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Robust and Energy-efficient Data Gathering in Mobile Wireless Sensor Networks

***Abstract**. In Mobile Wireless Sensor Networks (MWSNs), nodes are supplemented with implicit or explicit mechanisms that enable these devices to move in space. Packet loss is one of the main challenges that occurs in such networks due to the mobility of the nodes or links failures and it comes in parallel with energy consumption. Many data gathering studies by considering energy-efficiency or reliability are done in MWSNs. However, these goals are generally orthogonal to each other. Apart from achieving proper energy consumption, data gatering approach proposed in this study also will ensure data delivery. In this paper, first, we propose a reliable forward routing mechanism to increase the rate of data delivery regarding the mobility of the nodes. Next, we propose an error recovery mechanism against link failures. On the other hand, by limiting a number of redundant and unnecessary responses from sensors,we have reduced the average energy consumption of the network. As a result, in the proposed data gathering approach, by utilization the aforementioned proposed mechanims, data packets are forwarded through the most reliable and energy-efficient paths and the lifetime of the whole network could be maximized.*

***Streszczenie.** W artykule przedstawiono niezawodny mechanizm routowania w celu zwiększenie ilości dostarczania danych w systemach mobilnych czujników bezprzewodowych. Następnie opisano system odzyskiwania utraconych połączeń. Dzięki osiągniętej redukcji powielanych odpowiedzi czujników, ograniczono średnie zużycie mocy. Osiągnięte rezultaty świadczą o efektywności proponowanego rozwiązania. (**Energooszczędny system, o wysokiej odporności, do zbierania danych w sieciach mobilnych czujników bezprzewodowych**).*

Keywords: Wireless Mobile Sensor Networks; Data aggregation; Energy consumption; Clustering; Error recovery
Słowa kluczowe: sieci mobilnych czujników bezprzewodowych, agregacja danych, zużycie energii, klasteryzacja, odzyskiwanie danych

Introduction

Wireless Sensor Networks (WSNs) consist of several sensor enabled nodes which are distributed in an environment and use batteries as their energy resources. Sensor nodes could be deployed in home, military, science, and industry applications such as transportation, health care, disaster recovery, warfare, security, industrial and building automation, and even space exploration. In those applications, phenomena monitoring is one of the key areas in WSNs.

In phenomena monitoring, sensor nodes are randomly dispersed over the interested area in order to pick up the signals by all kinds of sensors and the data acquiring unit. The sensors then will process and transmit the results to a sink node. The sink node requests sensory information by sending a query throughout the sensor field to be received at sensor nodes (or sources) [1-3, 8]. When the nodes find the received data matching the query, the data (or response) is routed back to the sink. For example, if the sensor nodes form a tree like structure and the base station plays a role as the root of the tree [4-5], the data items of the query responders can be transmitted hop by hop from the leaf nodes to the root.

Moreover, in gathering the data of the sensor node, in-network data aggregation is one of the effective approaches that could reduce the communication traffic. Such a technique could reduce wireless communication among nodes by minimizing redundancies in sensor measurements according to an aggregation function.

Some WSNs might contain mobile sensor nodes. Such networks are called Mobile Wireless Sensor Networks (MWSNs). In MWSNs, nodes can self-propel via springs, wheels, or they can be attached to transporters, such as vehicles. Sensors still have limited energy supply and the sensor network is expected to be functional for a long time. Thus, optimizing the energy consumption to prolong the network lifetime becomes an important issue. There is also a problem of instability of wireless network and high-fraction of packet loss caused by the mobility of network nodes. Furthermore, the conventional problems associated with a wireless channel such as fading and high error rate have negative effects on data transmissions between sensor nodes and sink and may also lead to packets loss.. A packet loss has a direct effect on the accuracy of the result. Therefore, a data gathering approach in MWSNs should be able to handle such issues.

In this paper, we propose a reliable and energy-efficient data gathering approach for addressing the issues of packet loss and energy consumption in MWSNs.

For conserving more energy, the proposed approach uses the advantages of both cluster based and tree based approaches wherein each node is related to a routing sub tree. Each sub tree overwhelms a cluster and the root node of each sub tree is the head node of the related cluster. In the proposed approach, all the nodes transmit their data to their neighbors instead of their cluster heads. Therefore, since the energy consumption in wireless transmissions is equal to the square of distance between two nodes in communication, the communication distance is reduced and the energy consumption of each node, each cluster and the average energy consumption of the whole networks is reduced; thereby, the network lifetime is increased.

Moreover, in the proposed approach, for addressing the problem of packet loss due to the mobility of the nodes and their imited energy, next hop node is selected according to some criteria which increase the chances of packet delivery. Furthermore, for performing a reliable packet transmission against link failures, when a packet is lost between two sensors, one backup sensor transmits the lost data. In the proposed mechanism, such backup parent corrects the error by aggregating the missing value into its own value. As a result, error recovery has no overhead since the lost packet is aggregated with another packet to be transmitted.

Finally, in achieving energy-efficient data gathering in MWSNs, the number of message transmissions could be considerably reduced by limiting the redundant and unnecessary responses from sensors.

Related works

In this section, we describe some previous data gathering approaches which mainly focus on two key issues: providing reliability and saving energy. In terms of energy consumption reduction, a Data Gathering algorithm based on Mobile Agent (DGMA) for cluster-based wireless sensor network was proposed in [6]. In this approach, a region where an emergent event occurs is clustered dynamically based on the event severity, by which the scale and lifetime of clusters are determined. In each cluster, a mobile agent is utilized to traverse every member node to collect the sensed data. In the higher level of the network, a virtual cluster is formed among the cluster heads and the base station. Furthermore, a multi-hop communication is adopted for sensed data delivery to the base station.

In [7] the authors proposed an energy-efficient distributed clustering protocol, named Geodesic Sensor Clustering (GESC). GESC aims to prolong the network lifetime by distributing energy consumption evenly, considering the localized network structure and the remaining energy of neighboring nodes. One of the main parts of the protocol is the estimation of the significance of the sensors relative to the network topology. The significance is calculated in the view of the local network at individual nodes. That means the significance of each node is distinct from other nodes.

Data query protocol with restriction flooding (DQPRF) [8] is an improved version of the directed diffusion approach [9] which disseminates the negative effect of flooding by controlling the interest messages. The proposed approach controls the flooding by using a cache in each node to check whether the interest message has been received in the past or not.

FTEP [10] is a dynamic and distributed CH election algorithm based upon two level clustering schemes. If energy level of current CH falls below a threshold value or any CH fails to communicate with cluster members, then the election process is started which is based on residual energy of sensor nodes.

In an Energy Efficient Multi Level Clustering (EEMC) [11], CHs at each level are elected on the basis of probability function which takes into consideration the residual energy as well as distance factor very efficiently. In this scheme whole information is sent and received by sink node for cluster formation.

Steiner Points Grid Routing was proposed by Chiu-Kuo Liang, et al.[12]. In order to reduce the total energy consumption for data transmission between source node and sink node, a different virtual grid structure instead of virtual grid in GGR is constructed. The idea is to construct the virtual grid structure based on the square Steiner trees [13].

In [14] the clustering routing algorithm is used to find out intra cluster and inter cluster links in wireless sensor network. Clusters are acted as a router, which maintain and distribute of the routing information. After a node is selected as cluster head, it will broadcast information that it is the cluster head to the rest of the nodes in the same cluster. The remaining nodes decide to join the cluster according to the size of the received signal.

In [15] three layers mobile node architecture to organize all sensors in MWSN is designed. In this paper, the Shortest Path (SP) routing protocol is used to adapt sensors to update the network topology. SP provides an elegant solution to node movement in multilayer MWSN and reduces energy dissipation.

Liu et al [16] proposed distributed clustering algorithm for data gathering in mobile wireless sensor network. The cluster formation was done using Cluster with Mobility mechanism (CM). Cluster head was elected using two distributed algorithms. It was observed that a better clustering factor and lesser energy consumption were achieved.

The Link Quality Estimation Based Routing (LQER) is proposed by Chen et al. [17]. LQER takes decision about data forwarding on the basis of a dynamic window (m,k) that stores the history of transmission success over the link.

The approach which was presented in [18] is based on multiple spanning trees. The authors in that research define a method to provide a fault tolerance to packet losses by forming a Directed Acyclic Graph (DAG). DAG allows having multiple parent nodes at each sensor. By using multiple parents as intermediate nodes, the method provides tolerance for the failure in wireless transmission. In our performance evaluation, we call this approach as Method1.

In Robust Energy Efficient Distributed clustering (REED) [19], a k-fault tolerant (i.e., k-connected) network is constructed. In such approach, fault tolerance is achieved by selecting k independent sets of cluster heads on top of the physical network, and thus each node can quickly switch to other cluster heads in case of failures or attacks on its current cluster head. The independent cluster head overlays also provide load balancing and security. This approach also periodically re-clustering the network, which consumes significant energy. Moreover, to maintain a list of k cluster heads requires a lot of storage space.

In cellular approach to fault detection and recovery [20], network is partitioned into a virtual grid of cells, where each cell consists of a group of sensor nodes. A cell manager and a secondary manager are chosen in each cell to perform fault management tasks. Secondary manager works as back up node which will take control of the cell when cell manager fails to operate. This protocol handles only those failures which are caused by energy depletion.

Referring to [21] ESRT is useful only under certain conditions. However, it is costly for longer paths with poor quality links.

The proposed approach In [22] reduces the impact of transient faults on the links and the loss of packets by retransmission of lost packets. However the approach has a large overhead in terms of both time and energy.

Proposed approach

We assume that the whole network is divided into several clusters; each cluster has a cluster-head. The clustering and the selection of the cluster-head can be done by using any existing protocol like LEACH [23], or more efficient approaches such as [16].

In the following, we describe the proposed approach in two main sections: *Reliable forward routing* in which the problem of packet loss due to the mobility of the nodes is addressed and *Data gathering* wherein our reliable and energy-efficient data aggregation approach is proposed.

Reliable forward routing

Packet loss is one of the main challenges that occurs due to the mobility of the sensor nodes in Mobile Wireless Sensor Network. In previous routing approaches, the nodes always transmit their data to the node which is the closest node to the destination. However, in MWSNs, according to the mobility of the nodes, a node may leave the radio range of its previous hop node which result in route breakage; therefore, in spite of selecting the shortest paths, we also need a solution for this problem. In our proposed algorithm, data packet is sent to the node which is the closest node to the destination and does not leave the radio range of its previous hop with the speed of v after time t. Here, 't' is a constant value which can be assumed different values according to the defined scenario.

For better understanding of the proposed algorithm, please refer to Figure 1 and the following explanation. In conventional algorithms, node 27 is the candidate of the next hop for the source since it has the nearest distance to the destination. However, considering the ability of the nodes to move in any direction (which is equal to $x = vt$), node 27 may leave the radio range of the source node.

Therefore, in the proposed algorithm, instead of node 27, node 6 is the candidate of the next hop as among the other neighboring node, it is the closest node to the destination which does not leave the radio range of the source node after time *t*.

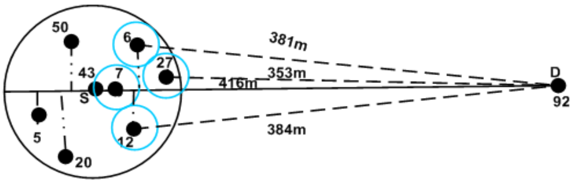

Fig.1. Selecting the next hop in the proposed algorithm

—— Mobility Area
—— Radio Range of Node S

Figure 2 illustrates a simple example of data forwarding process from source to destination in conventional algorithms and our algorithm. In conventional algorithms, the source node selects node 11 as the next hop because it has the minimum distance to the destination among the other single hops neighbors. Next, node 11 selects node 20 as the next hop and following that, node 20 selects node 27. This process is continued until reaching the destination node. On the other hand, in our algorithm, the source node selects node 11 as the next hop. However, in the next step, node 11 does not select node 20 as it may leave its radio range after time *t*. Hence, it could select node 21 which has more chance to receive its data packet.

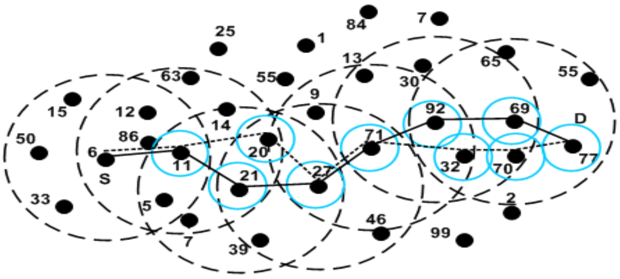

Fig.2. Route discovery process in the proposed algorithm in comparison with conventional algorithms

— — Radio range of a node
········ Selected route in conventional algorithms
—— Selected route in our algorithm
—— Mobility area

Moreover, in the proposed approach, we have categorized the edges into three types: primary, backup and side edges. Each node chooses a primary parent and it could also choose a backup parent. A primary edge is between a node and its primary parent and backup edge is between a node and a node which roles as a backup parent for the node. The side edges are among parents in which parents can be in collaboration. When an error occurs in a primary edge, the backup edge delivers the sent value. Parents coordinate using side edges so that the missing value is aggregated at most once (i.e., no more than 100% of the value is aggregated). It should be noted that a sensor can be a primary parent for some children and at the same time a backup parent for some others. Furthermore, we assume that errors occur independently in primary, backup and/or side edges.

In the proposed approach, there is an additional field in each packet that demonstrates the success or failure of a primary parent in receiving its child value. This field is called FS (Fault Status). When a primary parent does not receive a packet from its child, it will set the FS field of its own message to 1. The adjacent node of a primary parent, which can be the backup parent of the child node, can detect this error by snooping [5] on the side edge which is between them. However, it will aggregate that value to its local value before sending its own messages. Algorithm 1 illustrates the functions of primary and backup parents.

Algorithm 1 Data forwarding process in each parent

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For each node as a primary parent:
  If it receives a packet from a child:
  FS=0
  Aggregate the local value with the child's value and transmit the result to the parent
  Else
  FS=1
  Transmit the local value to the parent
For each node as a backup parent:
  If the FS value in the packet received at the sibling node is zero
  Transmit the result without aggregating the value of sibling node' child
  Else
  Aggregate the result with the missing value in the sibling node and transmit it to the parent
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According to Algorithm 1, when a node as a primary parent receives a packet from its child, it sets the FS value to zero, aggregates its own local value with its child's value and transmits the result to its parent. Otherwise, first, it changes the FS value to 1, to show that the value is lost. Then, it just transmits its own local value to its parent.

On the other hand, when a node as a backup parent receives a packet, first, it checks the value of FS in the packet received at the sibling node. If it finds the value of FS equal to zero (i.e. which means that the result of the child is received correctly), it transmits its result to its parent without aggregating the value of its sibling node' child to its own result. Otherwise, when the FS value is 1, it aggregates the value of its sibling node' child with its own result to recover the lost value.

Data gathering

In this section, we propose a reliable and energy-efficient data gathering scheme wherein data of the sensor nodes is aggregated and delivered to the base station reliably and with minimum number of messages to reduce the average energy consumption of the network. The proposed approach works in each cluster independently and is performed in two phases: *Tree construction and parent selection*, and *In-network data aggregation*.

Tree construction and parent selection

In this phase, first, the base station sends an information packet to the cluster heads and the cluster heads propagate the information packet to their cluster members. The information packet includes the information below:

Node ID: Each node should know it ID in prior.
Current Energy: Remaining energy of a node.
Hop Count: Number of hops from cluster head.
Speed: The speed of node's movement.

Each node upon receiving an information packet, considers the sender as one of its possible parents and stores its information. Then, it updates the fields of *Node ID* and *Current Energy* with its own information, increments the hop count and transmits the packet to its neighbors. This process is repeated until all the nodes in the cluster receive the information packet.

When the entire nodes received the information packet, each node selects it parent based on the following criterions:

1. First, among the possible parents, select two nodes which have the least hop distance from the cluster head

and do not leave the radio range of the node with the speed of *v* after time *t*.
2. Among the selected nodes, choose the node which has more residual energy as the parent.

All the above conditions lead to the best parent selection. Filter 1 facilitates in selecting the most reliable and shortest paths from nodes to cluster heads. On the other hand, Filter 2 selects the most durable nodes in routing process which increases the network lifetime.

In-network Data aggregation

In various scenarios of MWSNs, usually, the base station sends several queries about different attributes and the nodes respond to the queries. However, there is a problem in such applications. When we want to gather responses from all nodes, there are some duplicate or unnecessary data which can be received by sensor nodes multiple times. For example, for finding the maximum value of the network, only one value i.e. the greatest value is needed and transmitting other values is unnecessary and redundant. Such message overheads can increase the energy consumption of the network, considerably. For solving this problem, we propose our in-network data aggregation scheme as follows.

After tree construction and parent selection phase, sensor nodes should transmit their data towards the gateway. Our proposed algorithm could function in any topology of tree. We consider the depth of tree *D*, the maximum allowable round-trip time between two neighboring nodes *T* and the depth of the node in the tree *d* which is the number of edges from the sink node to the sensor node.

Before sending a query to the network, the gateway adds a Label with default value of zero to the query disseminates the query to the child nodes and waits for *D.T* for receiving the responses of its child nodes. When a node receives the query, it compares the Label of the query with its local value. If the Label's value becomes redundant, it updates the Label with its own value, forwards the query toward its children and waits for *(D.d).T* for receiving the responses of its children. If it does not receive any response up to *(D-d).T*, it sends it own value to the gateway. On the other hand, when it finds its own local value redundant, it only forwards the query without any update.

When the query reaches a leaf node, it compares its local value with the Label of the query. If the Label's value becomes redundant, it updates the Label with its own value and forwards the response toward its parents (Primary and backup parents); otherwise, it sends no response since its response is unnecessary.

In addition, when an intermediate node receives a response before the specified time, it compares the Label with its own local value. If its own local value becomes redundant, it only forwards the response without any update. On the other hand, when it finds the Label's value redundant, it updates the Label with its own value and forwards the response to its parent. However, when an intermediate node does not receive any response up to the specified time, it sends only its own local value to its parents.

Therefore, by using this mechanism, a number of redundant and unnecessary messages are limited and only the useful messages are transmitted to the gateway. For better understanding of the whole proposed approach, we describe an example in Figure 3 and Figure 4 in which the goal is achieving the Maximum value of the network.

According to the Figures, dotted arrows represent the backup transmissions and solid arrows state the primary transmissions between parents and children. In Figure 3, consider node B and C which are two sibling nodes. When they receive the query, they compare their local value with the value of the query Label and as their local values are greater than the Label's value, they update the Label with their own local values; thus, node B forwards 36 and node C forwards 32 to their children. As it is depicted, they send their values to their stepchild, too. On the other hand, when nodes D and E receive the query, they do not update the Label since their values are lower than the Label.

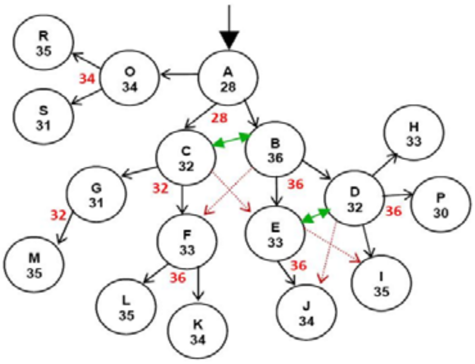

Fig.3. Querying the MAX aggregate value. The slotted arrows present the backup transmissions, the bidirectional arrows depict the communications between sibling nodes, the values in the circle illustrate the local values and the values on the arrows present the value of the Label.

In Figure 4, after the query reaches the leaf nodes, node M and node R which have greater values than the Label's value, update the Label's value with their own local value and send their responses towards the root. Consequently, intermediate nodes forward the responses towards the root.

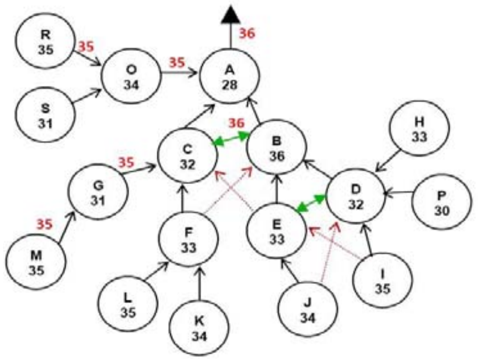

Fig.4. Forwarding the results toward the root

In the proposed approach, the snooping technique can be also used that allows nodes to locally suppress local aggregate values by listening to the answers that neighboring nodes report and exploiting the semantics of aggregate functions. For example, in Figure 4 node C can score its MAX value low when it hears a MAX from node B that is larger than its own. For dense network topologies where there is ample opportunity for snooping, this technique produces a dramatic reduction in communication, since at every intermediate point in the routing tree, only a small number of node's values will actually need to be transmitted.

Performance evaluation

The proposed approach is simulated and evaluated with J-Sim (Java-Based simulator) [24]. J-SIM is simulation software selected to implement the model. It was chosen because it is component-based, a feature that enables users to modify or improve it. J-Sim uses the concept of components instead of the concept of having an object for each individual node. J-Sim uses three top level components: the target node which produces stimuli, the sensor node that reacts to the stimuli, and the sink node which is the ultimate destination. For stimuli reporting, each component is broken into parts and modeled differently within the simulator; this eases the use of different protocols in different simulation runs. In our simulation analysis, sensor nodes are randomly distributed in a 160m×160m area. The radio range of each node is 30*m* and the default parameters of radio communication model of J-sim are used. Two mobility models are used in the evaluation: Random Waypoint without pause time [31], and Reference Point Group [32] mobility model. We have chosen these models since they are simple and can be applied to large number of scenarios.

Our energy model is similar to the energy model as in [23]. In this model energy consumption for transmitting k bit is equal to:

$$E_{TX}(K,d) = E_{elec} \times K + \varepsilon_{amp} \times K \times d^2$$

And the energy for receiving k bit is equal to:

$$E_{RX}(K) = E_{elec} \times K$$

In these equations, *d* denotes the distance between two nodes and the parameters below are the constant values which are defined previously as below:

$$\varepsilon_{amp} = 100 \text{ pJ/bit}/m^2 \qquad E_{elec} = 50 \text{ nJ/bit}$$

We have compared our approach with LEACH [23] as a famous energy-efficient approach in WSNs and the approach in [16] as a modern energy-efficient clustering approach in MWSNs which we call in our simulations as Method 2. Moreover, we have evaluated and compared the reliability of the proposed approach with Method1 [18] and TAG-Re (TAG with Retransmission) [4] as those two approaches are similar and fault-tolerant related approaches. There are two factors i.e. network size and fault ratio that affecting the amount of packet loss and energy consumption.

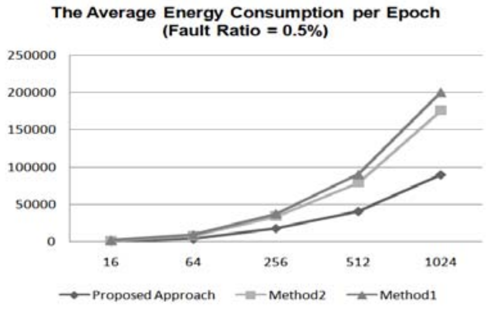

Fig.5. Average energy consumption per epoch Vs. Network Size (Fault Ratio = 0.5%)

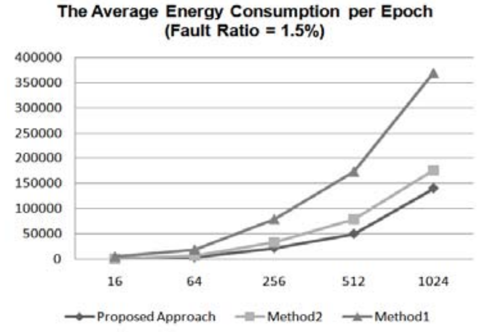

Fig.6. Average energy consumption per epoch Vs. Network Size (Fault Ratio = 1.5%)

Thus, In Figure 5, for measuring the average energy consumption of the aforementioned approaches, the fault ratio is set to value of 0.5% and the network size is varied between 16 to 1024 nodes. Then, in Figure 6, the fault ratio is increased to 1.5% and the average energy consumption is calculated according to different network sizes.

When the fault ratio is low (as in Figure 5), the average energy consumption of our proposed approach is much better than Method2 and Method1. The reason is due to the limited numbers of redundant responses which reduces the number of transmissions and energy consumption. The average energy consumption of Method1 is in its best condition as it does not need to use its energy for fault correction mechanism, frequently. Also, as method 2 does not use any recovery mechanism against packet loss, changing the fault ratio has no effect on it.

On the other hand, when the fault ratio is high (as in Figure 6), the number of unsuccessful transmission goes higher; therefore, except Method2 which does not use any fault recovery mechanism, the average energy consumption of the approaches becomes higher as well. However, according to the proposed reliable and energy-efficient mechanisms of our approach, it can tolerate the faults with minimum energy consumption. Also, Method1 has the worst energy consumption in comparison with other approaches, referring to its error recovery overhead in transmitting multiple packets to several parents.

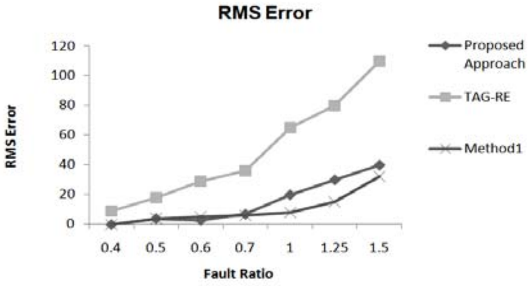

Fig.7. RMS error with different fault ratios

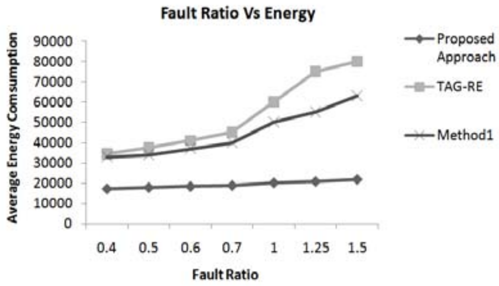

Fig.8. Average energy consumption with different fault ratios

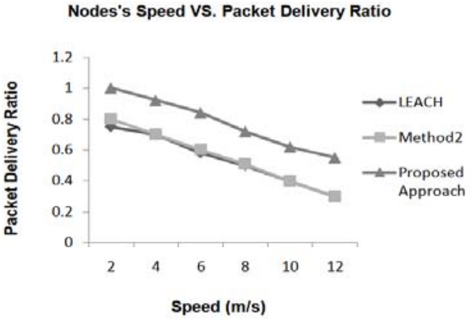

Fig.9. Impact of nodes' movement speed on packet delivery ratio

Figure 7 illustrates the amount of Root Mean Square (RMS) error in the mentioned approaches in a network of 256 nodes. According to the diagram, increasing the fault ratio will increase the RMS error. The proposed approach and Method 1 have the minimum RMS errors which are almost insignificant. This proves the robustness of these approaches in high fault ratios. The RMS error of TAG-Re is also acceptable, but it is more than the RMS error of the proposed approach as its retransmissions could be failed as well. We have not evaluated Method2 in this scenario as it has no error recovery mechanism.

Figure 8 depicts the tradeoff between fault tolerance and energy consumption in a network of 256 nodes. According to the figure, all the approaches use error recovery mechanism which adds some overhead to the network. In TAG-Re, any transmission failure leads to a retransmission which could increase the energy consumption. This can be seen more in high fault ratios. Method1 has better energy consumption than TAG-Re, especially when the fault ratio goes higher but it is not as efficient as our proposed approach because of two reasons: First, in Method1, multiple parents aggregate data from a child node which increases the average energy consumption. Moreover, by limiting a number of redundant and unnecessary messages in the proposed approach, the average energy consumption is always moderated.

Figure 9 presents the impact of nodes' movement speed on the packet delivery ratio. It illustrates that increasing the nodes' movement speed reduces the rate of packet delivery. In our approach, according to the proposed reliable forward routing mechanism, the rate of packet delivery is better than other approaches.

Conclusions

In this paper, we have proposed an energy-efficient and reliable data gathering approach in wireless mobile sensor networks in which data delivery is performed through the most reliable and energy-efficient routes. The routes are selected based on some key factors which determine the effectiveness of the routes. Moreover, for reducing the energy consumption of the network, a number of redundant and unnecessary responses from the sensor nodes is controlled. Furthermore, for delivering a correct aggregate result to the data sink, the available path redundancy in the network is used. These result in a high probability of completeness of responses, while still realizing significant power savings. The simulation results prove the effectiveness of the proposed approach in terms of energy conservation and reliability.

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