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Self-decision route selection for energy balancing in wireless sensor networks

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In many wireless sensor network (WSN) applications, data from the monitored environmental phenomenon only need to be sampled intermittently and transmitted to the base station. Hence, an intelligent protocol that balances the traffic load among the nodes and minimizes their energy usage, especially during routing and idle listening, which is necessary to extend the network lifetime. In this paper, a load balancing model that balances the rate of energy dissipation of the sensor nodes across the network is proposed. The proposed energy balancing scheme distributes the traffic load regularly and slowly over the sensor nodes during routing, such that the overall network life time is optimized, and the sensors die almost all at the same time. The proposed energy balancing protocol reduces the high energy consumption during the transmission and reception states, this is done by introducing multi-hop instead of single-hop communication of each node with the sink. Simulation results show that the proposed energy balancing protocol reduces the transmission energy usage by up to 64%, while the reception energy usage is reduced up to 67%. Moreover, the system throughput as well as the network lifetime increased up to 79% and 66%, respectively.

Key words: Wireless sensor networks, energy balancing, energy saving, lifetime.

INTRODUCTION

A wireless sensor network (WSN) is a group of sensor nodes (SNs) working in uncontrolled areas and organized into cooperative network (Akyildiz et al., 2002). Each node has processing capability, a radio, sensors, memory and a battery (Baronti et al., 2007). Since the SNs are usually operated by a limited battery power which may not be replaceable once deployed, it is therefore, vital that the sensor network is energy balanced in order to ensure an extended network lifetime.

Due to the same limitation, the network topology and the distance between communicating nodes remain critical deployment issues (Anastasi et al., 2009). In some cases, the nodes can be placed in a deterministic way, such that the WSN is energy-efficient if an appropriate placement strategy is employed (Akkaya and Younis, 2005). In most deployment scenarios however, problems such as harsh environmental conditions make deterministic node placement infeasible. Thus, random deployment remains the only option, which may not be energy efficient. As such, smarter techniques should be implemented to decrease energy consumption in the sensor nodes which tend to rapidly drain their batteries. This can be attained using various approaches. At the physical layer, energy consumption can be minimized by decreasing system-level power consumption during the hardware design or using suitable techniques such as dynamic voltage scaling or duty-cycle reduction. Alternatively, data link layer techniques could be employed to combat excessive energy usage in WSNs. These include using MAC protocols that consider collision, overhearing, listening and overheads resulting from the exchange of control packets (Kredo and Mohapatra, 2007). At the

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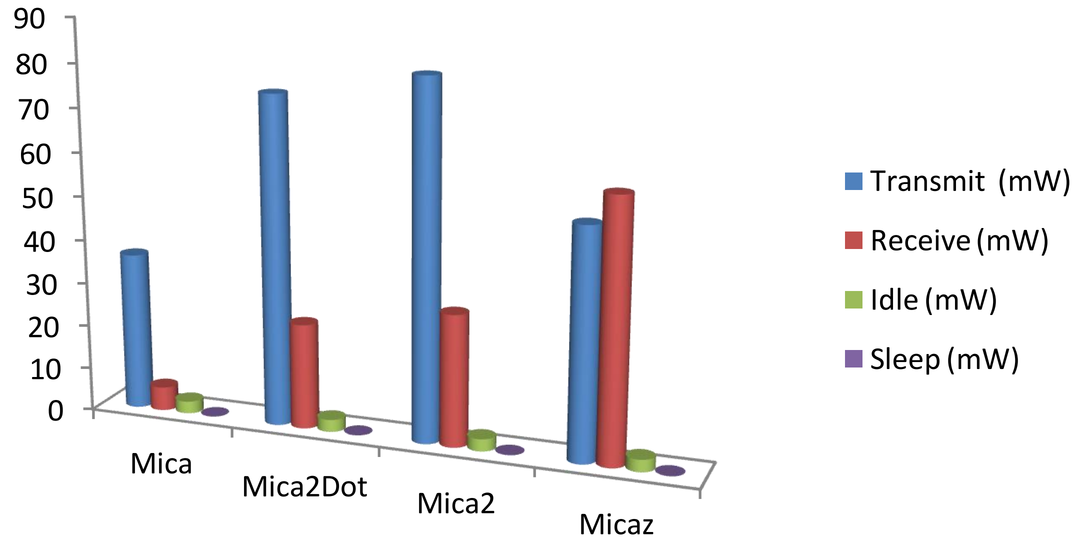

Figure 1. Energy consumption in radio sensor with different motes.

network layer however, energy consumption is principally due to data routing.

Therefore, most WSN routing protocols aim to minimize energy consumption using either average consumed energy or total energy dissipated (Lindsey et al., 2001). The amount of energy consumed by a SN depends heavily on the number of packet exchanges between the nodes, including the energy overhead due to route setups and maintenance.

The main objective of this paper is to minimize the high energy usage of the sensor node, especially during routing. This is because network activities start to be challenged when the first sensor node exhausts its battery; hence, the proposed energy balancing routing protocol prevents sensor nodes from directly transmitting to far off nodes when forwarding data to the sink, as this will cost unnecessarily high energy expense. As such, multi-hop communication strategy is employed, which takes advantage of other nodes which still have high residual energy.

PRELIMINARIES ABOUT ENERGY CONSUMPTION IN WSNs

Radio communication of sensor nodes incurs high energy costs on the sensor. As shown in Figure 1, the most energy consuming states of the radio system are the transmission and reception compared to idle and sleep in different crossbow motes namely: Mica, Mica2Dot, Mica2, Micaz (*Web-Page*). Hence, in this paper, only the energy consumption due to transmission and reception of data packets are considered.

Here, the main origins of energy consumption in WSN and the mechanisms to deal with them are discussed. In order to conserve energy at the routing layer, the following has to be noted:

1. Data transmission: Packet transmission causes the largest energy depletion and is proportional to the number of packets transmitted. Hence, energy conservation routing models must seek to reduce the number of transmissions.

Mathematically, the energy required to transmit *i*-bits through distance *d* is calculated based on (Heinzelman et al., 2000):

$$E^{Tx}(i,d) = (E^{elec} \times i) + (E^{emp} \times i \times d^2) \qquad (1)$$

where E^{elec} is the energy consumption of the electronics circuit during the transmission and E^{emp} is the energy consumption of amplifier.

2. Data receiving: Data reception and processing consume a great deal of energy as well. Hence, a good routing protocol must aim at decreasing the number of packet reception. Energy dissipation due to packet reception by a sensor node based on Heinzelman et al. (2000) is given by:

$$E^{Rx}(i) = (E^{elec} \times i) \qquad (2)$$

Another problem which should be considered in the reception mode is overhearing which also consumes energy during packet routing. Overhearing is detection of packet traversal by a node which is not the intended recipient. As such, the routing protocol should seek to decrease the number of overheard messages.

3. Idle state: During the idle state, the sensor consumes energy as well, but switching off the radio in idle mode minimizes the energy usage in this state.
4. Size of packet: The size of the packet in routing is an important factor to consider for the benefit of in-network processing such as, data aggregation or compression.
5. Distance: The distance between the sensor nodes during communication has a direct bearing on the amount of energy usage for packet traversal, in that the higher the distance, the higher the energy used for transmission.

The outlined energy consumption modes can be minimized by either sensor level schemes, where each sensor implements the scheme alone or by network level schemes, where the implementation is done through the cooperation of sensors in the network.

LITERATURE REVIEW

The majority of routing protocols for WSNs is aimed at decreasing the energy usage of sensor nodes by either explicitly taking energy into account during the route selection or by optimizing some metrics, such as minimizing the energy consumed per packet, reducing the cost / packet ratio, or minimizing the high energy depletion of any one sensor.

Approaches which minimize the energy consumed per packet in many cases lead to poor routes in that some sensor nodes may be unnecessarily overloaded and thus rapidly drain their batteries. One way to solve this problem is to maintain a balanced residual energy for all sensor nodes in the network. This is because the normal operation of the network may cease when a few nodes run out of energy, even if the majority of the nodes still have a near-full battery capacity.

Moreover, choosing the lowest energy cost paths may not always extend the lifetime of network because some of the sensor nodes over those paths may have limited residual energy, and hence, will deplete their energy very fast. As such, distributing the traffic load and energy consumption fairly across the sensor nodes is a more desirable strategy for routing protocols.

Many energy efficiency MAC and routing protocols have been presented to reduce energy usage in WSNs using sleep mode to turn off some SN (Deng et al., 2005; Yong et al., 2011), to saving energy and extend lifetime, during idle mode. In Wang et al. (2007), the authors presented dynamic awakening method, that makes sleep time longer for SNs by estimating the idle phase for each node during sensing and transmission mode. Hence, the SNs within the desired object range switch to active mode on time and serve like sensing candidates. Their dynamic scheme improves the energy efficiency and reduced the total consuming energy in the sensor network. In Chen et al. (2008), a new network layer energy efficient routing strategies are proposed, where sleep state of some nodes were considered as well.

A prominent energy-efficient algorithm for clustered networks is the low energy adaptive clustering hierarchy (LEACH) (Heinzelman et al., 2000). LEACH uses data aggregation techniques and a cluster head selected in a random way. It is a routing model based on hierarchical topology and energy efficiency. Matrouk and Landfeldt (2009) proposed the routing based on energy–temperature transformation (RETT-gen), which is a modification of the LEACH protocol, taking into consideration residual energies of the sensors in routing decisions. They disseminate equally the energy load over all SNs in networks thereby extending the network lifetime. However, the persistent problem in this protocol and other clustering protocols is that the cluster formation process as well as the probabilistic cluster-head selection incurs high overheads and complexity.

Rogers et al. (2005) proposed the self organized routing (SOR) protocol, where nodes conserve energy by employing other nodes as mediators to increase the survival time of the network. They introduced payment schemes for sensor nodes that act as mediators. Payment received by a node depends on whether it transmits its own packet or acts as a mediator for others. The protocol is energy efficient due to the self interest orientation of the nodes, using local information to make informed decisions.

Ok et al. (2009) proposed a distributed energy balanced routing (DEBR) protocol, which decentralizes the data traffic in the network in a way that prolongs the lifetime of the network. The algorithm made a tradeoff between packet delay and energy. Despite the applicability of the algorithm in many WSN scenarios, it assumes that each SN is within the direct communication range of the sink, which is not true for multi-hop routing.

Hence, our proposed energy balancing scheme uses the nodes with high residual energy to take part in the data packet relaying to the sink, and excludes nodes with low residual energy; thereby extending the ability of the SNs to communicate with each other as long as possible.

PROPOSED ENERGY BALANCE ROUTING PROTOCOL

Network model

A wireless sensor network can be designed as a connected graph G(V,E), where V is the set of sensors and E represent the set of communication links. Let 1 represent two sensors which are directly connected while 0 represent two unconnected sensors. Given a sensor node v϶V with transmission range R, if v is transmitting, all nodes within the carrier sensing of V will not be able to access the medium when the channel is busy. The transmitted packets from V can follow one of the possible paths in the graph G(V,E) that connects v to the sink node. In the proposed model, a node can transmit data packets to any neighbor within range. All sensors are static. All the sensors have equal initial energy and only the energy consumed due to the transmission and reception of packets is considered.

Energy and lifetime models

Recall that energy consumption in WSN is mainly due to the radio system in active mode. In fact, the energy consumed in the sleep and idle modes are so small compared to transmit and receive modes that they are assumed to be negligible in the proposed energy balancing model. The energy consumption of some sensors in the different modes is presented in Figure 1.

Let sensor node x has N bits of packets to transmit or receive during active mode (per unit time). Accordingly, the total energy consumption ToEnC(x) for x can be calculated as:

$$ToEnC(x) = EnC^{Tx}(x) + EnC^{Rx}(x) \quad (3)$$

where the $EnC^{Tx}(x)$ and $EnC^{Rx}(x)$ are the circuit energy consumption for the node x during the transmission and receiving states respectively. The energy consumed due to transmission $EnC^{Tx}(x)$ is given by

$$EnC^{Tx}(x) = EnC^{elecT} + EnC^{amp} \quad (4)$$

where EnC^{elecT} is the electronic circuit energy consumed due to the transmitter, which is calculated as:

$$EnC^{elecT} = EnC^{mx} + EnC^{Sny} + EnC^{filt} + EnC^{dac} \quad (5)$$

where EnC^{mx} , EnC^{Sny}, EnC^{filt} and EnC^{dac} are the energy consumption of the mixer, frequency synthesizer, filter and digital to analog converter respectively, and EnC^{amp}, the energy consumed by the power amplifier.

In the same manner, the energy consumption in the receiving state $EnC^{Rx}(x)$ is given by

$$EnC^{Rx}(x) = EnC^{elecR} \quad (6)$$

where EnC^{elecR} is the electronic circuit energy consumption at receiver and calculated as:

$$EnC^{elecR} = EnC^{mx} + EnC^{Sny} + EnC^{filt} + EnC^{lna} + EnC^{ifa} + EnC^{adc} \quad (7)$$

where EnC^{lna}, EnC^{ifa} and EnC^{adc} are the energy consumption of the low noise amplifier, the intermediate frequency amplifier and the analog to digital converter respectively.

Based on Equations (3) to (6), the energy consumption per packet bits $EnC_{Pkt}(x)$ is given by

$$EnC_{Pkt}(x) = ToEnC(x)/N \quad (8)$$

Therefore, the lifetime of sensor node x based on Equation (8) is given by

$$LT(x) = \frac{E_{init}}{EnC_{Pkt}(x)} \quad (9)$$

where E_{init} is the initial energy of the sensor node.

The network lifetime is the time spent from deployment until the complete energy depletion of the first sensor node. This means that, the lifetime of the greediest node in the network must be maximized in order to improve network lifetime. This problem can be represented by the following minimization function:

$$MaxLT(x) = \min(maxEnC_{Pkt}(x)) \;\; x \in V \quad (10)$$

The equation indicates that maximizing network lifetime is a function of minimizing the energy depletion rate of sensor nodes with high energy consumption.

The fundamental steps of the proposed algorithm

Each sensor node maintains table that hold the node identification (node ID), transmission power and the residual energy of the neighboring node. The brief procedures of the scheme are as follows:

1. Initialization: At initialization, each sensor broadcasts a neighbor discovery message to the neighbors. The message includes the node ID and residual energy. Each of the receiving nodes of this packet records the sender node as its neighbor.
2. Updating routing table: The table captures the changes in the energy levels of neighbors. When a sensor node transmits data, all its neighbors receive this data and record the current residual energy of the sender node. Any time the energy level of a sensor changes, all the routing tables get updated.
3. Route selection: Using the information available in the routing table, each node makes a self decision routing based on its available energy as well as the energy level of its neighbors. Thus, a sensor x selects sensor y as the best next hop for sending packets to the sink only if the energy level (*EL*) of y satisfies the following condition y=$\max_{z \epsilon Nx+x}(EL_z)$, without any regard to whether y is within one-hop distance to the sink. If the best next hop is the sensor node itself and has a direct path to the sink, it sends the packets directly to the sink node; thus completing the routing process. Otherwise, it routes the packets to the best next hop among its neighbors, which then follows the same procedure as before.

However, if both a direct and an indirect path lead to equal energy consumption, the direct path is chosen to minimize the number of transmission hops and the delay.

Using this self decision strategy, the wireless sensor network becomes energy balanced resulting prolonged network lifetime.

PERFORMANCE EVALUATION

Simulation environment

The proposed energy balancing scheme is simulated by deploying 10 sensor nodes in a 400×400 m^2 field, with a random CBR traffic being generated by different nodes. The data payload size is 64 byte with 3 s interval time. Moreover, the initial energy is 1.2 Joule, Mica-Motes for energy model and simple linear for battery model are used. The sensors are fitted with omnidirctional antennas with the channel frequency 2.4 GHz, 250 Kbps data rate. Before a node starts to transmit data, carrier sensing is performed in order to determine whether any of its neighbors is transmitting.

The simulation was carried out using QualNet v5 simulator. The results of the proposed model are compared with the Hop-based Spanning Tree (HST) model which uses AODV routing (Perkins and Royer, 1999), with shortest path route discovery.

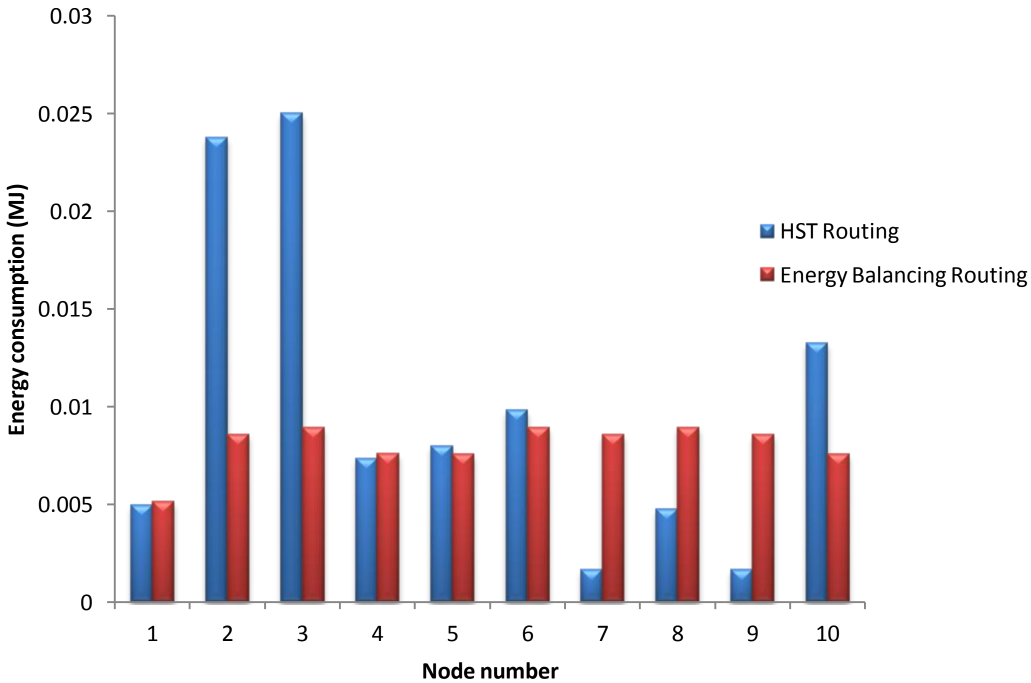

Figure 2. Energy consumption in the transmission state.

RESULTS AND DISCUSSION

The proposed energy balancing model was compared with the HST model in terms of energy consumption due to the packet transmission as shown in Figure 2. Here, our proposed algorithm shows better performance regarding energy conservation compared to the HST algorithm. At node 2 and 3 for example, which are nearer to the sink, the HST model consumed 0.024 and 0.025 mJ respectively, whereas the proposed load balancing scheme only consumed about 0.01 mJ in each case. This shows that the proposed model minimizes energy consumption by up to about 64% compared to the HST model. The reason for this improvement is because these two nodes are closed to the base station and in HST, all nodes route their packets to the sink through them, thereby draining their energy fast. In the proposed load balancing scheme however, the load is distributed across multiple paths based on sensors' energy level, which avoids routing data using the same path all the time.

On the other hand, nodes 7 to 9, which do not deplete their energy much in the HST model because they were not critical to the WSN, have now been used in our proposed model as alternative routes for packets in the proposed load balancing model; thus, saving the energy of critical sensor nodes such as 2 and 3.

Figure 3 shows the energy consumption of the sensors due to the packet reception in the proposed scheme compared to the HST model. It can be seen that the proposed energy balancing routing does much better than the HST model at Nodes 2, 3, 6, 8, 10 in terms of energy savings. In fact, at Node 3, the proposed load balancing achieves up to 67% reduction in energy usage in the receiving mode. The reason for this large savings is because the critical sensors are prevented from receiving many packets from their neighbors as the packets are routed using alternative routes with energy-abundant nodes. Conversely, the HST model only looks for shortest path routes, which may not necessarily be the most energy efficient route. Similarly, the proposed model used the non critical sensors with abundant energy as the alternative routes, resulting in the increase in their energy usage as indicated by sensor Nodes 7 and 9. In the HST however, these nodes are left unexploited while critical sensor nodes die so fast due to excessive routing.

Figure 4 shows the results of the proposed energy balancing scheme compared to the HST in terms of total energy usage of the nodes. It is clear that sensor Nodes 2 and 3 consume much higher energy than the others during routing, causing them to exhaust their energy fast, while other nodes such as 7 and 9 still have high energy levels. On the other hand, the proposed energy balancing scheme distributes the large data traffic directed at the critical nodes to the high energy level nodes. This leads to the reduction of energy usage by Nodes 2 and 3 by up to 57 and 67%, respectively, compared to the HST model.

Figure 5 shows the proposed scheme compared with the HST model in terms of lifetime of the sensor nodes. Again, the proposed load balancing algorithm maintains a near equal lifetime for all the deployed nodes since it

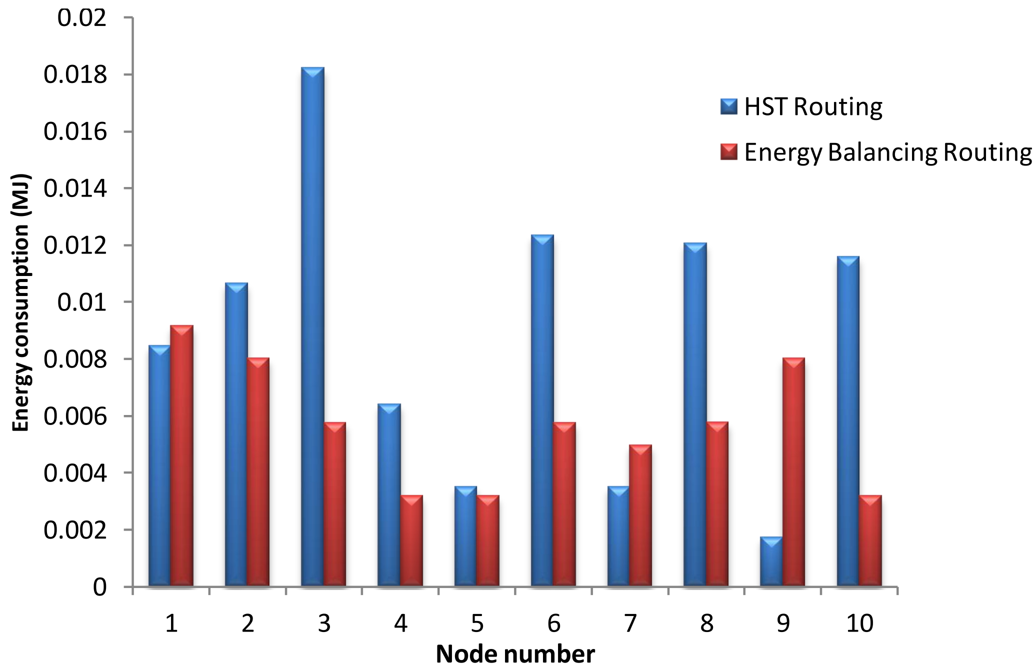

Figure 3. Energy consumption in reception state.

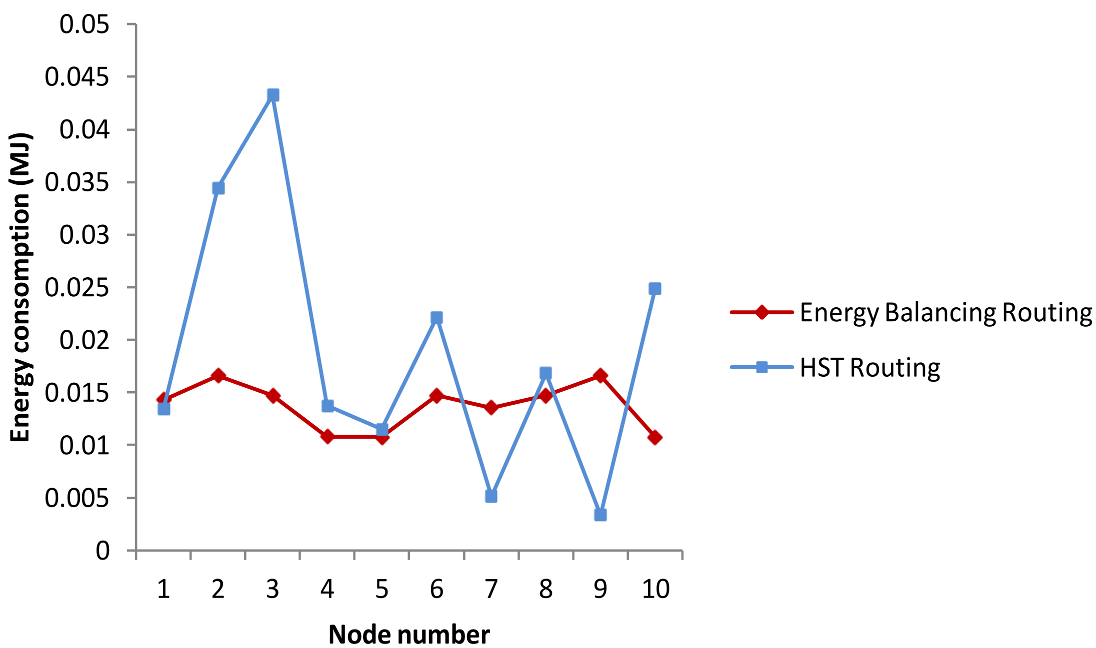

Figure 4. Total energy consumption.

ensures that all nodes are used evenly. In contrast, the HST model shows high disparities in the lifetimes of the different sensors as the bottleneck nodes quickly die out. Clearly, our proposed load balancing scheme improves lifetime by up to 66%, by making use of the high energy level of other nodes such as 7 and 9.

In Figure 6, the energy consumption with time in transmission mode of the proposed load balancing scheme is compared with that of the HST model. Again, the proposed load balancing showed better performance

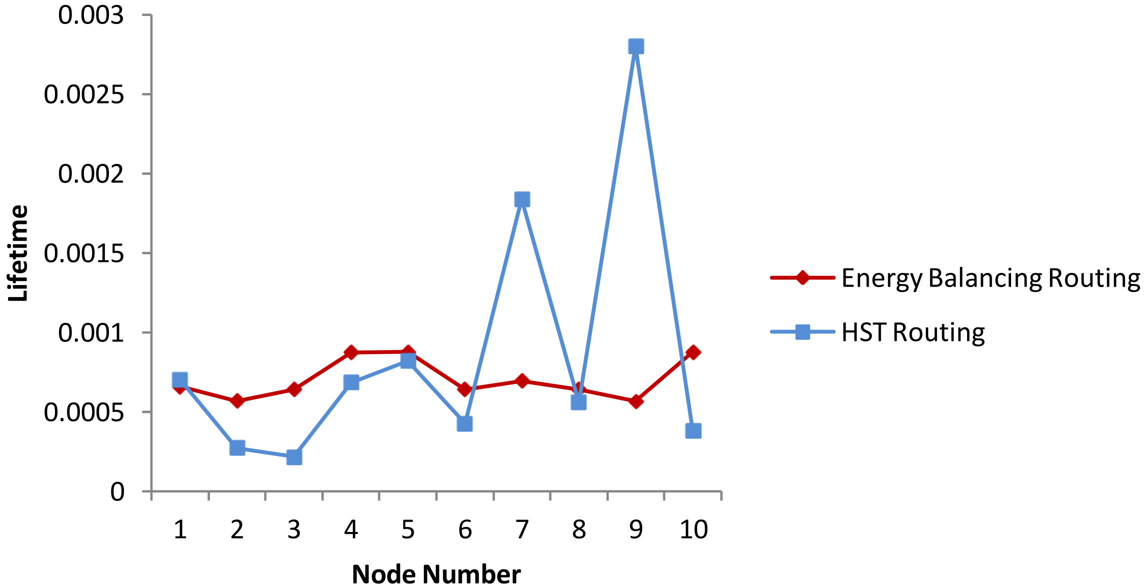

Figure 5. The network lifetime.

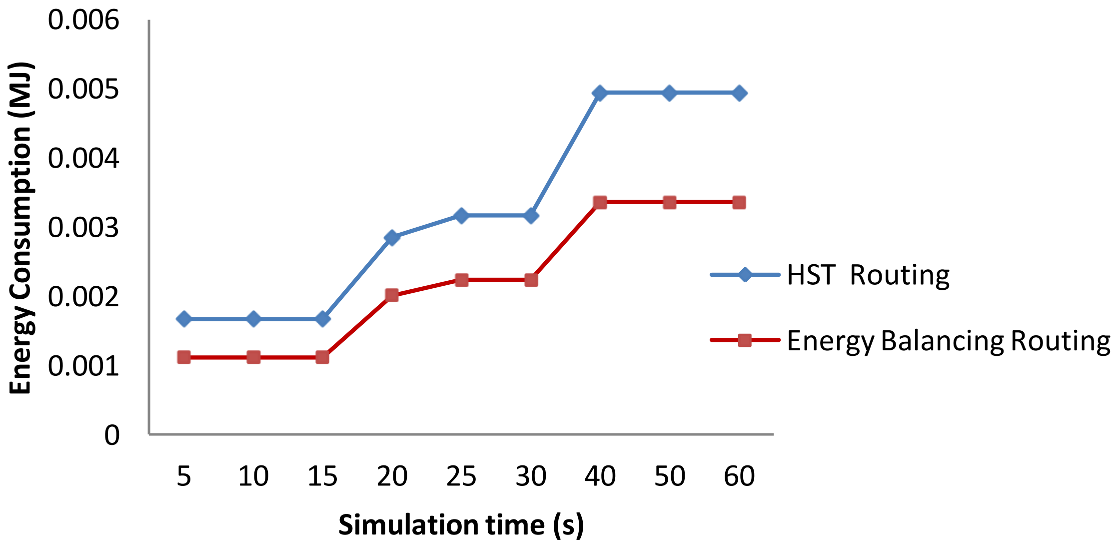

Figure 6. Energy consumption in transmission mode with different time.

with time. When the simulation time was 60s for example, the energy consumption of the HST model is 0.005 mJ, while the proposed load balancing scheme is only 0.003 mJ, an improvement of 40%. In fact, the improvement in terms of energy savings of the proposed scheme tend to increase with simulation time, as indicated by the widening gap between the two curves. The same situation recurred in the receiving mode, as shown in Figure 7.

Figure 8 shows the total energy consumption of the network for the whole simulation time. Just as in Figures 6 and 7, the energy savings of the proposed load balancing scheme far exceeded that of the HST model. At 60s for example, the HST model shows energy consumption of 0.0092 mJ, whereas the proposed load balancing scheme only consume 0.0058 mJ, thus showing a 37% improvement in energy savings. Again, this large energy savings by the proposed scheme can be attributed to the fact that congested sensors with high traffic volume are avoided as alternative routes are found,

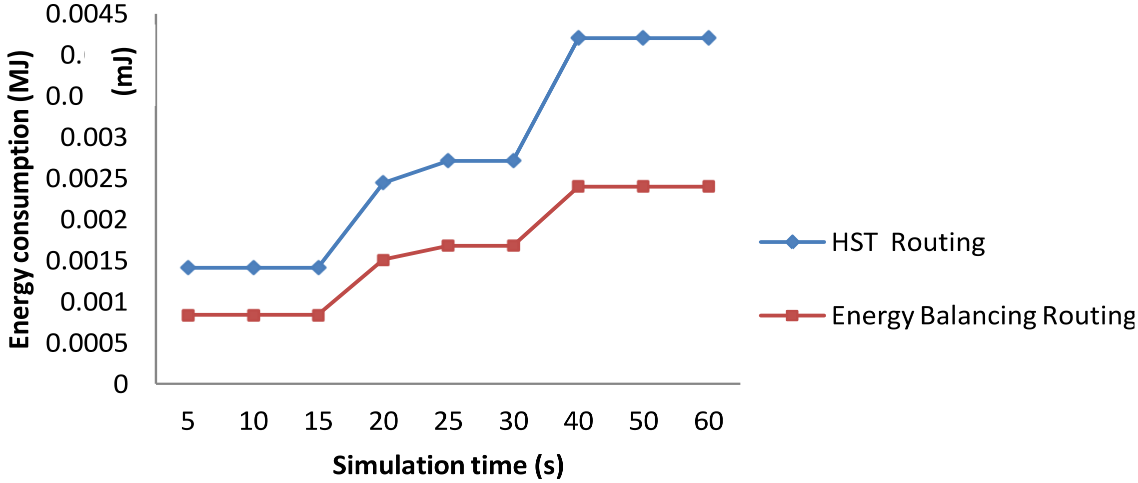

Figure 7. Energy consumption in receiving mode with different time.

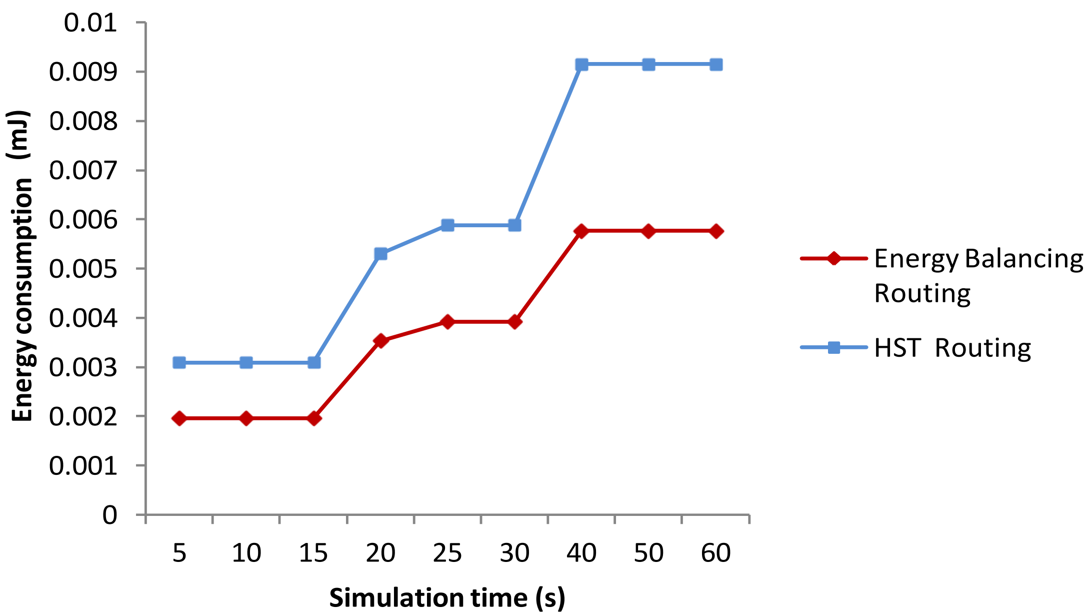

Figure 8. Total energy consumption with different time.

for want of load balancing.

Figure 9 shows the throughput of the proposed load balancing scheme compared with that of the HST model. As in the previous cases, the throughput of the proposed scheme exceeds the HST model at all instances of the simulation time. At 25 s for example, the HST model only achieves 465 bits/s, whereas the proposed load balancing scheme attained 836 bits/s, which is a 79% improvement in the achieved throughput. This stems from the fact that the proposed balancing scheme avoids congestion in bottleneck nodes, as it searches for new routes to the destination, whereas the HST model only uses shortest path. Hence, in the proposed scheme, packet drop is minimized, due to minimal number of congestion.

Conclusion

In wireless sensor networks, the sudden death of critical nodes can lead the entire network to malfunction. This is usually caused by the uneven depletion of battery power

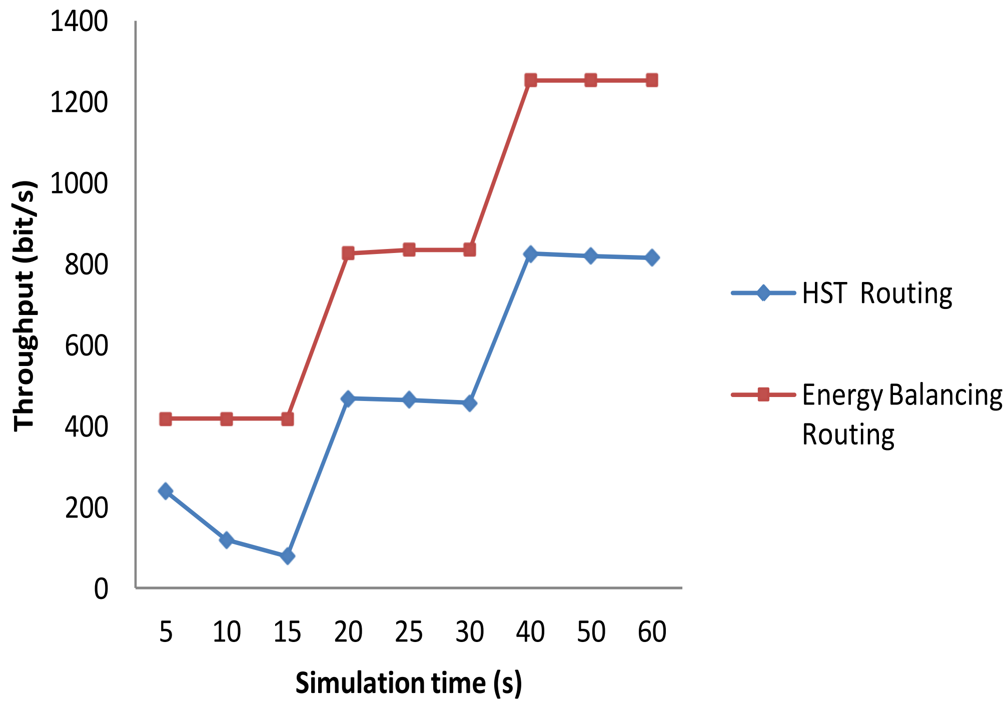

Figure 9. Throughput.

of the nodes. While critical nodes experiencing heavy traffic load deplete their energy fast and die out, nodes in sparse regions in terms of data traffic continue to enjoy high energy levels. In this paper, a distributed load balancing scheme is proposed, where the route selection for data packets not only considers shortest path to the sink but also the current residual energy of the sensor nodes. In our proposal, nodes with limited residual energy are avoided as routers, substituting them with alternative routes using nodes with higher residual energy. The performance of the proposed scheme is then simulated using QualNet and the results showed that the proposed load balancing scheme achieves up to 64% and 67% reduction in energy usage in the data transmission and reception modes respectively. In addition, the network lifetime as well as throughput improves by up to 66% and 79% respectively.

Despite the improvement in network lifetime, throughput, and energy consumption, a limitation of the proposed scheme may prove suboptimal for delay-sensitive applications. However, this limitation is much less significant compared to the aforementioned improvements it afforded.

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