www.ietdl.org

Published in IET Communications
Received on 20th October 2010
Revised on 2nd June 2011
doi: 10.1049/iet-com.2010.0932

In Special Section on Smart Space Technological Developments

ISSN 1751-8628

Reliable routing for low-power smart space communications

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Abstract: Smart space (SS) communication has rapidly emerged as an exciting new paradigm that includes ubiquitous, grid and pervasive computing to provide intelligence, insight and vision for the emerging world of intelligent environments, products, services and human interaction. Dependable networking of a SS environment can be ensured through reliable routing, efficient selection of error-free links, rapid recovery from broken links and the avoidance of congested gateways. Since link failure and packet loss are inevitable in SS wireless sensor networks (WSNs), the authors have developed an efficient scheme to achieve a reliable data collection for SSs composed of low capacity wireless sensor nodes. WSNs must tolerate a certain lack of reliability without a significant effect on packet delivery performance, data aggregation accuracy or energy consumption. An effective hybrid scheme is presented that adaptively reduces control traffic with a metric that measures the reception success ratio of representative data packets. Based on this approach, the proposed routing scheme can achieve reduced energy consumption while ensuring minimal packet loss in environments featuring high link failure rates. The performance of the proposed routing scheme is experimentally investigated using both simulations and a test bed of TelosB motes. It is shown to be more robust and energy efficient than the network layer provided by TinyOS2.x. The results show that the scheme is able to maintain better than 95% connectivity in an interference-prone medium while achieving a 35% energy saving.

1 Introduction

Recent advances in technology miniaturisation, wireless networking and sensor technology combined with contemporary research unveil the integration of wireless sensor networks (WSNs) at a global scale to a tighter coupling between the virtual and real world [1, 2]. This reveals the vision of future physical environments, specifically, smart space (SS) communications. Smart space is a defined physical space (e.g. home, building, office) with pervasive, ubiquitous and context-aware capabilities and thus providing automatic and adaptive services to its users by means of wirelessly connected sensor nodes [2]. These sensor nodes may have various capabilities of sensing, actuating, communicating and computing. In low-power WSNs, the unreliability of the links and the limitations of all resources bring considerable complications to routing [1, 3]. Even though most deployed WSNs use stationary nodes or have low mobility, the channel conditions vary due to the effects such as asymmetrical low-power radio performance or multipath fading effects, which alter the patterns of radio wave reflections [3, 4]. Since sensor nodes are typically battery-powered and the ongoing maintenance may be impracticable, the progressive reduction of the residual power needs to be considered jointly with other factors as an essential factor in the parent selection process to control nodes' energy drain to ensure the achievement of reliable load balancing for the extension of the lifetime of the individual nodes and consistent energy usage within the entire network [5–7].

In a context-aware system with thousands of data items describing the current situation, it is obvious that this data needs to be filtered and aggregated in order to distribute the processing and the traffic efficiently. The need to aggregate data exists also from the perspective of the WSN, since energy is limited and there is a strong requirement to reduce communication traffic. However, the main drawbacks of the existing reliability-oriented routing protocols for WSNs are merely 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 [3, 5]. This results in the arbitrary routing of traffic to sensor nodes with potentially low energy capacity. Consequently, these overloaded relay sensor nodes deplete their residual power faster than their peer nodes. This significantly reduces the lifetime of these sensor nodes and can adversely affect the entire network [3, 5, 7].

2 Research contribution

This paper aims to facilitate and integrate low capacity wireless sensor nodes to form SSs while efficiently taking into account the communication reliability and resources usage which is crucial for a SS of wirelessly connected resource-constrained sensor nodes. This paper focuses on the development of a reliable, energy-balancing routing scheme for network lifetime maximisation. The routing scheme combines the reliability metrics of [6] and the energy balancing of [7, 8]. The proposed solution takes into consideration the WSNs characteristics of resource limitations and communication patterns in favour of reliable and energy-efficient data dissemination. In addition, it allows a child sensor node to dynamically search for a reliable set of alternate parent nodes with more residual energy. The latency implications of specific parent selection are also factored. Therefore this paper develops a novel routing scheme that consumes less energy while reducing topology repair latency and supports various aggregation weights by redistributing packet relaying loads. Our new scheme aims to decrease unnecessary route message transmissions using adaptive beaconing while achieving a high success rate of packet delivery and moderate energy consumption. This concept is proven by experimental testbed implementation, measurements comprising interference-prune channels and large-scale computer simulations to validate the experiments.

3 Related work

A common characteristic of the existing collection tree protocols (CTPs) is the use of network layer beacons to propagate route information 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 the lowest quality hop [4]. As an example of the immediate cost approach, if a child sensor node decides to select its parent based on its current link quality; it would pick the neighbour 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 upstream link qualities of the parents towards the base station. 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 also has weaknesses. 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 if the sum or the average of its link qualities is the highest among multiple available routes [6, 8].

These CTPs can be either classified as a proactive distance vector routing protocols such as MintRoute [9], or reactive distance vector routing protocols such as MultihopLQI [10] and CTP [11]. The advantages and disadvantages of such routing classes are well investigated and discussed in [1, 3, 12]. For example, in reactive protocols, sensor nodes do not need to maintain route entries to the base station as routes are requested on demand, thus saving memory space. Associated with this benefit are a number of drawbacks, including the fact that route request messages use a broadcast mechanism which can easily lead to broadcast flooding. The unique communication architecture of WSNs creates the potential for the selection of a suboptimal route. This is due to the limited topological information available to the sensor node, the delay that is incurred in acquiring a route and the energy profile of relay sensor nodes [13, 14]. Consequently, these are factors that should be considered when using a reactive routing protocol. Our proposed routing scheme adopts a similar mechanism to route propagation but uses a joint *ad hoc* proactive and reactive approach.

From the reliability point of view, the CTPs vary in the way they determine the route cost metric. MintRoute [9] employs the expected number of transmissions (ETX) reliability metric [15]. ETX represents the cost in terms of the ratio of the expected number of received packets to the number of packets actually received on the immediate link. MultihopLQI [10] and CTP [11] are developed as variants of MintRoute [9]. While CTP attempts to improve upon MintRoute by summing the link costs across all hops, MultihopLQI uses a cumulative function of the hardware-based link quality indicator (LQI) as a cost metric. This hardware-based LQI is provided by IEEE802.15.4-compliant radio frequency (RF) transceivers such as those found on TelosB motes [16]. MintRoute and CTP use ETX [15] as a routing cost metric of the single-hop sender and window mean exponentially weighted moving average estimator [17] as an average filter. However, the aforementioned collection protocols are reliability-oriented protocols and do not explicitly employ energy or load balancing in their routing schemes [18, 19]. Arbutus [19] is also a CTP but load balancing is 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 utilisation of network resources, it does not jointly consider communication patterns with link reliability and energy-wise metrics in determining an optimal load balanced topology. There is no doubt that a better distribution of relayed loads will lead to the more efficient use of bandwidth, leading to less contention and consequently lower energy consumption [20, 21].

Another important challenge in low-power WSNs deals with balanced energy usage for packet transmissions as it has been shown in [8, 20–23]. For example, if packets are frequently relayed through relay sensor nodes along a selected route, these relay sensor nodes will deplete their batteries faster and fail earlier than their peers on other routes. The proposed routing scheme appropriately adapts to such situations through awareness of the relaying loads and the energy level of the relay sensor nodes. The scheme also aims for load balancing between relay sensor nodes in terms of balanced energy usage and minimised energy dissipation for packet transmissions via adaptive beaconing and in-network aggregation of data packets. The proposed scheme adopts a flexible approach that combines some of the advantages of the energy-aware protocols [7, 8] on the top of the reliability-oriented protocols [6, 10]. It also accommodates fault tolerance and adaptability to link and topology changes, while minimising communications overheads.

4 Routing scheme description

4.1 Overview

Communication overheads are the major energy consumer of sensor nodes. The proposed scheme aims to add minimal communication overheads for network configuration and multihop data dissemination. Based on our existing work in [6–8], the proposed routing scheme uses multiple metrics including channel state information (CSI) (e.g. received strength signal indicator and LQI), links estimations based on packet transmissions (e.g. packet reception ratio and packet error ratio) and residual energy capacity. In addition, the proposed scheme makes use of other parameters in the

doi: 10.1049/iet-com.2010.0932

routing cost function (e.g. node identifier, cyclic redundancy check, number of hops, aggregation load and latency). Furthermore, the proposed scheme is a hybrid (i.e. reactive and proactive) routing protocol designed to adaptively provide enhanced balanced energy usage on reliable routes and to employ ready-to-use neighbourhood routing tables in order to allow sensor nodes to quickly find a new parent upon parent loss due to link degradation or when sensor nodes run out of energy.

4.2 Overhearing-based data aggregation

Using the broadcast nature of the contention-based wireless medium, a sensor node can easily observe its neighbourhood by overhearing periodic beacon packets. The proposed solution reduces the energy consumed when transmitting packets by embedding useful routing information into the overheard packets to allow for taking the advantage of traffic overhearing and also minimising control traffic. As a result, it maintains low packet error rates and improves packet delivery, while minimising redundant packet transmission and retransmissions throughout the network. Fig. 1 shows the communication range for a sensor node 1. While node 1 is sending its packets to its current valid parent 2, it can overhear the packets sent from 3 to 4 and from 5 to 6. Using this overheard information, sensor node 1 can change its current parent from 2 to 4 or to 6 in order to reduce the aggregation load on 2. This reduces the likelihood that time-sensitive, aggregated data will be dropped at the overloaded sensor node 2. Assuming the following are met: sensor node 4 compared to node 2 has a lower aggregation load, better link quality with 1, higher residual energy; and node 4 has a higher id compared to node 1; node 3 sends its packets to 4 within its vicinity. In terms of energy dissipated for transmissions, it is more efficient for sensor node 1 to send its data packets to 4, where its data packets can be aggregated with 3 and 4's data packets. However, aggregating sensor node 1's data packets with 3's and 4's is dependent on the aggregation queue state information maintained in sensor node 4. Node 4 must not be overloaded with aggregated data packets in order to allow the routing scheme to ensure the 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. It can be enabled or disabled based on the application and physical topology. Since this distributed parent selection process is performed dynamically on a packet-by-packet basis, this approach is adaptive and the topology of aggregation can change to accommodate different situations based on the aggregation or relaying load.

However, aggregating data packets at each sensor node of the selected route requires extra processing energy which increases energy consumption. The parent selection process also consumes energy. To ensure a high success reception ratio of data packets, it requires control traffic, which again demands extra energy. Considering all these factors, data packet delivery efficiency (η) is used as a measure of the effectiveness of this approach in minimising packet transmissions throughout the network. Data packet delivery efficiency (η) is the ratio of the total number of data packets received at the base station to the total number of control and data packets in the network. This is expressed in (1). η is used as a benefit metric to gauge end-to-end packet delivery performance of the routing scheme in terms of route message transmission weight. Conversely, the reciprocal of data packet delivery efficiency, namely, data packet delivery cost ($1/\eta$) is used in Section 6.4 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.

$$\text{Delivery efficiency}\,(\eta) = \frac{\text{Number of received data packets}}{\text{Number of sent data and control packets}} \tag{1}$$

4.3 Estimating the energy cost

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 balancing, these nodes will deplete their residual energy faster, thereby making the network worthless. In Fig. 2, it is supposed that an optimal multihop route r is constructed by N linearly adjacent sensor nodes transmitting with a given transmission power level of P_{tx}. A data packet is relayed over the route r with similar link reliabilities from source sensor node n_i 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_{n_i} by node n_i at each hop. Equation (2) expresses E_r as a function of the HC from the sensor node n_i at which the packet is generated along the route r

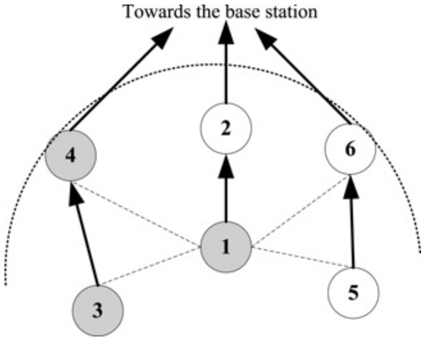

Fig. 1 *Overhearing neighbourhood traffic*

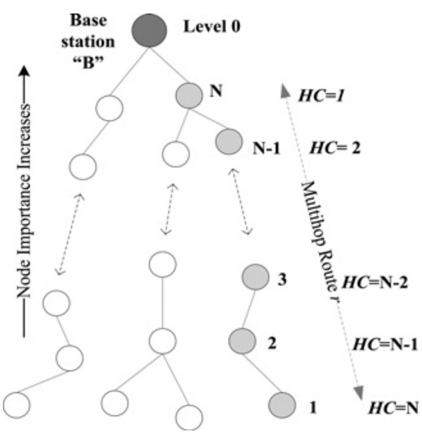

Fig. 2 *Calculating energy cost over route r*

towards the base station, where HC $= (N + 1 - i)$ and E_{n_i} is the average consumed energy by an individual node n_i.

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

In this work, the following assumptions are made: the packet transfer rate at all sensor nodes along the routing path r is the same; the time $t_{n_i,r,b}$ required for forwarding the packet is the same at each relay node and the transmission power is fixed for all sensor nodes. However, E_{n_i} is increasing as the sensor node n_i becomes closer to the base station as it forwards more packets from its downstream nodes. For example, the most critical sensor node is node n_N, which is the closest sensor node to the base station and always consumes the maximum amount of energy as a result of relaying packets originated at all $(N - 1)$ sensor nodes, for example, $n_1, n_2, \ldots, n_{N-1}$, 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 HC (also known as tree depth or level number). The next step focuses on the derivation of the average consumed energy E_{n_i} 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 neighbour node n_{i+1} with link reliability probability $P_{n_i,r,n_{i+1}}$ which is the readiness of a sensor node n_i to relay a data packet towards the base station through a selected route r of $(N + 1 - i)$ hops. Parent selection process uses the link reliability probability to embody the link quality metric of the routing scheme. A sensor node n_i may also send directly to the base station 'B' with probability $P_{n_i,r,B}$ based on its location, where $P_{n_i,r,B} = 1 - P_{n_i,r,n_{i+1}}$. Therefore the average dissipated energy of node n_i is E_{n_i} which is expressed by (3)–(5). Assuming the following assumption is met: each sensor node generates an equal amount of traffic with a transmission power of P_{tx} and the traffic is relayed over a route r through a chain of N adjacent sensor nodes with consistent spacing using the nearest-neighbour routing approach. A similar assumption is discussed in [23]. However, the assumption neglects the complexity of the wireless channel. All energies in the following derivations are normalised by P_{tx}. Recalling that $i = N + 1 - \mathrm{HC}$ and $P_{n_i,r,n_{i+1}} = 1 - P_{n_i,r,B}$.

$$E_{n_i} = \left(\left(\sum_{j=1}^{i} P_{n_j,r,n_{j+1}}\right) + \mathrm{HC} \times P_{n_i,r,B}\right) \tag{3}$$

$$E_{n_i} = \left(\sum_{j=1}^{i} [1 - P_{n_i,r,B}] + (N + 1 - i) \times P_{n_i,r,B}\right) \tag{4}$$

$$E_{n_i} = (N + 1) - \left(\mathrm{HC} + \sum_{j=1}^{i-1} P_{n_j,r,b}\right) + (\mathrm{HC} - 1)P_{n_i,r,B} \tag{5}$$

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 $P_{n_N,r,B} = 1$. The functional network lifetime can be estimated in (6) based on the energy consumption of node n_N in terms of the single-hop link reliability probability $P_{n_i,r,B}$ between node n_N (where $i = N$ and HC $= 1$) and the base station 'B'.

$$\begin{aligned} E_{n_N} &= (N - \sum_{j=1}^{N-1} P_{n_j,r,B}) \\ &= (N - [P_{n_1,r,B} + P_{n_2,r,B} + \cdots + P_{n_{N-1},r,B}]) \end{aligned} \tag{6}$$

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 to the energy dissipation of node n_{N-1}, the sum of $(N - 1)$ one-hop link reliability probability of $P_{n_i,r,B}$ or $1 - P_{n_i,r,n_{i+1}}$ must be smaller than the value of order of N 'O(N)'. The $(N - i + 1)$ link reliability probabilities can be estimated by solving (6) using two-dimensional matrices for $(N - i + 1)$ hops along the route r.

$$\begin{bmatrix} N & 1 & \cdots & 1 \\ 0 & (N-1) & \cdots & 1 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 2 \end{bmatrix} \begin{bmatrix} P_{n_1,r,B} \\ P_{n_2,r,B} \\ \vdots \\ P_{n_{N-1},r,B} \end{bmatrix} = \begin{bmatrix} N-1 \\ N-2 \\ \vdots \\ 1 \end{bmatrix}$$

To consider the benefit of energy balancing of the proposed routing scheme, it is informative to allow gauging of the energy discharge behaviour in terms of energy depletion rate $R(e_{n_i})$ of a critical sensor node n_i. The total residual energy capacity of this sensor node's battery e_{n_i} is divided into energy levels, and at the beginning it is assumed that the initial energy capacity of all sensor nodes is 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 $R(e_{n_i})$ at which the residual energy capacity e_{n_i} of node n_i is reduced can be expressed in (7) which is only valid for $t_{n_i,r,i+1} > 0$, where $t_{n_i,r,i+1}$ is the time spent by 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, $t_{n_i,r,i+1}$ is also identical to the time spent for node n_i for receiving or aggregating a packet from node n_{i-1}. $R(e_{n_i})$ is measured in energy unit per second.

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

Consequently, the functional lifetime T_{n_i} of an individual 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 $e_{n_i}(t_0)$ by energy depletion rate $R(e_{n_i})$ as in (8).

$$T_{n_i} = \frac{e_{n_i}(t_0)}{R(e_{n_i})} \tag{8}$$

Given these assumptions, the maximum relay sensor node's lifetime T_{n_i} is achieved by minimising $(1/T_{n_i})$. Logically the maximum lifetime of a given route r is determined by the weakest intermediate or relaying sensor node, which is that with the highest cost. While $P_{n_i,r,n_{i+1}}$ is the probability of forwarding a packet to the next hop n_{i+1} through the

IET Commun., 2011, Vol. 5, Iss. 17, pp. 2491–2500
doi: 10.1049/iet-com.2010.0932

route r, $P_{n_i,r,n_{i-1}}$ is the probability of receiving a packet from node n_{i-1} through the route r. Hence, $R(e_{n_i})$ is a bidirectional function of the energy expenditure for relaying the projected network traffic by receiving and transmitting packets at a given energy depletion rate of $(P_{n_i,r,n_{i+1}} \times e_{n_i})_{tx}$ and $(P_{n_i,r,n_{i-1}} \times e_{n_i})_{rx}$, respectively. Similarly, for a WSN of m randomly deployed sensor nodes, where every sensor node has k available routes towards the base station, the entire network's functional lifetime T_{WSN} can be maximised as in (9).

$$T_{\mathrm{WSN}} = e_{n_i}(t_0) \sum_{j=1}^{k} \sum_{i=1}^{m} \left[\frac{t_{n_i,r_j,n_{i+1}}}{(P_{n_i,r_j,n_{i+1}} \times e_{n_i})_{tx} + (P_{n_i,r_j,n_{i-1}} \times e_{n_i})_{rx}} \right] \tag{9}$$

4.4 Bounded real-time aggregation deadlines

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 minimise these transmissions to improve the energy-efficiency and cost-effectiveness of low-power, duty-cycled WSNs. Therefore aggregating smaller relayed data packets into larger encapsulated packets bounded by the maximum transmission unit could significantly minimise the number of packet transmissions and improve energy savings. However, in real-time applications, these encapsulated data packets vary in their deadlines and sensitivity to end-to-end delay. These deadlines are governed by the importance of the sensing measurements. As shown in Fig. 3, the average end-to-end delay is the sum of all single-hop delays along the selected route r_j. Owing to on-flight aggregation when the delay calculations occur, 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_{agg}. This time is known as the per-relay aggregating or encapsulating delay. In this case, the average (n_i-to-B) end-to-end delay $\Delta t_{n_i,r_j,B}$ is estimated on-flight on route r_j between sensor node n_i at the point of data encapsulation and the base station 'B' by summing the individual delays as stated in [24]. However, the total accumulated per-relay encapsulating delay including propagation on route r_j must not exceed the remaining time $\Delta t_{\mathrm{remaining}}$ which is the time left before the associated real-time deadline $\Delta t_{\mathrm{deadline}}$ expires. In other words, per-relay aggregating delay Δt_{agg} 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 $\Delta t_{\mathrm{arrive}}$ to be aggregated with other

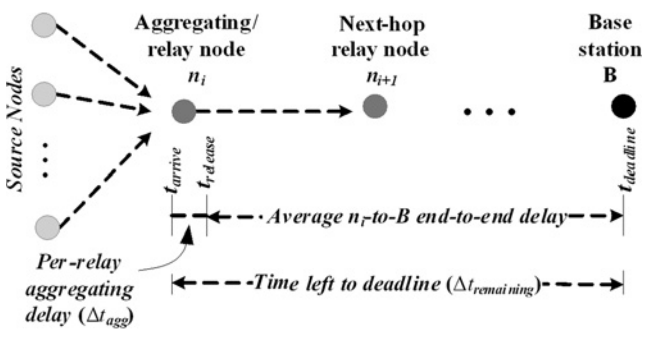

Fig. 3 *Calculating aggregating delays*

data packets, Δt_{agg} must be bounded and the encapsulated packet is sent at an appropriate dispatch or release time $\Delta t_{\mathrm{release}}$. Subsequently, this dispatched, encapsulated, data packet might also be re-encapsulated on further hops and Δt_{agg} must permit receipt within the packets delivery deadlines. In the case where $\Delta t_{\mathrm{agg}} \le 0$, $\Delta t_{n_i,r_j,B}$ is negative and the arriving packet must be relayed immediately without encapsulating delay. In other cases the arriving packet can be delayed for $\Delta t_{\mathrm{agg}} = \Delta t_{\mathrm{remaining}} - \Delta t_{n_i,r_j,B}$.

Since the packet encapsulates more than one data element over the route of $(N-i)$ relay sensor nodes, the encapsulated packet at relay node n_i must be dispatched once either sensor node n_i reaches its memory limit or one of these packets reaches the end of its minimum dispatch time of $\min(\Delta t_{\mathrm{release}})$. This time must satisfy the accumulated condition

$$\sum_{k=i}^{N} [\min(t_{\mathrm{release}_k}) - t_{\mathrm{arrive}_k}] \le \sum_{k=i}^{N} \Delta t_{\mathrm{agg}_k}$$

over a route of $(N-i)$ nodes.

5 Evaluation methodology

Our proposed scheme is evaluated experimentally using testbed experiments in addition to large-scale simulations. The experiments were conducted using 30 Crossbow TelosB motes (i.e. TPR2420CA model) [16] running the TinyOS-2.x [25]. The TelosB combines a low-power 8 MHz MCU with 10 kbytes RAM, integrated antenna and an IEEE 802.15.4-compliant Chipcon CC2420 RF transceiver chip [26]. The CC2420 provides the data link layer and offers a data rate of up to 250 Kbps. The TelosB operates within the 2.4 GHz ISM band and employs the offset quadrature phase-shift keying modulation scheme. The interested reader should consult [16, 27] for more details about the TelosB 2.4 GHz platform which is designed for low-power WSNs. The TelosB motes are deployed randomly within an outdoor area of approximately $100 \times 100\ \mathrm{m}^2$ and commence transmitting with the same residual power capacity using fresh AA batteries. The only exception is the base station which is powered via a USB port on a laptop running Linux. This acts as a bridging device that has IEEE802.15.4 coordinator functionality. The base station relays control packets from the laptop to deployed sensor nodes. These control packets contain adjustment parameters (e.g. transmission rates of originated packets). The base station relays the collected data packets sent by sensor nodes to the laptop to be saved in a metrics log file. In a tree topology, longer routes were stimulated by picking a routing tree root (i.e. the base station) at the perimeter or 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 10×10 grid with uniform 10 m spacing between motes and a single stationary base station deployed at one corner to ensure a deep routing tree. IEEE 802.15.4 is used as the medium access control (MAC) and physical layer protocol with bandwidth of 250 Kbps, consistent with our experimental parameters. The wireless medium is simulated in network simulator 2 (ns2) using the multipath shadowing propagation model [4] as it characterises the realistic propagation behaviour in an outdoor environment. The energy consumed for communications are measured by implementing the ns2 radio energy model configured with

doi: 10.1049/iet-com.2010.0932

power parameters matching those of the Chipcon 2.4 GHz CC2420 [16, 27]. At the beginning of each simulation, each sensor node is assigned with the same initial energy level. The base station features a persistent energy supply as is usually the case in real WSN applications.

Our routing scheme is compared with the baseline TinyOS-2.x MultihopLQI [10]. The MultihopLQI routing layer is a well-established and well-tested CTP that is part of the TinyOS-2.x distribution and has been recently used in real WSNs deployments as stated in [11, 28, 29]. Therefore the benchmarking with MultihopLQI is considered a reasonable evaluation. Evaluation metrics include network connectivity, to assess the significance of wireless link reliability on packet loss probability; average end-to-end delay in terms of delivery rate; average dissipated energy and network lifetime.

6 Experimental testbed results

6.1 Network connectivity and link dynamics

The dynamic conditions of the communication channel require a periodic update of the link quality information. TinyOS-2.x MultihopLQI merely uses link quality information at the physical layer of each received beacon individually. The link quality information is hardware-based and provided by the radio circuitry of the IEEE 802.15.4-compliant radio transceiver. This pure reliance on one form of CSI leads MultihopLQI to inappropriately react with the asymmetric links which is a typical feature of low-power WSNs [17, 28, 30, 31].

The proposed scheme solves the asymmetric link problem by taking the average of the link quality values to provide better packet delivery ratio estimations. It also uses bidirectional link estimations based on required retransmissions for active bidirectional monitoring of link status. This allows the proposed solution to properly switch to alternate parents when exceeding a threshold of maximum transmission failures. As illustrated in Fig. 4, with the MultihopLQI protocol, sensor node 1 chooses sensor node 4 as its parent, but node 4 never receives acknowledgment packets back from node 1. This is a result of an asymmetric link between 1 and 4 that makes node 4 unreachable for node 1's packets. In the proposed scheme, this problem can be solved using averaged link quality values and allowing a child sensor node to pick its parent from the same level. Sensor node 1 can switch to an alternate neighbouring node. For example, node 2 becomes a valid parent for node 1 after the maximum transmission failure threshold is exceeded due to link asymmetry and transmission range between nodes 1 and 4. Routing loops can be avoided using the node identification (id) as a tiebreaker in addition to tree level number.

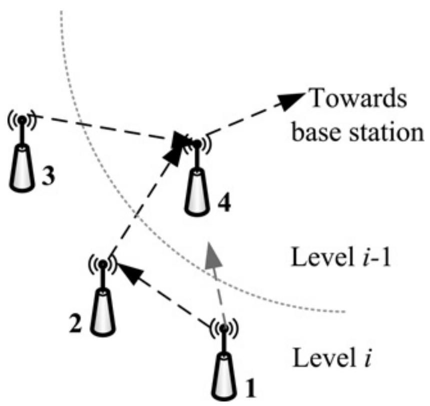

Fig. 4 *Link asymmetry problem*

Fig. 5 shows how the proposed routing protocol builds its multihop route in the deployed topology in terms of end-to-end delivery delay and HC via a snapshot of the transmitted packets' sequence numbers. During the beginning of the transmission or epoch, the proposed routing protocol has a slightly higher delivery delay due to the overheads of route configuration. However, it immediately improves its delivery performance with lower retransmissions and lower control packet rate. As a result, the end-to-end packet delay decreases gradually despite traversing a longer route.

6.2 Recovery from link failures

The proposed scheme provides a faster recovery from broken links due to the hybrid approach utilising backup neighbouring routing tables. This can be seen in Fig. 6*a* when a link is broken at 100 ms after the transmission epoch. When an alternative energy-efficient and reliable route is established using consecutive repair phases, the average end-to-end delay decreases considerably. Consequently, the average throughput is improved even though the number of hops has increased, which may negatively affect the timeliness of time-sensitive data packets. This chosen, reliable, route requires a lesser number of retransmissions to successfully deliver a data packet at an average delivery rate of 99.6% at 120 ms. On the other hand, MultihopLQI provides an average delivery rate less than 78% after the same period of time. As the time passes, 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 the parent selection process takes some time. As MultihopLQI maintains only a state for one parent node at a time, neither routing tables nor blacklisting are used. However, this resulted in additional energy cost associated with the significantly increased packets retransmissions required to successfully deliver a data packet. In view of the cost of beaconing route messages (i.e. control packets), over long run of 7 h, the beaconing rate is adaptive on a per sensor node basis. It starts with a slightly high rate in the proposed

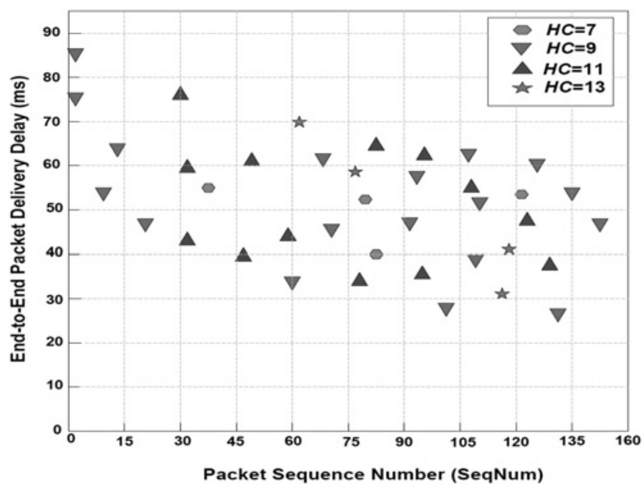

Fig. 5 *Route configuration delay in terms of HC*

doi: 10.1049/iet-com.2010.0932

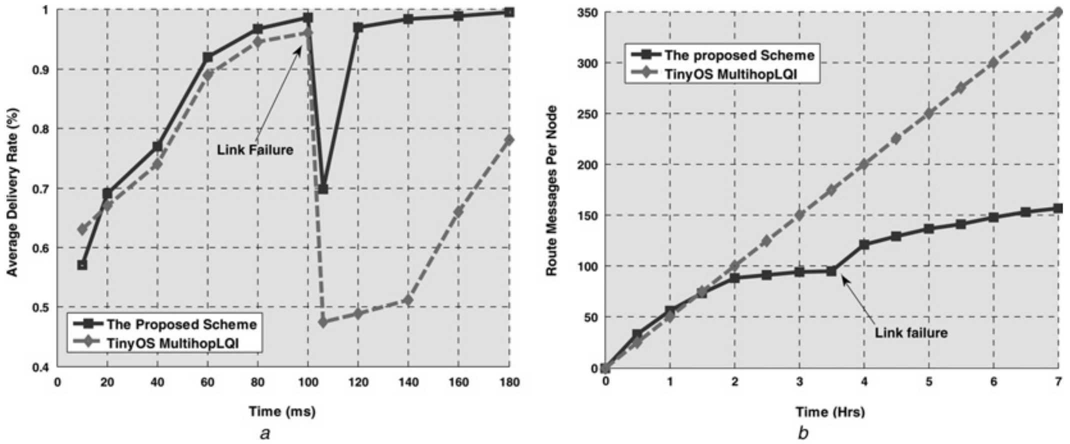

Fig. 6 *Recovery from broken links*

a Average delivery rate
b Route messages per node

scheme at the beginning due to the rapid establishment of the routing tree, then begins to decrease and stabilises at a lower rate. Fig. 6*b* illustrates, on hourly basis, the average number of route messages that are transmitted per sensor node in order to build and maintain the routing tree.

The message beaconing pattern in the proposed scheme is slightly raised at the fourth hour due to an intentional link failure. This failure was introduced to demonstrate the rapid reconstruction of an alternative, but longer, route. Once again it adaptively embarks on an uneven rate pattern in order to become stable eventually. By comparison, MultihopLQI avoids routing tables by only maintaining a state for the best parent sensor node at a given time. It keeps transmitting control beacons at a constant rate of 30 beacons per second, considerably higher than our proposed scheme.

6.3 End-to-end packet delivery delay

In order to jointly evaluate the reliability and delivery performance of the routing scheme, a number of intermediate wireless sensor nodes were switched-off or removed to create broken routes between source sensor nodes and the base station. Figs. 7*a* and *b* illustrate the end-to-end delivery performance of our scheme and MultihopLQI, respectively, in terms of end-to-end delay and HC when a route is broken after packet number 150. The proposed scheme reacts efficiently and responds swiftly to recover from a broken link along the preselected path. It maintains an alternative, energy-efficient and reliable route to recover. This route reconfiguration time is 66.40 ms. This newly constructed route is used temporarily as a backup route to deliver source-originated data packets in a timely manner towards the base station. However, the alternative route may require additional hops, leading to an increase in the average end-to-end packet delivery delay. In this case it is slightly increased to 81.32 ms. In contrast, MultihopLQI is incapable of rapidly recovering from broken routes if a wireless mote on a preselected route is removed. Even though MultihopLQI results in a shorter average end-to-end delay for packet delivery of about 78.43 ms, recovering from the broken route takes a much longer time of around 98.52 ms. Overall, MultihopLQI lacks stability, frequently restructuring its routing tree in response to changes in its LQI, hardware-based, reliability metric. Although MultihopLQI did recover from link failure, its delivery ratio was noticeably reduced. This leads to a lower average packet delivery rate for MultihopLQI as compared to our proposed scheme, validating the aforementioned results.

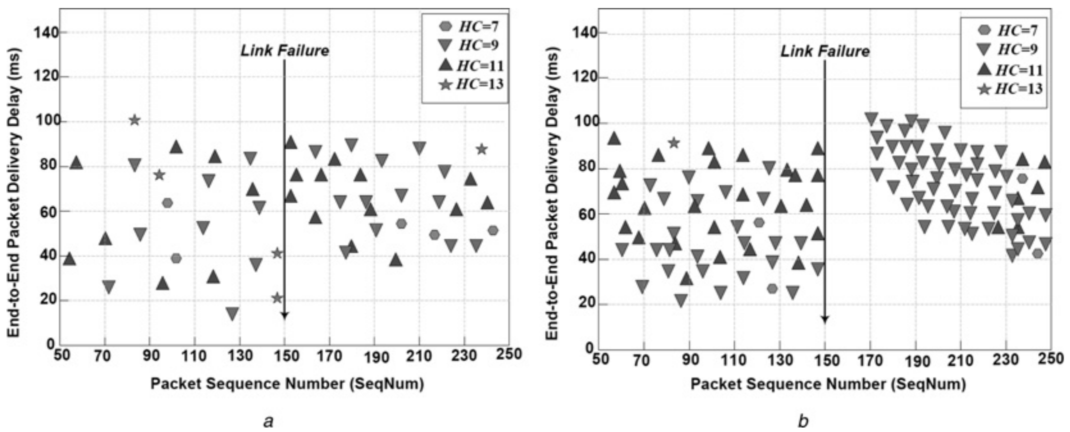

Fig. 7 *End-to-end packet delivery delay*

a Proposed scheme
b TinyOS MultihopLQI

6.4 Routing overhead

In the MultihopLQI protocol, sensor nodes broadcast control packets at a constant rate. In terms of energy, non-adaptive high rate beaconing expends more energy for unnecessary transmissions in conditions requiring infrequent topological changes. In addition, most relayed packets are routed through optimal routes based mainly on link quality. As a result, the selected route will be used frequently and the sensor nodes along this route will be exhausted quickly. This leads to an imbalance in the energy utilisation throughout the entire network. Compared to MultihopLQI, our scheme makes trade-offs between routes based on link reliability and energy efficiency in favour of a more even distribution of forwarded packets among the relaying sensor nodes. In addition, our scheme broadcasts fewer route messages over the life of the network. As a result, our scheme consumes only about 35% of the energy required for route message transmissions as compared to MultihopLQI. To estimate the average amount of energy consumed by relay sensor nodes for delivering a data packet towards the base station, the packet delivery cost $(1/\eta)$ is used as a routing overhead metric. This cost metric $(1/\eta)$ accounts for the ratio of the total number of control and data packets to the total number of data packets received at the base station. On average, our scheme achieves higher delivery efficiency while incurring a significantly lower control overhead than that of MultihopLQI. Fig. 8 demonstrates how the packet delivery cost $(1/\eta)$ for our scheme and MultihopLQI changes over the long run and gives an estimation of the average energy cost incurred for packet transmission throughout the network.

7 Simulation results

7.1 Functional network lifetime

Using simulations of a larger network featuring 100 sensor nodes with a range of source nodes between 30 and 70 in number, our proposed scheme balances the energy consumption and keeps updating energy-efficient routes. Overall, Fig. 9 shows that the network lifetime declines as the number of deployed sensor nodes increases, due to the high volume of control and data packets that are retransmitted throughout the sensor network. Compared with MultihopLQI, our scheme results in a slower and a more graceful linear degradation of the network lifetime. This leads to a substantial improvement in the expected life of a WSN. Although MultihopLQI has an occasional ability to balance the traffic load based on link quality estimates, the large numbers of redundant packet copies that are retransmitted between different sensor nodes depletes the available energy more rapidly. To this end, the simulation results agree with the assertion made earlier that the proposed scheme can reduce the energy consumed for transmissions and maximise the network lifetime.

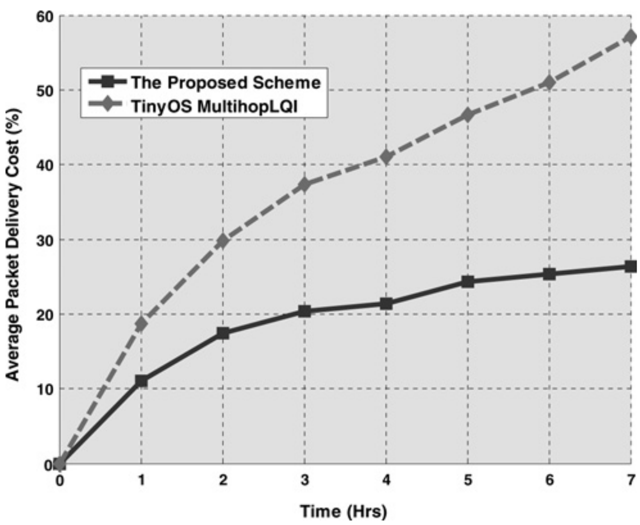

Fig. 8 *Packet delivery cost $(1/\eta)$*

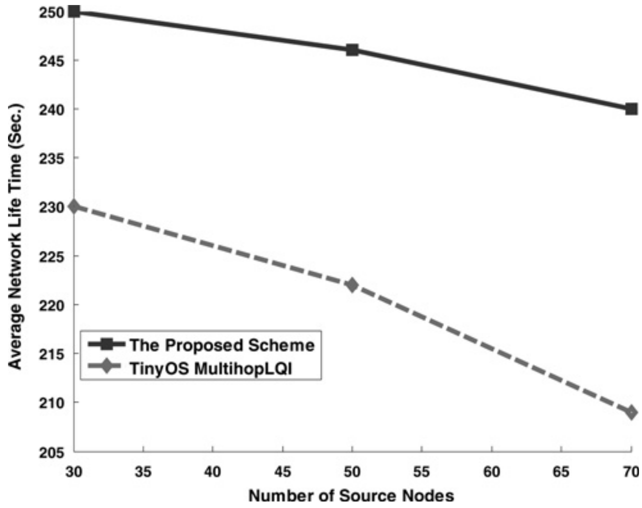

Fig. 9 *Average network lifetime*

7.2 Average dissipated energy

Fig. 10 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 average dissipated energy by the sensor nodes in all routing schemes increases with the number of source nodes.

Compared with MultihopLQI, the proposed routing scheme performs favourably with energy consumption increasing linearly with the number of source nodes. In contrast, MultihopLQI dissipates more energy for the same number of source nodes and the energy dissipation increases considerably as the number of generating nodes

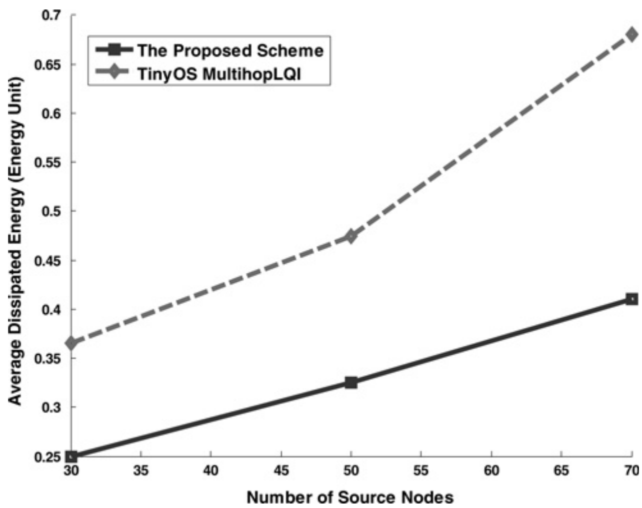

Fig. 10 *Average dissipated energy*

IET Commun., 2011, Vol. 5, Iss. 17, pp. 2491–2500
doi: 10.1049/iet-com.2010.0932

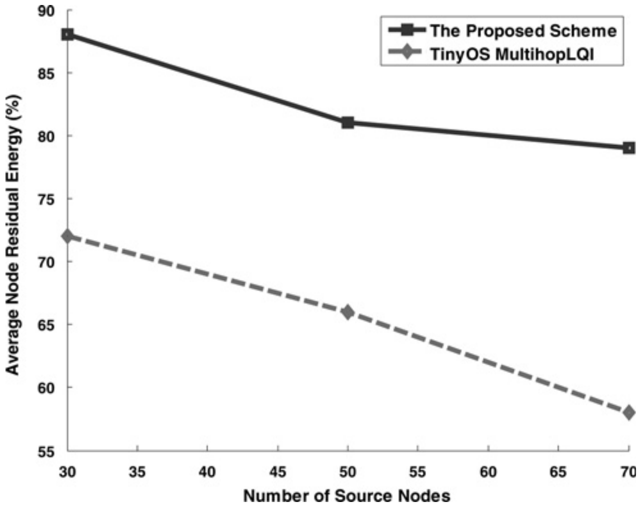

Fig. 11 *Average residual energy*

grows. This suggests that our scheme is capable of supporting larger WSN than MultihopLQI.

Fig. 11 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 cannot reduce the redundant data copies in the network which is the result of the high traffic load handled by each individual forwarding node. This degrades the average remaining energy level with MultihopLQI much faster than our routing scheme which keeps a balanced network workload towards the base station to maintain balanced energy dissipation.

8 Conclusion and future work

In this work, a reliable energy-efficient collection tree routing protocol is proposed based on a per-hop load-balancing routing scheme. It leverages recent advancements in the standard network layer components provided by the TinyOS2.x implementation of MultihopLQI. Our proposed routing scheme consumes less energy while reducing topology repair latency and supports various aggregation weights by redistributing packet relaying loads. It transmits a smaller number of route messages than MultihopLQI. The decrease in route message transmissions of our scheme is a result of using adaptive beaconing. This resulted in lower beaconing rates and lower control cost while the network topology stabilises; thereby achieving lower energy consumption. Our routing scheme performs well with a high success rate of packet delivery and moderate energy consumption.

The experiments conducted here have highlighted the substantial performance gains of the proposed solution. Our ongoing work aims to further validate the performance of the proposed routing protocol in large-scale WSNs. We also aim to improve the protocol through the inclusion of other routing metrics and examine other routing protocols that consider energy and security aspects.

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