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Traffic Eavesdropping Based Scheme to Deliver Time-Sensitive Data in Sensor Networks

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Abstract—**Due to the broadcast nature of wireless channels, neighbouring sensor nodes may overhear packets transmissions from each other even if they are not the intended recipients of these transmissions. This redundant packet reception leads to unnecessary expenditure of battery energy of the recipients. Particularly in highly dense sensor networks, overhearing or eavesdropping overheads can constitute a significant fraction of the total energy consumption. Since overhearing of wireless traffic is unavoidable and sometimes essential, a new distributed energy efficient scheme is proposed in this paper. This new scheme exploits the inevitable overhearing effect as an effective approach in order to collect the required information to perform energy efficient delivery for data aggregation. Based on this approach, the proposed scheme achieves moderate energy consumption and high packet delivery rate notwithstanding the occurrence of high link failure rates. The performance of the proposed scheme is experimentally investigated a testbed of TelosB motes in addition to ns-2 simulations to validate the performed experiments on large-scale network.**

Keywords-ad hoc wireless sensor networks; overhearing; data aggregation, energy efficiency.

I. INTRODUCTION

Overhearing problem is common in wireless sensor networks. Although several MAC protocols for Wireless Sensor Networks (WSNs) have been proposed using short control packets to avoid overhearing of long data packets, overhearing the control packets still consumes considerable overhead energy. Since overhearing is unavoidable and, this paper proposes a distributed energy optimization scheme that exploits the overhearing effect as an approach to gather the required routing information for time-sensitive delivery of aggregated data packets. In other words, the proposed scheme dynamically transforms the constructed routing tree using easily received overheard information to improve the efficiency of data aggregation. It allows each sensor node to adaptively choose a new parent if it appears to improved the efficiency of aggregation. This adaptive proposed scheme reduces the number of message transmissions and achieves a 35% energy reduction, compared to the reliability-oriented scheme where aggregation occurs opportunistically. The proposed scheme exploits the overheard information to reduce the unnecessary overhearing energy consumption along routing paths where sensor nodes observe their neighbourhood and dynamically adapt their participation in the multihop routing tree. The main drawbacks of the existing reliability-oriented routing protocols for WSNs that they are purely based on link quality estimations; 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 arbitrarily diverting the traffic load to sensor nodes with low energy capacity. Consequently, the overloaded relay nodes will deplete their residual power faster than their peer nodes and the network lifetime significantly decreases. This paper focuses on a balanced energy dissipation scheme for network lifetime maximization, taking advantages from both the reliability-oriented routing protocols [1,2,3] and the energy-aware routing protocols [6,11,28]. 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.

The proposed solution considers both characteristics of resource limitations and communication patterns in favour of real-time 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 presented in this paper is based on the experience gained in our previous experiments in [12,13,23,30] and aims to include large-scale simulations to validate these experiments.

II. UNDERLYING LAYER

In general, medium-access control (MAC) protocols for wireless networks manage the usage of the radio interface to ensure efficient utilization of the shared bandwidth. MAC protocols designed for WSNs have an additional goal of managing radio activity to conserve energy. While traditional MAC protocols must balance throughput, delay, and fairness concerns, WSN MAC protocols place an emphasis on energy efficiency as well. There are several aspects of a traditional MAC protocol that have a negative impact on wireless sensor networks, including Collisions, Overhearing, idle listening and Control packets overhead. Furthermore, the more nodes fail in the network, the more control messages are required to reconfigure the system, resulting in more energy consumption.

MAC protocols for WSNs generally reduce energy consumption by putting radios to a low-power sleep mode, either periodically or adaptively when a node is neither receiving nor transmitting. An essential consequence is that a

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sensor node needs to be aware of its neighbours' sleep/active schedules, since sending a message is only effective when the destination node is awake. A typical solution is to have all nodes synchronize on one global schedule. In such schedule-based protocols, energy waste owing to overhearing, collision and idle listening can be minimized. However, grouping communication into pre-allocated sub-channels for each node within small active periods requires precise time synchronization which is a non-trivial problem [16,18,26]. Also, such synchronized protocols may enhance delay predictability and increase packet drops due to buffer overflows. On the other hand, contention-based protocols employ a shared channel which is allocated on-demand for all sensor nodes. These asynchronous protocols are not as energy-efficient as schedule-based protocols, but they scale more easily across changes in node density or traffic load. Also, they are more flexible as network topology changes, e.g., IEEE802.15.4 protocol [4]. And the most important advantage, fine-grained time synchronization is not required. Due to the highly dynamic nature of sensor networks, these advantages make asynchronous protocols the preferred option as an underlying network layer for the performed experiments of the proposed scheme.

III. TRAFFIC EAVESDROPPING BASE SCHEME

The proposed scheme is built-up on the top of our previous work in [12,13,23,30]. The proposed solution reduces the energy consumed when transmitting packets by embedding routing information in the overheard packets and minimising control traffic. As a result, it maintains low packet error rates and improves packet delivery while minimizing redundant packets transmission and delay of time-sensitive data packets.

A. Efficient Aggregation based on Eavesdropping

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 that sensor 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 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 adaptively and the topology of aggregation can change to accommodate different situations based on the aggregation or relaying load.

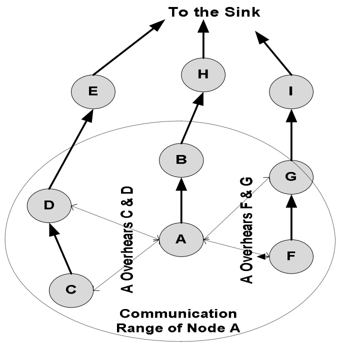


Figure 1. Eavesdropping-Based Packet Delivery

B. Time-Sensitive Packet Delivery

Since all sensor nodes in the sensor network have the chance to participate in relaying data packets in 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 packets transmissions and improves 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. 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* (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 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 immediately without encapsulating delay; otherwise, the arriving encapsulated data packet can be delayed for Δt_{enc}.

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

Since packet encapsulating is done for more than one packet with different deadlines over a route of *N-i* relay sensor nodes, the encapsulated packet at relay sensor node n_i must be dispatched as soon as one of the encapsulating packets reaches its preset deadline $t_{deadline}$. This deadline must be the minimum appropriate dispatch time with $min(t_{release})$ that satisfies the accumulated times in equation 2 over route of *N-i* nodes.

$$\sum_{k=i}^{N} \left(\min(t_{release_k}) - t_{arriving_k} \right) \leq \sum\nolimits_{k=i}^{N} \Delta t_{enc_k} \qquad (2)$$

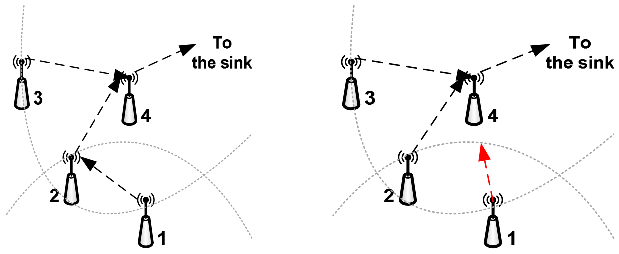
IV. PERFORMANCE EVALUATION

The proposed scheme is evaluated using an experimental testbed in addition to simulations. The testbed uses Crossbow's TelosB motes (TPR2420CA) [9] that run TinyOS-2.x [4]. TelosB bundles IEEE 802.15.4–compliant CC2420 RF transceiver chip 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 [9,24] for more details about TelosB-2.4 GHz platform that was designed for low-power WSNs. All deployed TelosB motes 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 and acts as a bridging device that has IEEE802.15.4 coordinator functionality. 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 to be saved in metrics log file. Longer routes were stimulated by picking routing tree root at the perimeter or the corner of the deployed testbed to be the base station.

In simulations, 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 [9][24]. 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. The proposed scheme is evaluated experimentally and using simulations against the baseline protocol of TinyOS-2.x MultihopLQI [2,21,22]. As the simulation part is still in progress, few simulation results are presented here in terms of different numbers of sensor nodes up to 100 nodes. 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. *Experimental Results*

1) Link Dynamics: The pure reliance on one form of channel state information (CSI) in MultihopLQI leads to inappropriately react with the asymmetric links which is typical feature of low-power WSNs. The proposed solution 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. Figures 2 (a) and (b) show the instantaneous communication ranges of nodes 1 and 4. As illustrated in figure 2 (b), with MultihopLQI protocol, sensor node 1 loses her current parent sensor node 4 even it gets route meessages beaconing from node 4. As a result of routing loops prevention in MultihopLQI, node 1 can not choose node 2 as its ew paernt because both are at the same level of the routing tree. Asymmetric link between 1 and 4 makes node 4 unreachable for node 1's packets. To solve this problem and to increase the participation in the parent slection, the proposed scheme allows node 1 to select node 2 as its new parent even both are at the same level as shown in figure 2 (a). Routing loops at the same level are avoided by using node *id* as tierbreaker. Based on averaged link quality values, sensor node 1 will switch to other neighbor reachable node, i.e., node 2, to be its new valid parent after maximum transmission failures due to link asymmetry and transmission range. During the beginning of the transmission, the proposed scheme has a slightly higher delivery delay due to higher number of hops. 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 twoards the sink.



a. The proposed Scheme
b. The Baseline Protocol

Figure 2. Asymmetric Link Problem

2) Network Connectivity: The proposed scheme provides a faster recovery from the broken links thanks to the hybrid approach of looking up in backup neighboring routing tables as it can be seen in figure 3 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. 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 scheme 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 proposed scheme 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 at a slightly high rate in the proposed scheme at the beginning due to the rapid establishment of the routing tree then begins to decrease and becomes stable at lower rates.

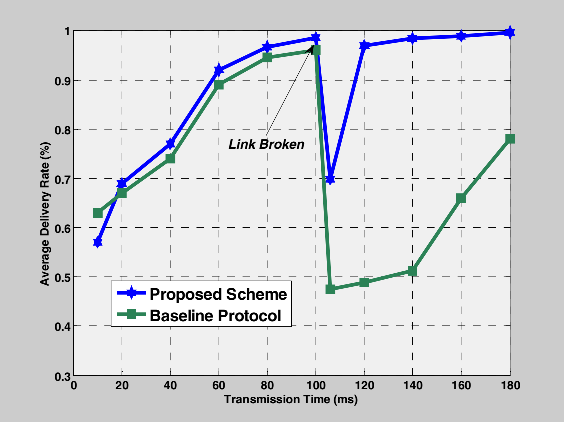


Figure 3. Network Connectivity due to Link Failure

3) Routing Overhead: Figure 4 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 proposed scheme is slightly raised at the fourth hour due to intentional link failure, this is with the aim of rapidly reconstruct 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 its preset constant rate of 32 beacons every second; thereby the beaconing of control packets is considerably kept at a higher rate in MultihopLQI and linearly increases over long run in terms of 7 hours.

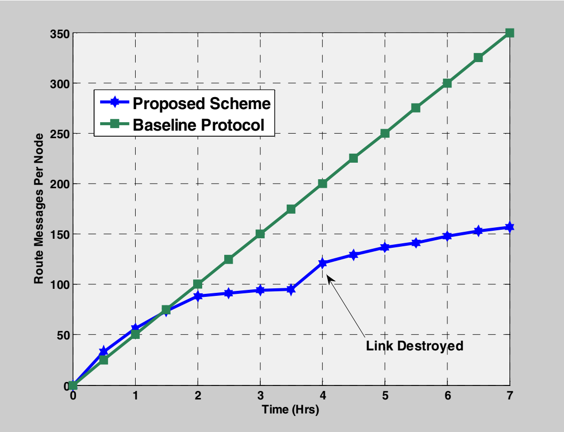


Figure 4. Routing Overhead due to Route Messages

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. The proposed scheme 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 energy-efficient 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. 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 to rapidly recover 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. As an overall, MultihopLQI has 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 scheme which achieves a higher average packet delivery rate with lower routing overhead.

4) 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 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 proposed scheme makes trade-offs between routes based link reliability and energy efficiency in favour of consistently distributing the weight of forwarded packets among the relaying sensor nodes. In addition, the proposed scheme broadcasts fewer route messages over the long run of network's operating time. As a result, the proposed scheme 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 packet delivery cost is used as a routing overhead metric. This cost metric accounts for the ratio of the total number all control and data packets to the total number of data packets received at the base station. As an average, the proposed scheme achieves higher delivery efficiency while incurs a significantly lower control overhead than that of MultihopLQI. Figure 5 showcases how the packet delivery cost for the proposed scheme and MultihopLQI changes over long run and gives an average estimation of the energy cost spent for delivering packet transmission throughout the network. The proposed scheme transmits a smaller amount of route messages or control packets than MultihopLQI. The decrease in route messages transmissions of the proposed scheme 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 scheme.

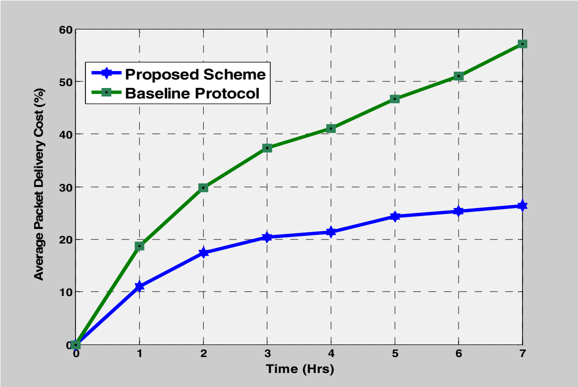


Figure 5. Packet Delivery Cost

B. *Simulation Results*

1) Functional Network Lifetime: Using simulations of larger network of different numbers of sensor nodes up to 100 nodes, the proposed scheme balances the energy consumption and keeps updating energy efficient routes. In general, figure 6 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 7 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 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 scheme outperforms MultihopLQI with the variation of the number of source nodes.

Figure 8 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 resulted by a high traffic load handled by each individual forwarding node. This makes the average remaining energy level with MultihopLQI to degrade much faster than the proposed scheme which keeps a balanced network workload towards the base station to maintain balanced energy dissipation.

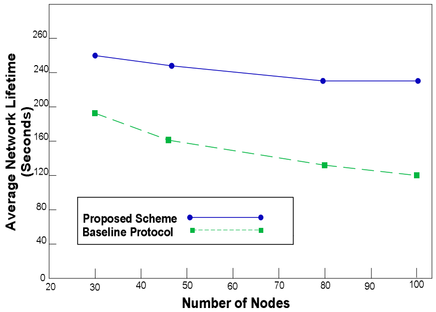


Figure 6. Average Network Lifetime

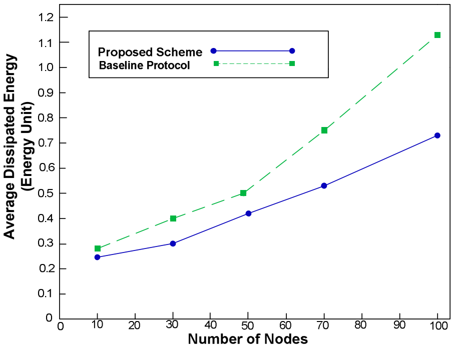


Figure 7. Average Dissipated Energy

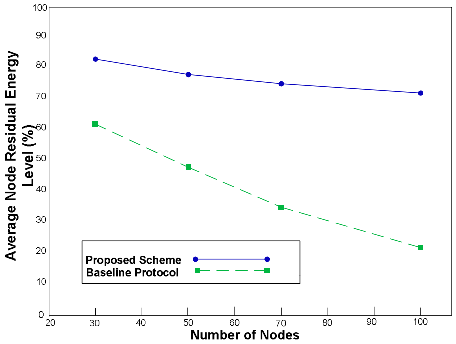


Figure 8. Average Residual Energy

V. CONCLUSION AND FUTURE WORK

In this work, a reliable energy-efficient collection routing protocol is 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. Our proposed scheme consumes less energy for 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. From reliability viewpoint, it creates a routing tree using estimated numbers of transmissions and/or retransmission to the base station and link quality estimations based on sequence numbers of successfully received packets. The proposed scheme performs well as it shows a high success rate of packet delivery and moderate energy consumption.

Few simulation results are presented here as the simulation part is still in progress. While the experiments conducted here have highlighted the substantial performance gains of the proposed solution, the ongoing work aims to improve the performance of our proposed scheme by extending the experiments to simulations on larger networks using other metrics and comparing with energy-aware routing protocols.

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