality estimations; they are unaware of the communication patterns and the energy status of relay sensor nodes. This results in arbitrarily diverting the traffic load to sensor nodes with low energy capacity. This leads these overloaded relay sensor nodes deplete their residual power faster than their peer nodes. This significantly reduces the life time of sensor nodes. This paper focuses on developing an energy-aware and reliability-oriented scheme for network lifetime maximization, which jointly accounts for the reliability metrics in [1,2,3] and the energy metrics in [6,28] with load balancing in [11]. In other words, the proposed solution considers both characteristics of resource limitations and communication patterns in favour of reliable and energy-efficient data dissemination. In addition, it allows a child sensor node dynamically search for a reliable set of valid parent nodes with more residual energy and also takes in account the tradeoffs between latency and energy. The work in this paper is built on the existing work in [12,13,23], extending the experiments to include an outdoor sensor network testbed comprising interference-prone channels, and large-scale simulations to validate these experiments.

II. RELATED WORK

In mote-dominated WSNs, MintRoute [1], MultihopLQI [2] and Collection Tree Protocol (CTP) [3] are multihop reliability-oriented routing protocols. These protocols are successive evolution of the TinyOS-based collection tree routing layers [4]. The major difference between each of these protocols is how the route cost is calculated. MintRoute employs Expected Number of Transmissions (ETX) reliability metric [5] as a route cost function in terms of the ratio of the expected number of received packets to the number of packets received on the immediate link. MultihopLQI and CTP are developed as a variant of MintRoute. While CTP attempts to improve upon MintRoute by adding the link costs across all hops to determine the cost of a route, MultihopLQI protocol uses the same principle by accumulating route cost computations but differs from CTP in the sense that the cost is a function of the hardware-based link quality indicator (LQI) provided by IEEE802.15.4-compliant RF transceivers such as those found on TelosB motes [9] and used as the experimental platform in this paper. MintRoute and CTP use ETX [5] as a routing cost metric of the single-hop sender and (WMEWMA) [10] as an average filter. However, the aforementioned collection protocols do not explicitly employ any form of energy or load balancing. Arbutus [11] falls in this group of collection protocols, but has load balancing as its primary objective. It 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. Although the main objective of load balancing routing is the efficient utilization of network resources, none of the recent studies reviewed takes jointly communication patterns with link reliability and energy-wise metrics into account with load balancing. There is no doubt that a better distribution of relayed load leads to the more efficient use of bandwidth, leading to less contention and consequently lower energy consumption.

In general, the aforementioned collection protocols have one common feature which is the use of network layer beacons to propagate route information in the network using either an immediate or an accumulative link cost approach for route cost computation. However, these approaches are not always optimal as routes are only as good as its lowest quality hop. As an example of the immediate cost approach, a child sensor node decided to select its parent based on its current link quality; it would pick the neighbor sensor node with the highest link quality as its next hop to the base station. However, since the link quality is time-varying, the child sensor node cannot deduce the dynamics of link qualities between predecessor parents and the base station based on immediate link estimations. On the other hand, the accumulative link cost approach uses the sum of the link quality values along a route and then averaging these values. However, this approach is also not the best. For example, although a route has a broken immediate link between two adjacent sensor nodes along the routing path, the child sensor node would still select this route is the sum or the average of its link qualities is the highest among multiple routes.

These collection protocols can be either classified as proactive distance vector routing protocols as in MintRoute [1] or reactive distance vector routing protocols as in MultihopLQI [2]. The advantages and disadvantages of such routing classes are well known as stated in [14,15,16]. For instance, sensor nodes do not need to maintain route entries to the base station in built-in routing tables as routes are requested on demand, thus saving memory space. Associated with this benefit there are some drawbacks, including the fact that route request messages are sent into the network using a broadcast mechanism, which can easily lead to a broadcast flooding. The unique communication architecture of the WSNs makes some possibilities of selecting a suboptimal route due to limited topological information that is available to the sensor node [17], the delay that is incurred for acquiring a route [18], and the energy profile of relay sensor nodes [6], are factors that should be considered when using a reactive routing protocol. As a result, the proposed routing scheme adopts a similar mechanism to route propagation but using jointly ad hoc proactive and reactive approach.

Another important challenge in battery-powered WSNs deals with balanced energy usage for packet transmissions. It has been shown in [7,8,19,20] that the network lifetime is extended if the rate of energy consumption across the network is uniformly distributed. For example, if a selected route is the preferred path and all routed data packets are 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. The proposed scheme appropriately adapts to such situations through awareness of the relaying loads and energy levels of the relay sensor nodes. It also aims for load balancing between relay sensor nodes in terms of balanced energy usage and minimized energy dissipation for packet transmissions by means of adaptive beaconing and in-network aggregation of data packets. To that end, the proposed routing scheme adopts a flexible approach that combines some of the advantages of the energy-aware protocols on the top of the reliability-oriented proactive and reactive protocols. The routing protocol also accommodates fault tolerance and adaptability to link and topology changes, while minimising overheads.

Finally, MultihopLQI routing layer is a popular, well-established and well-tested collection tree protocol that is part of the TinyOS-2.x distribution and has been recently used in real WSNs deployments as stated in [3,21,22]. Therefore, the benchmarking with MultihopLQI is considered a reasonable evaluation to test the routing scheme against such protocol.

III. ENERGY-AWARE RELIABILITY-ORIENTED ROUTING

Communications overheads are the major energy consumer during the operation of sensor nodes. The proposed solution is known as a reliable load balancing routing (RLBR) scheme which aims to add minimal communication overheads for network configuration and multihop data dissemination. The proposed routing scheme is built-up on the top of the existing work in [12,13,23]. The proposed solution reduces the energy consumed when transmitting packets by embedding routing information in the overheard packets as explained in the following subsection and also minimising control traffic. As a result, it maintains low packet error rates and improves packet delivery while minimizing redundant packet transmission and retransmissions throughout the network.

A. Cooperative Packet Encapsulation

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. Using this 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 the aggregation load on B. This reduces the likelihood that time-sensitive aggregated data will be dropped at the overloaded sensor node B. Assuming the following are met: 1) sensor node D has less aggregation load, better link quality with A, higher residual energy and larger id; 2) 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. Node D must not be overloaded with aggregated data packets to keep the routing scheme stringent to time-sensitive deadlines of the forwarded data packets. As various deployments could result in different data patterns, this feature of data aggregation is kept optional as it is application-specific 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 is adaptive and the topology of aggregation can change to accommodate different situations based on the aggregation or relaying load.

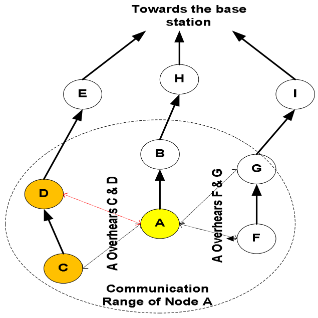


Figure 1. Cooperative Routing Based on Overhearing

To gauge the end-to-end routing overhead of this cooperative routing approach of minimising packet transmissions in terms of route message transmissions weight, *data packet delivery cost* ($1/\eta$) is 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. *Data packet delivery cost* ($1/\eta$) accounts for the ratio of the total number of all control and data packets in the network to the total number of data packets received at the base station as in equation 1.

$$\eta = \frac{\textit{Number of sent data and control packets}}{\textit{Number of received data packets}} \tag{1}$$

B. *Energy Cost Estimation*

From an 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 more distant peers. Without appropriate countermeasures to ensure network lifetime maximisation by balancing the energy dissipation, these nodes will deplete their residual energy faster; thereby making the network worthless. Assuming that that the most energy efficient selected multihop route r is constructed by N adjacent sensor nodes transmitting with a given transmission power level to relay a data packet over the route r with similar link reliabilities from source sensor node n_1 towards the base station b. The total average dissipated energy E_r required to forward one packet from each of the sensor nodes n_i 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 average amount of energy consumed E_{ni} by node n_i at each hop. Equation 2 expresses 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_{ni} is the average consumed energy by an individual node n_i.

$$E_r = \sum_{i=1}^{N} [hc \times E_{n_i}] \tag{2}$$

Since it is assumed that the packet transfer rate at all sensor nodes along the routing path r is the same, the time $t_{ni,r,b}$ required for forwarding the packet is also considered to be the same at each relay node. Also the transmission power is fixed for all sensor nodes. However, E_{ni} 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 originated at all (N-1) sensor nodes, e.g., n_1, n_2, …, n_{N-1}, along the route r towards the base station.

To this point, total average energy dissipation E_r required to forward one packet from each of the sensor nodes n_i to the base station along the routing path r has been considered as a function of *hop count "hc" or tree depth* (also known as *level number*). The next step focuses on the derivation of the average consumed energy E_{ni} of node n_i as a function of the *link reliability* metric of the multihop route r. A sensor node n_i may forward a packet to its nearest neighbor node n_{i+1} with *link reliability probability* $P_{ni,r,ni+1}$ which is the readiness of sensor node n_i to relay a data packet towards the base station b through a selected route r of (N+1-i) hops. A sensor node n_i may also send directly to the base station b with probability $P_{ni,r,b}$ based on its location, where $P_{ni,r,b}$=1-$P_{ni,r,ni+1}$. Therefore, the average dissipated energy of node n_i is E_{ni} which is expressed by equations 3 to 5. The *link reliability probability* embodies the link quality metric of the routing scheme used for parent selection.

$$E_{n_i} = ((\textstyle\sum_{j=1}^{i} P_{n_j,r,n_{j+1}}) + hc \times P_{n_i,r,b}) \tag{3}$$

But, $P_{n_i,r,n_{i+1}} = 1 - P_{n_i,r,b}$.

$$E_{n_i} = (\textstyle\sum_{j=1}^{i}[1 - P_{n_j,r,b}] + (N+1-i) \times P_{n_i,r,b})$$

$$E_{n_i} = (\textstyle\sum_{j=1}^{i}[1] - \sum_{j=1}^{i}[P_{n_j,r,b}] + (N+1-i) \times P_{n_i,r,b})$$

$$E_{n_i} = (i - \textstyle\sum_{j=1}^{i-1+1}[P_{n_j,r,b}] + (N+1-i) \times P_{n_i,r,b})$$

$$E_{n_i} = (i - (\textstyle\sum_{j=1}^{i-1}[P_{n_j,r,b}] + \sum_{j=1}^{1}[P_{n_j,r,b}]) + (N+1-i) \times P_{n_i,r,b})$$

$$E_{n_i} = (i - \textstyle\sum_{j=1}^{i-1} P_{n_j,r,b} - P_{n_i,r,b} + (N+1-i) \times P_{n_i,r,b})$$

$$E_{n_i} = (i - \textstyle\sum_{j=1}^{i-1} P_{n_j,r,b} + P_{n_i,r,b}((N+1-i) - 1) \tag{4}$$

But, $i = N + 1 - hc$

$$E_{n_i} = (N+1) - (hc + \textstyle\sum_{j=1}^{i-1} P_{n_j,r,b}) + (hc-1)P_{n_i,r,b} \tag{5}$$

On the other side, node n_N is the closest to the base station and consumes the maximum amount of energy for transmitting and relaying all packets from its downstream child sensor nodes to the base station b. Sensor node n_N can also transmit directly to the base station with one-hop *link reliability probability* $P_{nN,r,b}=1$. From a network lifetime standpoint, the functional network lifetime can be estimated based on the energy consumption of node n_N in terms of the single-hop *link reliability probability* $P_{ni,r,b}$ between node n_N (where, $i=N$ and $hc=1$) and the base station b.

$$E_{n_N} = (N - \sum_{j=1}^{N-1} P_{n_j,r,b})$$

$$E_{n_N} = (N - [P_{n_1,r,b} + P_{n_2,r,b} + ... + P_{n_{N-1},r,b}]) \qquad (6)$$

In order to moderate the energy dissipation of all these N -1 sensor nodes, that are participating in constructing the preselected multihop route r from node n_1 node n_{N-1}, to the energy dissipation of node n_N, the sum of (N-*1*) *one-hop link reliability probability* of $P_{ni,r,b}$ or (1- $P_{ni,r,ni+1}$) must be smaller than the value of *order of N* "O(N)". The (N-i+1) *link reliability probabilities* can be estimated by solving equation 6 using two dimensional matrices for (N-i+1) hops along the route r.

$$\begin{bmatrix} N & 1 & ... & 1 \\ 0 & (N-1) & ... & 1 \\ : & : & ... & : \\ 0 & 0 & ... & 2 \end{bmatrix} \begin{bmatrix} P_{n_1,r,b} \\ P_{n_2,r,b} \\ : \\ P_{n_{N-1},r,b} \end{bmatrix} = \begin{bmatrix} N-1 \\ N-2 \\ : \\ 1 \end{bmatrix}$$

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 7 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*.

$$R(e_{n_i}) = \frac{\left((P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_{i-1},r,n_i} \times e_{n_i})_{rx}\right)}{t_{n_i,r,n_{i+1}}} \qquad (7)$$

Consequently, from the 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 8.

$$T_{n_i} = \frac{Initial\ energy\ capacity\ level}{Energy\ depletion\ rate} = \frac{init\_e_{n_i}}{R(e_{n_i})} \qquad (8)$$

Considering the abovementioned assumption, maximizing an individual relay sensor node's lifetime T_{ni} can be attained by minimising ($1/T_{ni}$) given in equation 9. This leads to the fact that 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.

$$\frac{1}{T_{n_i}} = \frac{R(e_{n_i})}{init\_e_{n_i}} = \frac{\left((P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_i,b,n_{i-1}} \times e_{n_i})_{rx}\right)}{init\_e_{n_i} \times t_{n_i,r,n_{i+1}}} \qquad (9)$$

Similarly, for a wireless sensor network of m sensor nodes and 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 10.

$$\frac{1}{T_{WSN}} = \frac{1}{init\_e_{n_i}} \sum_{j=1}^{k} \sum_{i=1}^{m} \left(\frac{(P_{n_i,r_j,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_i,r_j,n_{i-1}} \times e_{n_i})_{rx}}{t_{n_i,r_j,n_{i+1}}} \right) \qquad (10)$$

C. Calculating Packet Encapsulating Delay

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 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 to be 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* (n_i-*to*-b) *end-to-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 [26]. 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 send off or release the encapsulated packet at a appropriate release time $t_{release}$. Consequently, this dispatched encapsulated data packet might also be re-encapsulated again at next hops 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 immediately without encapsulating delay; otherwise, the arriving packet can be delayed for Δt_{enc} as expressed in equation 11. Since packet encapsulation is being more than one packet 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 12 over route of *N-i* sensor nodes.

$$\Delta t_{enc} = \Delta t_{left} - \Delta t_{n_i, r_j, b} \tag{11}$$

$$\sum_{k=i}^{N} \left(\min(t_{release_k}) - t_{arriving_k} \right) \leq \sum_{k=i}^{N} \Delta t_{enc_k} \tag{12}$$

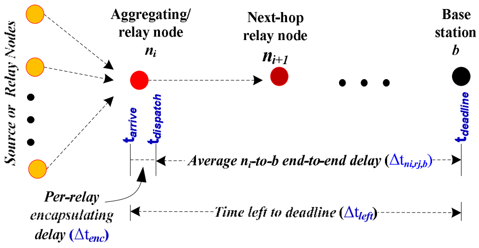


Figure 2. Calculating Encapsulating Delay

IV. PERFORMANCE EVALUATION

In this section we evaluate the proposed protocol, using testbed experiments as well as simulation. We run the experiments using 30 Crossbow's TelosB motes (TPR2420CA) [9] that run the TinyOS-2.x [4]. TelosB bundles low-power 8MHz MCU with 10kbytes RAM, integrated antenna, and IEEE 802.15.4–compliant CC2420 RF transceiver chip [25] that provides the data link layer and offers up to 250kbps data rate. TelosB operates within 2.4GHz ISM band and employs the OQPSK modulation scheme. The interested reader should consult [9,24] for more details about TelosB-2.4 GHz platform that was designed for low-power WSNs. All TelosB motes are deployed randomly and commence transmitting with the same residual power capacity using fresh AA batteries in exception to the base station which is connected directly to a laptop running Linux using its USB port which acts as a bridging device that has IEEE802.15.4 coordinator functionality [25]. The base station relays control packets from the laptop to deployed sensor nodes. These control packets contain adjustment parameters, e.g., originated packets transmission rates. The base station relays also the collected data packets sent by sensor nodes to the laptop where they are saved in metrics log file. Longer routes were stimulated by picking a routing tree root at the corner of the deployed testbed.

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 the corner to increase the depth of the routing tree. IEEE 802.15.4 is used as the MAC and physical layer protocol with bandwidth of 250Kbps. The wireless medium is simulated in ns-2 using the multipath shadowing propagation model [29] as it characterizes the realistic propagation behavior of outdoor environment. The energy consumed for communications are measured by implementing ns-2 radio energy model configured with power parameters from the Chipcon 2.4GHz CC2420 [25]. At the beginning of each simulation, each sensor node is assigned with the same initial energy level. The base station has its persistent energy supply as it is usually the case in real WSN applications.

Our routing scheme is evaluated experimentally and using simulations against TinyOS-2.x MultihopLQI. 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, and average dissipated energy, and network lifetime.

A. Mote-Based Testbed Results

1) Network Configuration: 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. The proposed solution (RLBR) solves the asymmetric link problem by taking the average of the link quality values for better packet delivery ratio estimations based on averaging filter. It also uses bidirectional link estimations based on required retransmissions for active bidirectional monitoring of link status. This renders the proposed solution to properly switch to new valid parents when exceeding a threshold of maximum transmission failures. As illustrated in figure 3, 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 neighboring node, e.g., node 2, to be its new valid parent after maximum transmission failures due to link asymmetry.

Figure 4 shows how the proposed routing protocol builds its multihop route in the deployed topology in terms of end-to-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 slightly 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 even though with a route consists of more number of hops.

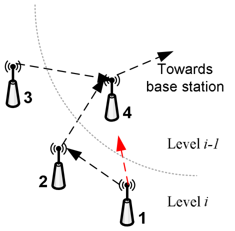


Figure 3. Asymmetric Links

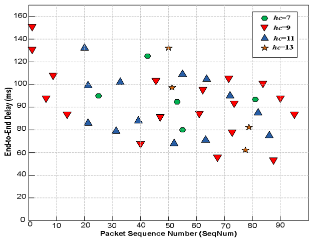
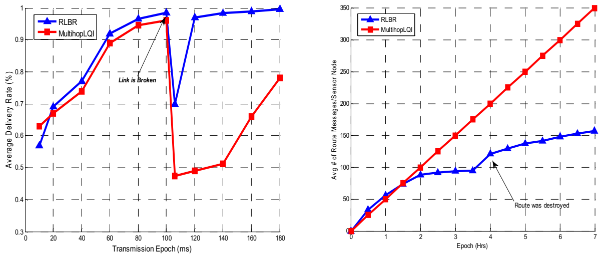


Figure 4. Configuration Delay

2) Average 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 neighboring routing tables. This can be seen in figure 5 (a) when 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 which may affect the timelines of data packets. This chosen reliable route requires only a 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 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 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 RLBR at the beginning due to the rapid establishment of the routing tree then begins to decrease and becomes stable at lower rates. Figure 5 (b) showcases on hourly basis the average number of route messages 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 RLBR is slightly raised at the fourth hour due to intentional link failure, this is with the aim of rapidly reconstructing an alternative route with more number of hops and more sensor nodes 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 periods.

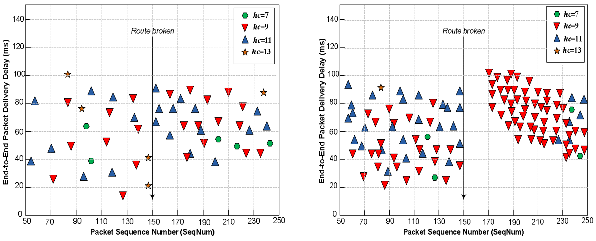


(a) Average Delivery Rate due to Link Failure

(b) Average Number of Route Messages per Node

Figure 5. 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 allow the occurrence of broken routes between source sensor nodes and the base station. Figures 6 (a) and (b) illustrates the end-to-end delivery performance of the 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 a sequence number 150. The proposed routing protocol reacts efficiently and responds swiftly to recover from a broken route due to the removal of a wireless sensor mote along the preselected path. It maintains an alternative energy-efficient and reliable route to recover and compensate the failed one within the 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 a timely manner towards the base station. However, the alternative route might be a slightly longer and constructed with additional number of hops. 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 MultihopLQI requires shorter average end-to-end delay for packet delivery of about 78.43ms due to using a route with shorter hops, it slowly recovers from the broken route after a much longer time. 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 a shorter time. This leads to a lower average packet delivery rate for MultihopLQI compared to the RLBR which achieves a higher average packet delivery rate and validates the earlier results in figure 5 (a).



a. RLBR b. MultihopLQI

Figure 6. Route Recovery

3) Packet Delivery Cost: Using MultihopLQI protocol, sensor nodes broadcast control packets at constant periods and its beaconing rate doesn't adjust with topological dynamics in favor of energy efficiency. In terms of energy, the non-adaptive high rate beaconing is more expensive and is not energy efficient as it expends more energy for unnecessary transmissions in low topological changes as well as most relayed packets are routed through the best routes based mainly on link quality as cost metric. As a result, the optimal route will be used frequently and the sensor nodes along this route will be exhausted quickly. This leads to additional energy consumption and thus imbalances the energy utilization throughout the entire network.

Compared to MultihopLQI, the RLBR makes trade-offs between routes based on link reliability and energy efficiency in favour of consistently distributing the weight of forwarded packets among the relaying sensor nodes. In addition, the RLBR broadcasts fewer route messages over the long run of network's operating time. As a result, the 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 compared to MultihopLQI. As an average, the RLBR achieves higher delivery efficiency while incurs a significantly lower control overhead than that of TinyOS network layer of MultihopLQI.

Figure 7 showcases how the packet delivery cost ($1/\eta$) for the RLBR and MultihopLQI changes over long run and gives an average estimation of the energy cost spent for delivering packet transmission throughout the network. The RLBR transmits a smaller amount of route messages or control packets than MultihopLQI. The decrease in route message transmissions of the RLBR is a result of avoiding unnecessary route message transmissions using adaptive beaconing. This results in lower beaconing rates and lower control cost while network topology stabilizing; thereby achieving a much lower energy consumption in the proposed routing scheme.

B. Simulation Results

1) Functional Network lifetime: Using simulations of larger network size of 100 sensor nodes with different numbers of source nodes between 30 and 70, the proposed scheme balances the energy consumption and keeps updating energy efficient routes. In general, figure 8 shows that the network lifetime has a deteriorating trend as the number of deployed sensor nodes increases due to a high traffic load of control and data packets that are retransmitted throughout the sensor network. Comparing with MultihopLQI, the network lifetime with the proposed scheme is more stable with different numbers of deployed sensor nodes and degrades more gradually when the number of sensor nodes increases. This leads to maximizing the operational network lifetime. In MultihopLQI, the large numbers of redundant packets copies that are retransmitted between different sensor nodes rapidly deplete the available energy. However, MultihopLQI can occasionally balance the traffic load based on link quality estimates. To this end, the simulation results agree with assumption made earlier by the proposed scheme that the energy consumed for transmissions can be reduced and the network lifetime can be maximized by considering data transmitting patterns and encapsulating stimulus-related relayed data packets along the routing path.

2) Average Dissipated Energy: Figure 9 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 increasing trend as the number of source nodes becomes higher. However, the proposed scheme can cause lower energy consumption. Comparing with MultihopLQI, the proposed routing scheme performs quite well where the energy consumption increases steadily 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 after escalating the number of generating nodes. It demonstrates that the proposed routing scheme outperforms MultihopLQI with the variation of the number of source nodes.

Figure 10 shows the change in the node's average residual energy level after a period of data transmission. It is obvious that increasing the number of source nodes has an impact on the individual node's residual energy level. As an overall trend, the average remaining energy level decreases with higher number of source nodes. MultihopLQI can not reduce the redundant data copies in the network which is the result of the high traffic load handled by each individual forwarding node. This makes the average remaining energy level with MultihopLQI to degrade much faster than our routing scheme which keeps a balanced network workload to maintain balanced energy dissipation.

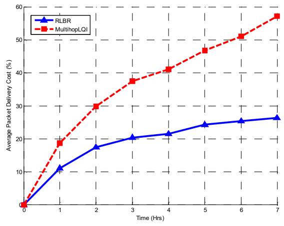


Figure 7. Delivery Cost

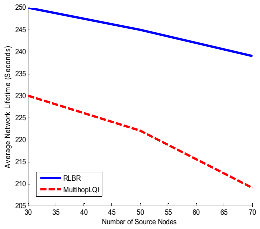


Figure 8. Network Lifetime

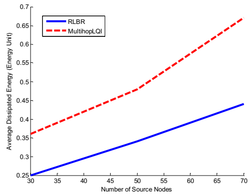


Figure 9. Energy Dissipation

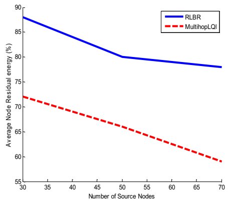


Figure10. Residual Energy

V. CONCLUSION AND FUTURE WORK

The paper develops an energy-aware scheme for reliable data delivery in sensor networks based on eavesdropping neighboring traffic and a per-hop load balancing mechanism of the routing layer. The proposed routing scheme consumes less energy while reducing topology repair latency and supports various aggregation weights by redistributing packet relaying loads. It also allows for adapting the amount of traffic to the fluctuations in network connectivity and energy expenditure. From reliability viewpoint, it creates a routing tree using estimated numbers of transmissions and link quality estimations of successfully received packets. The proposed 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, the ongoing work aims to improve the performance of the proposed routing protocol by extending the experiments to simulations on larger networks using other routing metrics.

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