Reliable Routing Scheme for Indoor Sensor Networks

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***Abstract*—Indoor Wireless sensor networks require a highly dynamic, adaptive routing scheme to deal with the high rate of topology changes due to fading of indoor wireless channels. Besides that, energy consumption rate needs to be consistently distributed among sensor nodes and efficient utilization of battery power is essential. If only the link reliability metric is considered in the routing scheme, it may create long hops routes, and the high quality paths will be frequently used. This leads to shorter lifetime of such paths; thereby the entire network's lifetime will be significantly minimized. This paper briefly presents a reliable load-balanced routing (RLBR) scheme for indoor ad hoc wireless sensor networks, which integrates routing information from different layers. The proposed scheme aims to redistribute the relaying workload and the energy usage among relay sensor nodes to achieve balanced energy dissipation; thereby maximizing the functional network lifetime. RLBR scheme was tested and benchmarked against the TinyOS-2.x implementation of MintRoute on an indoor testbed comprising 20 Mica2 motes and low power listening (LPL) link layer provided by CC1000 radio. RLBR scheme consumes less energy for communications while reducing topology repair latency and achieves better connectivity and communication reliability in terms of end-to-end packets delivery performance.**

Keywords-indoor wireless sensor networks; reliable routing; energy balancing; lifetime maximization.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) provide the ability to collect information cheaply, accurately and reliably over both small and vast physical regions. Unlike other large data network forms, where the ultimate I/O interface is a human being, WSNs are about collecting data from unattended physical environments. Therefore, reliable and energy efficient routing is a key issue in WSNs deployments. From energy efficiency standpoint, the existing TinyOS-based routing protocols for wireless sensor networks (WSNs) are steadily improving for forming a reliable tree-based data gathering but they are still inferior over custom solutions concerning energy consumption [17][18][19]. In other words, these protocols are reliability-oriented but unaware of the energy status of relaying sensor nodes and do not explicitly apply energy balancing in their routing schemes; thereby diverting load to sensor nodes with low energy capacity. As a result, this paper focuses on balanced energy dissipation routing scheme for lifetime maximization by taking the advantage from reliability-oriented routing schemes and traditional energy-aware routing schemes.

Since the communications overheads are the major energy consumer during a sensor node's operation, the proposed routing scheme, RLBR, is a simple but reliable routing algorithm, aims to cause minimal communication overheads for network configuration and multihop data dissemination. Although the main objective of load balancing routing is the efficient utilization of network resources, the literature [1][19][20][22] lacks such protocols that take jointly link reliability and energy-wise metrics into account with load balancing. There is no doubt that a better distribution of load leads to the more efficient use of bandwidth, which means that there is less contention and consequently less energy is consumed, but it is not self-contained for achieving complete energy efficiency. Furthermore, WSNs are not necessarily energy-homogeneous, and there is thus insufficient information about the sensor nodes' load tasks to enable the energy-wise selection of the paths. The current load of a given sensor node can be used to estimate the potential dissipation of energy but it does not contain a record of past activities and the residual energy level of the sensor node remains hidden. RLBR scheme allows a child sensor node dynamically searches for a new reliable parent node with more residual energy. This dynamic adaptation strategy can alleviate the energy-hole problem as stated in [10][23]. The experimental work done in this paper aims to investigate the indoor performance of RLBR scheme in terms of reliability, packet delivery, and energy efficiency.

The remainder of the paper is organized as follows. In section II, the related work is introduced. Section III presents the proposed routing scheme. Section IV describes briefly the implementation platform, Experiment methodology and testing setup. The experimental results are illustrated in section V. Finally, Section VI ends the paper with conclusion and future work plan.

II. RELATED WORK

Since the wireless links in low-power WSNs are not stable, the reliability-oriented routing protocols for WSNs purely rely on either Channel State Information (CSI) from broadcast control traffic or delivery cost estimates from unicast traffic using Expected Number of Transmissions (ETX) reliability metric [21]. The earlier common form of CSI, the Received Signal Strength Indicator (RSSI), used to be considered a predictor of link quality of some platforms such as Mica2 CC1000 RF transceiver [7][8]. The RSSI has early been recognized as a good predictor of link quality; specifically, it

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has been shown that the RSSI, if higher than the sensitivity threshold, about -87dBm, correlates very well with the packet reception rate [18,19]. As for link estimation by means of delivery cost estimates, the ETX link metric is proposed in [21]; the idea is to estimate the total number of transmissions needed to get a packet across a link, and use the route with the minimum ETX. ETX has been shown to be very robust, especially on top of an Automatic Repeat Request (ARQ) scheme [19] which strengthens low quality links. However, using ARQ scheme in the link layer, the child sensor node will retransmit the unacknowledged packet and degrade the network throughput. The traditional way of estimating the ETX relies on link symmetry assumption. While this may be reasonable in mobile ad hoc networks (MANETs) due to mobility, it is not accurate in typical WSN deployments where packets losses on the direct and reverse channel are not correlated even though sensor nodes are static [19]. The observations in [2][3][4][17][19][22] states that it is vital to use link layer acknowledgments to evaluate the ETX metric. For example, MintRoute [17] experiences the asymmetric link problem inappropriately as child sensor nodes might not get their packets acknowledged from their current parents albeit maximum number of successive transmission failure is reached. RLBR scheme solves the asymmetric link problem by using active bidirectional monitoring of link status and switching to a new valid parent when exceeding a threshold of maximum successive transmission failures, and puts the old invalid parent into blacklist to avoid switch oscillation.

Since the data rate in WSNs is typically low, route messages do not need to be exchanged frequently and the rate of route message exchanges is very low as in MintRoute. In terms of energy dissipation cost, this helps MintRoute to reduce its energy consumption in low data rates. However, MintRoute is more expensive at high data rates. Also MintRoute takes a long time to convey the topological changes to the whole network (i.e., due to node failure or damage); during this period, many packets are routed through optimal paths, which consume additional energy and thus offsets the benefit of energy balancing in reliability-based routing schemes. Hence, RLBR scheme considers the acceleration of route message exchange rate for propagating the topological changes. Although MintRoute protocol balances the traffic load with occasional switches of nodes' parents which is a direct consequence of its Minimum Number of Transmissions (MT) metric, MintRoute protocol does not explicitly apply a metric that considers workload balancing. Hence, the proposed routing scheme is proposed to address load balancing in energy efficient manner by maintaining a reliable set of valid parent nodes in the routing table to allow sensor nodes to quickly find a new parent upon parent loss due to the existing of node failure or routing hole.

III. RELIABLE ENERGY BALANCED ROUTING SCHEME

The proposed routing scheme, RLBR, is a hybrid, reactive and proactive, designed to adaptively provide enhanced balanced energy usage on reliable routes and to employ ready-to-use neighborhood routing tables in order to allow sensor nodes to quickly find a new parent upon parent loss due to link degradation or run-out of energy. The proposed routing scheme is built on our ongoing work stated in [24][25][27]. As shown in figure 1, RLBR scheme uses hardware-based Channel State Information (CSI), e.g. received signal strength indicator (RSSI) measurements provided by CC1000 radio, and residual energy capacity with other locally overheard parameters, e.g., aggregation load, sensor node-*id*, and tree-level, including software-based link estimations, e.g. packet reception ratio (PRR), to form a cost function for selecting the most reliable and energy-efficient route to the base station.

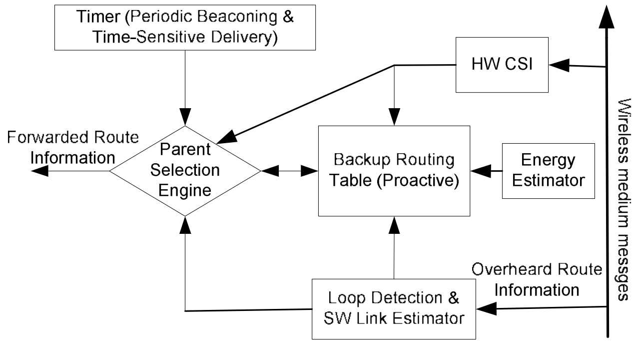

Figure 1. Routing Scheme Overview

The routing tree is a directed acyclic graph which relays packets towards the base station over multiple paths. The routing tree is built by assigning a *level number* to each sensor node depending on its distance (e.g., number of hops) to the base station, and delivers sensing data packets from higher-level to lower-level sensor nodes. The base station is at *level* 0. Each sensor node at level *i* can select a valid parent from its level *i* or from lower level *i*-1 towards the base station. The valid parent is selected by the routing metrics used in the routing cost function, i.e., link quality, residual energy, hop-count, aggregation load and latency. Selecting parents from the same level increase the flexibility of parent selection process. The routing tree starts with the easily-constructed shortest path tree, and then allows each sensor node to pick a new parent node if it appears to provide better routing cost with a higher link quality. Using the broadcast nature of the contention-based wireless medium, a sensor node can easily observe its neighborhood by receiving and overhearing route messages that initially originated other nodes. Each sensor node transmits beacon packets to update route information.

Upon parent loss, a sensor node with invalid parent waits for new route messages to restore a new valid parent node. During the waiting period to join its new parent, some sensor nodes may possibly discard some of their received packets due to buffer overflow of aggregation load. This waiting time is limited by delay constraints threshold in order to keep the network responsive to topological changes due to link dynamics or inconsistent energy dissipation. For instance, if the quality of the link between a sensor node and its current parent degrades under the threshold or the energy capacity of its parent is low, this sensor node will cancel its current parent and instantaneously sends out a route message to inform its downstream children sensor nodes, if any, and waits a certain time until a new valid parent is selected *reactively* during the route searching phase. As soon as sensor node joins its new valid parent, it broadcast a route message to inform its downstream children; but if a sensor node couldn't join a new valid parent and its parent becomes invalid for longer than the waiting time, it will select its parent from the recent updated *proactive* multipath backup, i.e., routing table, to reduce the recovery delay time. Hence, the network will quickly reorganize its routing tree during route searching phase by maintaining a reliable set of valid parent nodes in the built-in routing table to allow sensor nodes to quickly find a new valid parent upon parent loss due to link degradation or energy routing hole. In other word, if a sensor node's parent becomes invalid for longer than certain delay time, it searches for an alternative valid parent in its neighborhood routing table that has been updated recently. The routing scheme *proactively* caches valid parents toward the base station based on received or overheard neighborhood route information. Once a received route message indicates a valid path toward the base station, neighborhood management module updates the route information into the routing table. When the routing component looks up an alternative path to the base station, the lowest cost route will be selected, without waiting beacons a longer time to rediscover a route.

IV. EXPERIMENTAL EVALUATION

A. *Implementation Platform*

Considerable advances have been made in recent years in hardware [5] and software [6] for building wireless sensor networks. The implementation was based on real world testbed of wireless sensors nodes, specifically the UC Berkeley's Mica2 motes which are popular due to their tiny architecture, open source development and commercially available from Crossbow® Technology [5] with TinyOS operating system [6].

Mica2 (MPR400CB) mote is a low-power sensor device whose low cost can be attributed to its lack of limited resources. Mica2 is built with an 8-bit, 7.3828MHz Atmel® ATmega 128L processor, 128 kilobytes (KB) of in-system program memory, 4KB of in-system data memory, and 512KB of external flash (serial) memory for measurements storage [7]. Mica2 mote uses a low powered radio "Chipcon SmartRF CC1000 transceiver" which is a single-chip very low power radio frequency transceiver. CC1000 has 23 different digitally programmable output radio power levels ranges from -20dBm to +5dBm and linear RSSI to measure the strength of the received signal. [8].

The aforementioned resources of such wireless sensor platform seem unfit for computationally expensive or power-intensive operations and for communications which are much more expensive than computation on battery-powered wireless sensor devices. Therefore, explicit energy saving strategy is extremely essential to extend battery lifetime. Furthermore, to ensure a reliable long-term data gathering by sensor networks in fading channels [14], there are problems such as the ability of network sensor nodes to function correctly in such environments while minimizing packets retransmissions and maximizing the length of time the network is able to deliver data before nodes' batteries are exhausted.

B. *Experiment Methodology*

In this sensor network experiment, source nodes transmit data packets at the nominal rate to any nodes that can hear it. Receiving nodes forward the data to the base station initially depending on the local information that have been maintained in the node's neighbor table, so the most energy efficient path is selected. The work in this paper considers the following assumptions: the testbed network comprising homogeneous sensor nodes e.g., all nodes are identical with the same resources and initially with the same residual power; the network topology is static unless a node is replaced due to failures; the base station is fixed and the communications pattern is many-to-one; single radio channel; omni-directional whip antenna, and event-driven sensing mode.

C. *Testing Setup*

TinyOS was used as the development environment in this work, which is an event-driven operating system intended for low-power sensor networks with limited resources. The testing environment was conducted indoor in showground building and was done on a testbed network of 20 Mica2 sensor nodes with one perimeter base station used to collect messages sent within the network. To limit the transmission range, the motes were placed directly on the ground and to determine the distance which provides a reliable delivery rate but minimizes the possibility of a mote transmitting further than to adjacent motes; motes closer to the base station were placed at varied distances and the delivery ratios recorded. Then, the distance that provided a successful packet reception ratio (PRR) was used. PRR is calculated as the total number of packets received successfully divided by the total packets transmission epochs.

In such indoor environment, where the radio behavior is irregular due multipath fading channels, the radio power was initially reduced to the minimum output power setting -20dBm (10μW), and variable in-between spaces to provide a one-hop reliable delivery rate and to minimize opportunistic reception. The source sensor nodes generate packets, while the network operates for a given epoch; the number of messages received by the base station was recorded. The Mica2 motes were labeled with numbers and placed in predetermined locations. The base station mote was placed on the MIB520 Mote Interface Board which powered by an AC power supply and attached to a laptop that contains measurements log files.

V. EXPERIMENTAL RESULTS

Although the WSN is positioned in indoor environment with very limited ambient noise, multihop WSN has several challenges which represent in: the wireless link failures that limit the number of traversed packets that can be in flight concurrently from source to destination due to unreliable wireless transmission at each hop; MAC protocol contention problems from hidden nodes and/or exposed nodes; the physical-layer properties that may constrain the throughput achievable over a multihop route; end-to-end reliable delivery of data requires each delay-sensitive packet to traverse one or more intermediate hops from the source sensor node towards the base station in timely manner.

A. *Route Reliability*

The RSSI values seem to decreasingly fluctuate as the distance between sensor nodes increase. Although the indoor experiment is performed with stationary sensor nodes, the RSSI values of Mica2's CC1000 radio have a tendency to fluctuate as shown in figure 2 where the values presented are average values from the packets that are received and do not imply a steady link with fixed packet size. It was observed that within short distances of few meters, the RSSI were generally stronger with a small packet loss. For longer distance, at 10 meters, the link quality has a bit stronger RSSI readings. However, the RSSI readings follow an exponential diminishing while the successful packet reception ratio is still high; after approximately 12 meters of distance with low RF power and mote are placed on the ground, the signal is noisier and its strength deteriorates to the minimum receive sensitivity of the CC100 transceiver which is about -98dBm [7]. This extreme sensitivity can be interfered by another oscillator from neighboring Mica2 nodes. Hence, a distance of at least 65cm should be maintained between adjacent mica2 nodes to avoid local oscillator interference. However, at low transmission power levels, the sensor nodes are still able to communicate with each other. Using CC1000 RF chip's RSSI independently may not be adequate indicator of the link quality for reliable connectivity; even with high RSSI there might be severe interference. As a result, the link quality need to be computed based on bit or packet error ratio estimations.

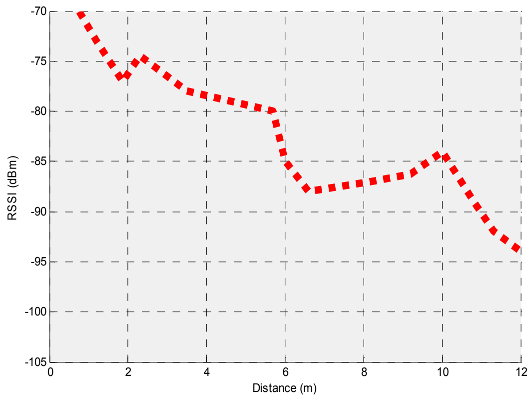

Figure 2. RSSI Indoor Mesurements

The experience with the experimental work done here has revealed several underlying issues that stem from the properties of the reliability-oriented routing layers provided by TinyOS, i.e., MintRoute, combined with the resource constraints of the mote platform. These issues include energy efficiency, long-term link estimations, count-to-infinity and routing loops. RLBR scheme considers the suitable countermeasures to address such issues. During the parent selection process, MintRoute uses link quality estimations with the surrounding neighbors together with cumulated route qualities estimations to the base station, but the hop count metric included in the route updates is completely ignored. This can lead to undesirable results in MintRoute, when a sensor node has optimal routes with two or more neighbors with the same best link quality. MintRoute will then arbitrarily choose one of them as its new parent node using its default minimum transmissions (MT) metric, which results in an optimal route that could be in some direction faraway from the base station and in the worst case in the opposite direction of where the base station is located. This results in an undesirable routing problem, e.g., routing hole. The natural occurrence of suboptimal routes is taken into account by the proposed scheme when performing parent selection by adopting, for instance, the tree-level number in terms of the least number of hops is used as a tiebreaker; this advantage does not apply for MintRoute. In MintRoute, only next packets transmission may probably reduce the already perceived link quality, which makes the current selective forwarder look less attractive.

In other words, the parent selection process in MintRoute is merely based on link quality. When the link quality degrades, neighboring sensor nodes will choose other sensor nodes with a better link quality. For example, creating routing holes in MintRoute is straightforward due to purely relying on the best link quality. When a sensor node has the base station as one of its neighbors, the sensor node will not automatically choose it as its parent. Instead, it will choose the neighbor with the best link quality. To be selected, a sensor node must have both a good send and receive quality. To get a high send quality, the high value must be included in a route update sent by the relay sensor node that caused a routing hole. To get a high receive value, this relay sensor node will have to keep sending packets to prevent the decaying of the receive value by the sensor node. The number of packets that might be lost also lowers the receive quality.

Figure 3 shows an example of how routing in MintRoute picks sensor node 14 as a parent for node 16 instead of node 19 and constructs the optimal route through sensor node 14 even though node 14 is in the opposite direction of where the base station is located. In figure 3, sensor nodes 11, 13 and 16 select node 14 as their parent with best ink quality using optimal routes that purely based on link quality estimations using MT metric. This leads MintRoute to cause a routing hole to the downstream child nodes at node 14. As a result, MintRoute is deemed to be unstable in packets transmission to be efficient.

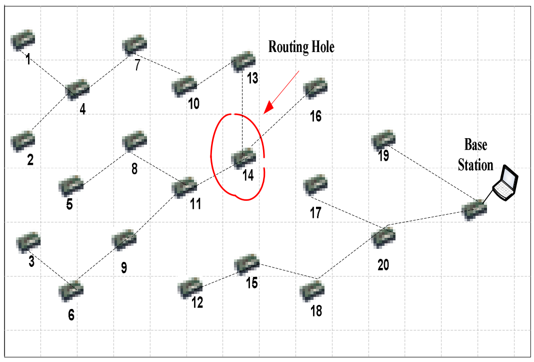

Figure 3. Status of Routing Hole Problem

B. *End-to-End Packet Delivery*

In multihop indoor WSN, the achieved packet delivery performance may be inferior than it should be for several reasons at different layers. At the MAC layer, specifically the

B-MAC used on Mica2 motes, CSMA-based MAC protocol backoff waiting times at each wireless sensor node could cause a packet to be lost before it has been transmitted if a sensor node senses a busy wireless channel for a maximum number of times. In this situation, the sensor node will simply discard the packet and move on to the next packet. Besides that, packet loss due to link failures or collisions leads to a high rate of link layer retransmissions; thereby resulting in a low packet reception ratio (*PRR*) and inversely a high packet loss ratio. As a consequence of packet retransmissions, a considerable amount of the energy is spent for repairing lost transmissions as well as for re-establishing asymmetric links.

At the physical layer, indoor environment surroundings, and the orientation of Mica2 motes and their antennas have unconstructive effect on packet delivery performance. In addition, high signal strength is a necessary but not a sufficient condition for good *PRR*, especially when a higher transmission power is used, conceivably due to the effect of Multipath Rayleigh Fading Channel (MRFC) [14]. Furthermore, there is a number of factors cause a packet to be corrupted and thereby packet is to be considered lost or not received at all at the destined recipient. In other words, a packet may be lost due to errors in the wireless transmission, signal degradation caused by multi-path fading, packet drop due to channel congestion, faulty mote hardware, and packet collision due to the hidden node problem [13]. In addition to this, packet loss probability is also affected by signal-to-noise ratio and distance between the transmitter and receiver. As a result, predicting the source of the packet loss is complicated and unclear in terms of the hardware. In addition, this indoor experimental testbed indicates that low-power radio connectivity is inconsistent, even though in ideal settings.

At the link layer, a packet loss due to link failures is the most common in WSN channels. When data aggregation is enabled, a single link failure will result in an sub-trees of aggregated values being lost. If the failure is close to the base station, the influence on the resulting aggregate can be significant. Figure 4 shows the impact of link failures on packet reception ratio at the base station for the proposed scheme and MintRoute with disabled link layer acknowledgements. Although link failure rate is very low, a small percentage of sent packets are lost due to packet collisions.

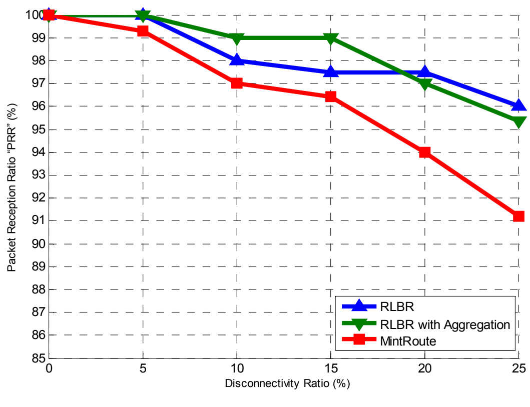

Figure 4. Avrage Packet Reception vs. Link Failure Ratio

As an overall, RLBR outperforms MintRoute owing to its lighter traffic as a result of data aggregation, which leads to fewer packet collisions. But when the link failure rate starts to increase above about 20%, the packet reception ratio of the proposed scheme with aggregation is lower than when aggregation is disabled; this is due to unsuccessful data aggregation along failed routes or due to outdated data packets. Thus each encapsulated packet contains more aggregated packets being lost. On average, without data aggregation, most sent packets are successfully delivered by greater than 95% and the packet loss is lower in RLBR even tough the link failure rate increases.

C. *Average Dissipated Energy*

Failed packets reception that may result from packet collision or link failure requires packet retransmission to be successfully received at the destined recipient. Figure 5 shows the total dissipated energy consumed for retransmissions due to packet loss or link failures. Since RLBR scheme has the feature of employing the implicit acknowledgements strategy as stated in [26] for less communication overhead, packet transmission is less than that in MintRoute. The fewer packets sent results the less energy consumed for packet receiving, overhearing, and failed packet retransmission. In addition, the total dissipated energy for packet transmission is still much lower in RLBR than in MintRoute also RLBR requires less computation overhead for parent selection process. On average, the proposed scheme saves around 35% on energy consumption for communication less than MintRoute. MintRoute keeps transmitting route message, e.g., control packets, at constant periods and the beaconing rate doesn't adjust with topological changes. In terms of energy, the non-adaptive beaconing followed by MintRoute [17] consumes additional energy and is not energy efficient even in low rate of link failures.

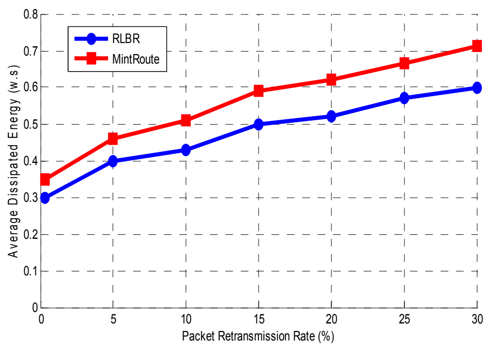

Figure 5. Average Dissipated Energy due to Link Failures

VI. Conclusion and Future Work

This empirical research in the context of WSNs has given a good understanding of the complex and irregular behavior of low-power indoor wireless channels. Since the wireless links in low-power WSNs are not stable, and the loss of packets happens frequently in communications, the link quality metric is mainly used by most reliability-oriented routing protocols to select the optimal link. However, WSNs are mainly powered by AA batteries and the resources are limited. If the reliability of communication is purely deemed as a routing cost metric, a number of nodes will be exhausted quickly. Consequently, this number of dead sensor nodes is extremely essential to the lifetime of the entire network; if these important sensor nodes fail to relay packets, the network's functionality will be ruined. In other words, if only the link reliability metrics are considered in WSNs, it may create a long hops route, and the high quality paths will be frequently used. This may lead to shorter lifetime of the high quality routes and longer delivery delays; thereby the entire network's lifetime will be significantly minimized. In the indoor experiments conducted in this paper, MintRoute protocol improperly assumes that links are stable with independent packet losses and uses this assumption to derive link quality estimations inaccurately based on long-term link estimations.

Therefore, a reliable, energy aware routing is a key issue for maximizing functional lifetime of the low-power WSNs. As an overall, the proposed routing scheme, RLBR, achieves over 35% energy savings over the standard network layer currently provided by TinyOS-2.x MintRoute and reaches a better connectivity rates and communication reliability in terms of end-to-end packets delivery performance. Finally, RLBR scheme performs well as it shows a high success ratio of packet delivery and moderate energy consumption.

Maximising the network lifetime is the subject of ongoing work on outdoor wireless sensor network testbed comprising IEEE802.15.4-enabled RF transceivers, i.e., CC2420 radio chip that provides a much more reliable RSSI/LQI/bit error patterns. In addition comparisons using intensive simulations are being considered in order to validate the experiments on large-scale sensor networks.

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