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RESEARCH ARTICLE

An integrated framework for wireless sensor network management

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ABSTRACT

Wireless sensor networks (WSNs) have significant potential in many application domains, ranging from precision agriculture and animal welfare to home and office automation. Although sensor network deployments have only begun to appear, the industry still awaits the maturing of this technology to realize its full benefits. The main constraints to large-scale commercial adoption of WSN have been the lack of available network management and control tools, such as for determining the degree of data aggregation prior to transforming it into useful information, localizing the sensors accurately so that timely emergency actions can be taken at an exact location, routing data by reducing sensor energy consumption, and scheduling data packets so that data are sent according to their priority and fairness. Moreover, to the best of our knowledge, no integrated network management solution comprising efficient localization, data scheduling, routing, and data aggregation approaches exists in the literature for a large-scale WSN. Thus, we introduce an integrated network management framework comprising sensor localization, routing, data scheduling, and data aggregation for a large-scale WSN. Experimental results show that the proposed framework outperforms an existing approach that comprises only localization and routing protocols in terms of localization energy consumption, localization error, end-to-end delay, packet loss ratio, and network energy consumption. Moreover, the proposed WSN management framework has potential in building a future "Internet of Things". Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
wireless sensor network; large scale; zone-based routing protocol; range-free localization; packet scheduling; data aggregation; first-come–first-served; priority scheduling; real-time data

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1. INTRODUCTION

Although sensor network deployments have only begun to appear, the industry still awaits the maturing of this technology to realize its full benefits. Limited energy of sensors also makes it difficult to operate the network for a long time. Hence, power consumption of sensor nodes should be properly utilized and reduced to prolong the lifetime of wireless sensor networks (WSNs). Most of the existing routing protocols of WSN deal with the energy efficiency of sensors. However, sensor nodes are also required to use a fault-tolerant routing protocol to ensure continued network operation in the harsh, remote, and unattended environment such as deep forest, deserts, mountain, and Iceland. Hence, designing a fault-tolerant and energy-efficient routing protocol that trades off between energy usage and reliability is an important research issue in WSN.

Because of the limited communication range of sensors, a large geographical area cannot be covered with inexpensive solution. Moreover, to relay data from fields to users through Internet, each base station (BS) of a number of WSNs needs to be connected to the Internet, which results in a large number of Internet subscriptions. However, the main constraints to the large-scale commercial adoption of sensor networks have been the lack of efficient network management and control tools, such as for determining the degree of data aggregation prior to transforming it into useful information, efficient routing, data packet scheduling, and localization techniques. Trade off energy consumption and end-to-end data transmission delay using limited or battery-powered sensor devices is another challenge in a large-scale deployment.

More specifically, most localization techniques in the literature [1–14] are designed for small-scale WSNs and any particular application. Some of these localization techniques use powerful sensor nodes equipped with Global Positioning Systems (GPS) to estimate their positions. However, equipping all the nodes with GPS is expensive, and GPS cannot function for indoor applications because there is no direct line of sight to the satellite. To reduce the cost, a few nodes are equipped with GPS, which are known as anchor nodes. These nodes broadcast their positions through beacons. The unlocalized nodes estimate their positions from the positional information of anchor nodes. However, these algorithms are mostly range-based and use special hardware or techniques such as the received signal strength indicator, the time difference of arrival, and the angle of arrival [14] to measure distance using static anchor nodes that are deployed at some predefined locations. On the other hand, range-free algorithms exploit a sensor's connectivity information instead of using energy-expensive distance estimation. Hence, range-free algorithms are energy efficient as compared with range-based algorithms. However, range-free algorithms mostly use a large number of static anchor nodes. In these algorithms, a node is also considered as an anchor node whenever its position is estimated. If there is any localization error for estimating the position of a node, the error is propagated to localize remaining nodes, which results in a large average localization error.

Similarly, existing routing protocols [15–25] and data aggregation [26–31] approaches are claimed to be energy efficient. However, most of these approaches either are not energy efficient because they use flooding for path establishment or can be improved to make them more energy efficient. These approaches use the number of hops as the length of data transmission path. However, the actual length of the shortest hop path can be longer than that of a larger hop path. A large number of switching between aggregation levels require a large number of control message transmissions. Moreover, these techniques are not fault tolerant and do not provide fast data delivery because they use a tree structure where nodes wait until they receive data from all child nodes at lower levels. Similarly, existing packet scheduling schemes [31–37] are not efficient in terms of average data waiting time and end-to-end data delay. These approaches use a first-come–first-served [38] and multilevel queue scheduling algorithm [38], which incurs a large end-to-end data transmission delay for real-time tasks as well as all types of traffic. Most existing localization, routing, data scheduling, and aggregation approaches are not scalable and fault tolerant.

Thus, we introduce efficient approaches for localization, routing, data scheduling, and data aggregation in terms of localization error, packet loss ratio, network energy consumption, and end-to-end data delay. However, to the best of our knowledge, no integrated framework consisting of localization, data scheduling, routing, and data aggregation exists for a large-scale WSN application. Thus, we introduce an efficient framework that integrates efficient network management components for sensor localization, routing, data scheduling, and data aggregation for a large-scale WSN. Then, we compare the proposed integrated framework with a new framework and find that the proposed framework outperforms the new framework in terms of localization error, localization energy consumption, and network energy consumption. The new framework is formed by replacing the localization and routing components of the proposed framework with the corresponding components of an existing approach [39], which only comprises localization and routing protocols.

The remainder of this paper is organized as follows. Section 2 presents general assumptions and defines terminologies that are used in designing an integrated framework for WSN. In Section 3, we briefly present each component (e.g., localization, routing) of the proposed large-scale WSN management framework. Section 4 presents the existing approach [39] that comprises localization and routing protocol. Section 5 evaluates the performance of the proposed framework and compares it with the newly formed framework. This section also evaluates the performance of the routing protocol of the proposed framework in terms of fault tolerance capabilities (packet loss ratio) and individual node energy dissipation. Finally, conclusions and future work are presented in Section 6.

2. PRELIMINARIES

In this section, we present general assumptions and define some important terminologies and metrics that are used in the proposed WSN management solutions.

2.1. Assumptions

- The WSN is homogeneous, that is, sensor nodes in the network have the same residual energy, sensing range (R_s), and communication range (R_c).
- The network is hybrid, that is, it consists of both static and mobile nodes. Sensor nodes are mostly static. However, only a few mobile anchor nodes are used to localize static unlocalized nodes. The anchor nodes are attached to a small vehicle and, thus, are mobile.
- The network is modeled as a unit disk graph (UDG), where any pair of sensor nodes communicates if the distance between this pair is less than the communication range. UDG is defined in Section 2.2.
- The sizes of a data packet and a special packet are fixed.
- Sensors use a time-division multiple-access (TDMA) scheme to transmit data.

2.2. Terminologies

This section defines some important terminologies and metrics that are used in the proposed WSN management solution.

A sensor network is represented by a graph $G(V, E)$, where the term V represents a set of nodes (or vertices)

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and the term E represents a set of communication links (or edges). Two nodes, u and v, communicate with each other if they are within their communication range R_c. This relation defines a common graph referred to as the UDG. However, because our proposed framework is in the context of sensor networks, we refer to the "double range property" [40], defined as $R_c = n \times R_s$, where R_s refers to the sensing range. In a simulation, we represent the network using UDG. In the network, a sensing hole is an area or point that is not sensed by any sensor node. The proposed framework also achieves fault tolerance capabilities to ensure the continuing operation of WSN even in case of node failure. It reduces packet loss ratio by creating alternative paths for any established path between a source node and the BS. In the following, we define some performance measures.

Localization accuracy is defined as the absolute difference between the actual positions of a node, that is, the position obtained via GPS and its estimated position that is obtained via the proposed or existing localization methods. Localization energy consumption is the total localization energy consumption (in joules), which include the energy consumption of anchor nodes to broadcast their positional information and consumption of both anchor and unlocalized nodes for transmitting a large number of messages to identify neighboring nodes. Network energy consumption is the sum of energy consumption of all nodes for sending and receiving data and special packets and processing and aggregating data packets. End-to-end data transmission delay is the time that is required to transmit sensors' data from the source node to end users. Packet loss ratio is used to measure the performance of the fault tolerance mechanism. It is defined as the number of packets that are lost without using any fault tolerance mechanism. That is, the packet loss ratio is the difference between the number of packets transmitted using a fault tolerance mechanism and the number of packets transmitted without using any fault tolerance mechanism.

3. PROPOSED FRAMEWORK

Sensors have a very short transmission range and, thus, cannot transmit data over a distant place. For instance, we can have a WSN for agriculture, health monitoring for elderly people, and home security in rural or remote areas, where there is no Internet or telecommunication infrastructure. Thus, WSNs can be integrated with other long-range wireless technologies such as Wi-Fi and WiMAX to transmit data to the central server at urban areas. Thus, we investigate a large-scale multimodal wireless network having a WSN integrated with Wi-Fi and WiMAX networks as illustrated in Figure 1. However, we consider only the WSN plane in this architecture to design and implement efficient network management components such as sensor localization, routing, data scheduling, and data aggregation so that WSNs for different applications can transmit data efficiently with lower sensor's energy consumption, packet loss ratio, and data transmission delay.

However, to the best of our knowledge, no integrated WSN management framework comprising sensor localization, routing, data scheduling, and data aggregation exists in the literature. Thus, we also introduce an integrated network management framework for this large-scale WSN. In the following subsections, we present each component of this WSN management framework.

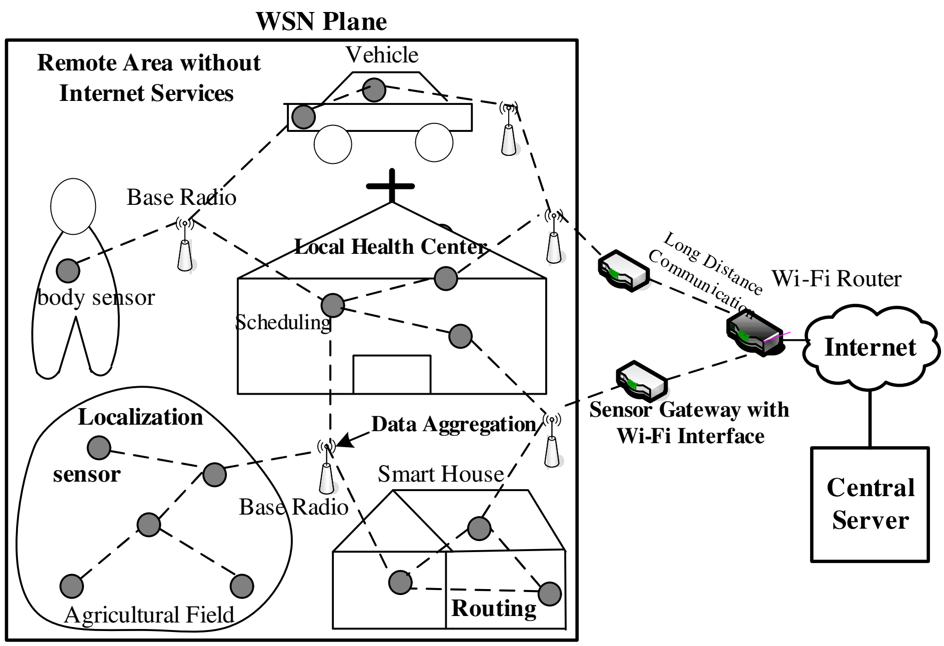

Figure 1. Large-scale wireless sensor network.

3.1. Localization of sensors

We introduce a range-free, energy-efficient localization technique using mobile anchor (RELMA) [41]. Once sensors are deployed randomly in the network area, they localize themselves using the location information of anchor nodes. We deploy a few mobile anchor nodes if the network is large. In a small network (e.g., the network model in our simulation model), we deploy only one mobile anchor node that is attached to a vehicle. The anchor node moves in low velocity in the network and broadcasts a message containing its position. If an unlocalized node P receives three or more anchor positions, it starts the localization process in the following three phases.

3.1.1. Phase I—RELMA method 1.

Sensing circles of three anchor nodes or positions intersect at three points and form the intersected region R (triangle). Using this method, we calculate the coordinates of the three intersected points of R. Then, the coordinate of P (X_P, Y_P) is estimated using Equation (1) as the centroid of R. The region R is much smaller than the intersected region of their communication circles. Hence, the estimated localization error is expected to be less. Figure 2 illustrates the location estimation using the RELMA method 1.

$$X_P = \frac{(X_1 + X_2 + X_3)}{3}, \quad Y_P = \frac{(Y_1 + Y_2 + Y_3)}{3} \quad (1)$$

3.1.2. Phase II—finding localization error.

The estimated position of P in R using RELMA method 1 in phase I is expected to result in a localization error. Thus, to estimate the error, E_P in P, we consider P as an anchor node and A_1 as an unknown node with coordinate (X'_1, Y'_1). Now, A_1 estimates its position using the estimated coordinate of P and two other anchor positions, A_4 and A_5, which are within the sensing range of A_1. Then, E_P can be calculated as the difference between the actual and estimated positions of A_1.

E_P in A_1 actually reflects the error in P because E_P occurs because of the error in the coordinate of P. If the localization error is less than a threshold value (mean of errors), the estimated coordinate of node P is considered as its location. Otherwise, RELMA uses phase III to estimate the position of P.

3.1.3. Phase III—RELMA method 2.

In this phase, the unknown node P estimates its position using neighboring sets (NSs) and distance approaches. A set of neighboring nodes that are in the sensing range of a node is known as its NS.

Neighboring distance (ND) (ND_{PA_i}) of a node P with its neighbor A_i (i.e., mobile anchor node) is the ratio of the number of neighboring nodes for A_i (NS_{A_i}) to the number of nodes resulting from $NS_P \cap NS_{A_i}$,

$$ND_{PA_i} = \frac{|NS_{A_i}|}{|NS_P \cap NS_{A_i}|}$$

where A_i, $1 \le i \le 3$, are three positions of the mobile anchor node that moved through the neighborhood of P. For instance, $|NS_{A_1}| = 8$, $|NS_P| = 9$, and $|NS_{A_1} \cap NS_P| = 5$, and so $ND_{PA_i} = 8/5$ in Figure 3. Now, the coordinate of P is estimated using the equations

$$X_P = \left(\frac{X_{A_1}}{ND_{PA_1}} + \frac{X_{A_2}}{ND_{PA_2}} + \frac{X_{A_3}}{ND_{PA_3}}\right) \times \left(\frac{1}{ND_{PA_1}} + \frac{1}{ND_{PA_2}} + \frac{1}{ND_{PA_3}}\right)^{-1} \quad (2)$$

and

$$Y_P = \left(\frac{Y_{A_1}}{ND_{PA_1}} + \frac{Y_{A_2}}{ND_{PA_2}} + \frac{Y_{A_3}}{ND_{PA_3}}\right) \times \left(\frac{1}{ND_{PA_1}} + \frac{1}{ND_{PA_2}} + \frac{1}{ND_{PA_3}}\right)^{-1} \quad (3)$$

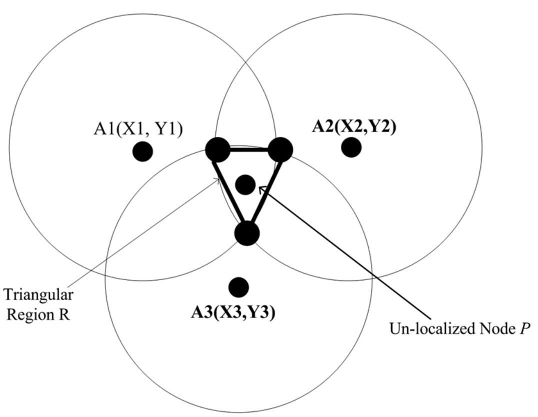

Figure 2. Centroid of a triangle formed by three intersected points (RELMA method 1).

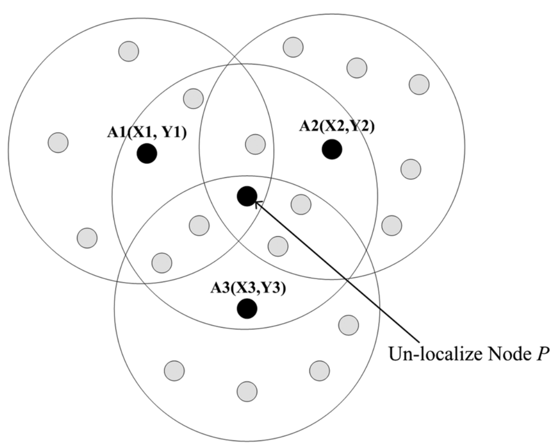

Figure 3. Neighboring set and distance localization approach (RELMA method 2).

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where (X_{A_1}, Y_{A_1}), (Y_{A_2}, Y_{A_2}), and (X_{A_3}, Y_{A_3}) are coordinates of three positions of the mobile anchor node and (X_P, Y_P) is the coordinate of P.

For a densely deployed sensor network, it is expected that the size of NS for each of the anchor nodes or positions and the unlocated node P is high, and for a small intersected region between an anchor node and P, the number of nodes that are contained in both the NS of the anchor node and P will be small. This results in a high value of ND for each of the anchor nodes. On the contrary, for sparse sensor deployment, the value of ND will be small. When the value of ND for each of the three anchor nodes for locating P is high, the value of the nominators of Equations (2) and (3) will be lower than the value that is expected for getting a more accurate coordinate of the unlocated node P. Hence, for the higher-value ND, a denominator with lesser value will normalize the coordinate of P. Similarly, for lower ND, the values of the nominator and the denominator will be high, which again normalizes the coordinates of P. However, this argument can be validated by measuring localization errors E'_P for node P. Similar to the approach in phase II, the position of A_1 is estimated using the NS and the ND of A_1 between P and two other anchor positions. Then, E'_P is estimated as the difference between the actual and estimated positions of A_1.

If $E'_P < E_P$, the coordinate of P that is estimated using RELMA method 2 is considered as its actual position. Otherwise, the coordinate P that is estimated using RELMA method 1 is considered as its actual position.

3.2. Routing protocol

Once sensors are localized, we use an efficient routing protocol referred to as the cluster-based routing and topology control approach (CRTCA) [42]. We incrementally integrate clustering, routing, and topology control approaches to construct this protocol.

The network area where sensors are deployed can be of any shape, for example, polygon, circle, triangle. However, these shapes can be circumscribed into a square as illustrated in Figure 4. Thus, we assume that the shape of the network is square, which is divided into a number of square zones by BS.

Then, the BS assigns the sensor nodes to different zones according to their geometric positions. For instance, if the network area is very small (e.g., 100 m × 100 m) and divided into four zones, then sensor nodes are distributed as follows. Nodes with positions between (0, 0) and (50, 50) reside in zone 1, whereas sensor nodes with positions between (50, 0) and (100, 50) reside in zone 2.

Figure 5 illustrates the zone construction. In case of manual deployment, a few more sensor nodes are distributed to zones, Z_c, that are adjacent to BS than to zones, Z_f, that are farthest from BS. This is because nodes in Z_f transmit their data through the nodes in Z_c. Hence, nodes in Z_c consume more energy and eventually have a shorter lifetime. Thus, distributing a few more nodes to Z_c balances individual node energy dissipation.

Then, BS divides each zone into a number of small squares in such a way that a sensor node in a square can cover the area of all neighboring squares. This is possible when the side, h, of a square and the sensing range, R_s, is related to $R_s = 2\sqrt{2h}$ (Figure 6). Thus, whenever a node is selected as active in a square, nodes in the neighboring squares are inactive or in sleep mode. For instance, node a_1 in Figure 6 can sense the area of its all neighboring squares. However, a few nodes are selected from the neighboring square as an alternative to the active nodes in case the active node fails to achieve fault tolerance. This also results in a very high probability of not having a sensing hole in the network.

Once active nodes are selected, we can consider that they are located at different levels on the basis of the number of hops they are away from the BS. Then, the path establishment method works as follows. Sensor nodes at level L_1

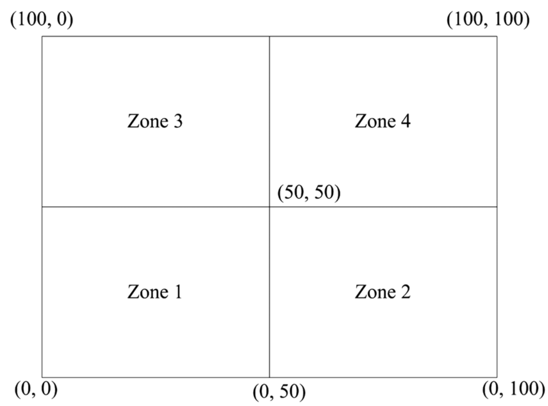

Figure 5. Network is divided into a number of square zones.

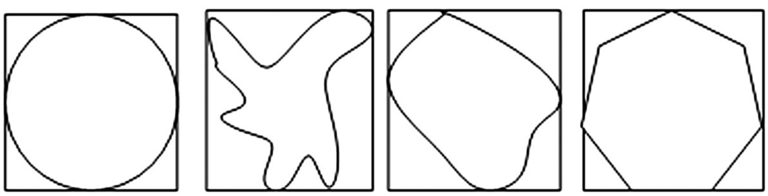

Figure 4. Monitoring area of a network circumscribed to a square.

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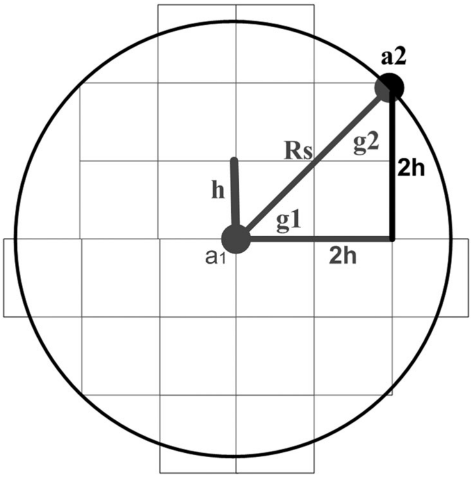

Figure 6. Active node selection.

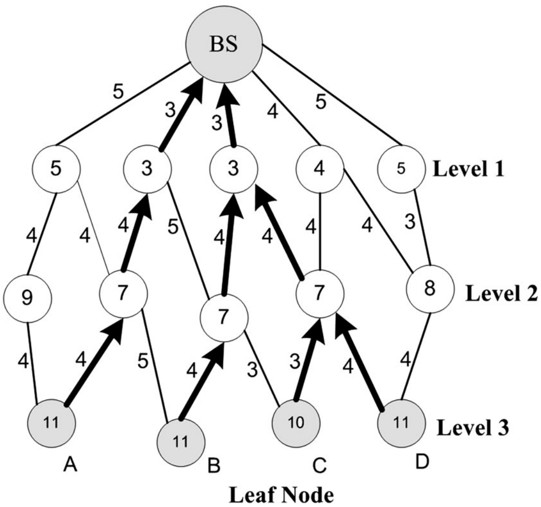

Figure 7. Path establishment.

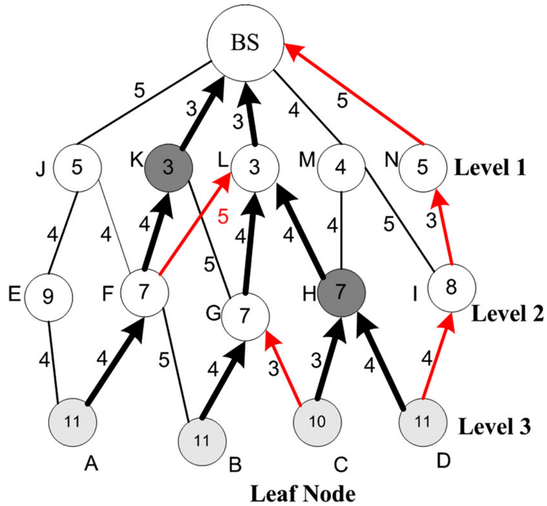

Figure 8. Alternative path.

calculate their distances to the BS and send this information to the sensor nodes at level L_2. Then, nodes at level L_2 calculate their distances to the sensor nodes at level L_1 and calculate the total distance to the BS. Thus, active nodes at level L_2 find out the shortest path to the BS. Similarly, nodes at the lowest level L_k compute the shortest path to the BS. Figure 7 illustrates the path establishment method. However, each active node at level L_i chooses an active node at level L_{i-1} as an alternative node, which is other than the active node on its shortest path. For instance, in Figure 8, node F at level 2 chooses node L at level 1 so that F can transmit data through L if K fails. The alternative path is shown as red arrows in Figure 8.

Once paths are established, data are transmitted from the source active node to the BS through intermediate active nodes. The setup phase, that is, zone creation, active node selection, and path establishment, is initiated at a certain number of rounds R_n, which is also calculated dynamically from the current energy status of the network. R_n is denoted using Equation (4).

$$R_n = \frac{prevNoOfRounds}{prevNetEnergy} \times currentNetEnergy \quad (4)$$

The proposed framework achieves fault tolerance, which is presented as follows.

3.2.1. Fault tolerance.

In the proposed CRTCA protocol of the framework, there are alternative paths for any established path between a source node and the BS. Thus, the proposed framework achieves fault tolerance, which represents the continuous operation of the network. It has two phases: (i) detecting failure of nodes (fault detection) and (ii) then detecting route data through alternative paths (fault recovery).

3.2.2. Fault detection.

The BS subscribes to nodes for some events of interests, such as "temperature greater than 40°C." If an active node x of the current data transmission path senses such an event of interest at its allocated time slot, x sends the data packet to the active node at the upper level. If x has no subscribed event to send to the active node at the upper level, x sends a small-sized special packet to notify the active node at the upper level that it (x) is still alive. If a neighboring active node or the BS does not receive any data or special packet from an active node, the BS assumes that the active node has failed. Then, the BS excludes the node from its allocated time slot and assigns an alternative node/path to transmit the data.

3.2.3. Fault recovery.

Fault recovery is achieved by allocating alternative paths for any established path between a source node and the BS.

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Hence, data are retransmitted through alternative paths if a node failure is detected. This has been presented in path establishment in detail (Figures 7 and 8). We evaluate the fault tolerance capabilities of the proposed framework in Section 5.

3.3. Packet scheduling

We use a priority-based dynamic data scheduling scheme in our proposed WSN management framework, where each node maintains a maximum of three levels into its ready queue for three different types of data. This is because we classify data as follows: (i) real-time data (highest or priority 1); (ii) non-real-time remote data, that is, data that arrive from the sensor nodes at lower levels (priority 2); and (iii) non-real-time local data, that is, data that are sensed at the current sensor node (lowest or priority 3). Non-real-time data are classified according to the location of sensor nodes to reduce the overall end-to-end data transmission of the network. Real-time data can preempt data at other queues. If there are no data available at the real-time highest-priority queue, then data at the second-highest-priority queue are processed. If the second-highest-priority data are processed at a node for α consecutive time slots, the lowest-priority data can preempt the second-highest-priority data. Thus, the proposed scheduling scheme achieves fairness via an appropriate setting of α. This priority-based data scheduling scheme is more suitable for heterogeneous WSN applications where both real-time and non-real-time data are transmitted. For instance, it can be used in a smart home to monitor temperature and humidity (non-real time) and health condition of elderly people (real time). Whenever a sensor sends data packets to the BS through intermediate nodes, the data type information is inserted in the packet header. Figure 9 illustrates the dynamic-priority data scheduling scheme.

We consider only two levels in the ready queue of sensor nodes that are located at the lowest level because these nodes do not receive data from any lower-level nodes. Other nodes have three levels in the ready queue and place non-real-time local data into the priority 3 queue.

Now, we formulate the average end-to-end delay for transmitting different-priority data to the BS. Let us consider a node x, residing at level l_k and sensing a real-time, priority 1 data to the BS through l_{k-1} intermediate levels. The end-to-end delay for sending these data satisfies the following inequality.

$$delay_{\text{pr1}} \geq l_k \times \left(\frac{data_{\text{pr1}}}{s_{\text{t}}} + \text{pr1}_{\text{proc}}(t) \right) + \frac{d}{s_{\text{p}}} + (l_k \times t_{\text{overhead}}) \quad (5)$$

where $data_{\text{pr1}}$ denotes the real-time data size, s_{t} denotes the data transmission speed, d is the distance from the source node to the BS, where $d = \Sigma_{i=1}^{l_k} d_i$, s_{p} denotes the propagation speed over the wireless medium, $\text{pr1}_{\text{proc}}(t)$ is the processing time of real-time tasks at each node, and t_{overhead} is an overhead in terms of context switching and queuing time (including time for preemption).

Similarly, the total end-to-end delay for sending a priority 2 (pr2) data packet satisfies the following inequality.

$$l_k \times \left(\frac{data_{\text{pr1}}}{s_{\text{t}}} + \frac{data_{\text{pr2}}}{s_{\text{t}}} + \text{pr1}_{\text{proc}}(t) + \text{pr2}_{\text{proc}}(t) \right) + \frac{d}{s_{\text{p}}} + (l_k \times t_{\text{overhead}}) \quad (6)$$

Finally, the end-to-end delay for transmitting pr3 packets will be exceeding

$$\alpha \times t(k) + l_k \times \left(\frac{data_{\text{pr3}}}{s_{\text{t}}} + \text{pr3}_{\text{proc}}(t) \right) + \frac{d}{s_{\text{p}}} + (l_k \times t_{\text{overhead}}) \quad (7)$$

where $t(k)$ denotes the length of a time slot of nodes at level l_k.

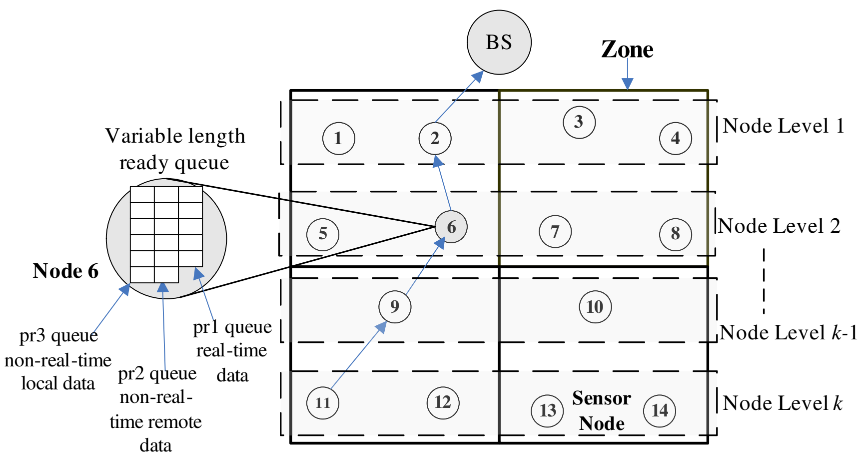

Figure 9. Three-class-priority packet scheduling scheme.

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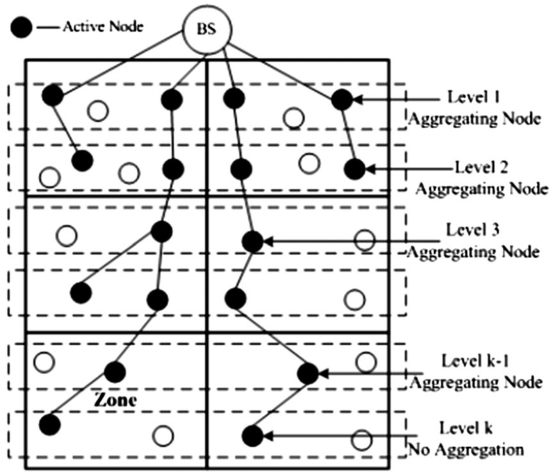

Figure 10. Data aggregation tree.

3.4. Data aggregation

Once data packets are scheduled, they are routed through the nodes of a path from the source node to the BS. We introduce a dynamic data aggregation scheme [43], where aggregation types and functions change automatically or by end user on the basis of the application types and requirements. For instance, data sensing time of sensors can be set to a specific time of a day or can be periodic or can be event-triggered on the basis of the data requirement or precision.

Figure 10 illustrates a data aggregation tree. Active nodes work using the TDMA scheme, where the length of time slots at different levels is variable. For instance, at time slot 1, the active nodes at the farthest level L_k sense the subscribed events and send corresponding data to the active nodes at upper level L_{k-1}. If a node x at level L_k does not have any subscribed event to send at time slot 1, node x sends a small-sized special packet to the node at the upper level with which x has an established path. At time slot 2, active nodes at level L_{k-1} receive data or special packet, send acknowledgement to nodes at level L_k and also transmit data or special packet to nodes at the upper level L_{k-2}. Hence, the length of time slot 1 is shorter than that of time slot 2. Moreover, the length of time slots at different levels can be adjusted on the basis of the data types and the aggregation functions. In normal aggregation policy, the length of the time slot of sensor nodes at the lowest level is the minimum that is incremented (by a constant) at the upper levels. However, for real-time and time-critical emergency applications that stop intermediate nodes to aggregate data, time slots for nodes at different levels are almost equal to reduce end-to-end data transmission delay.

4. EXISTING FRAMEWORK

To the best of our knowledge, no integrated framework comprising sensor localization, routing, data scheduling, and data aggregation exists in the literature. However, we find an existing approach [39] that comprises sensor localization and routing protocols. Thus, we build a new WSN management framework by replacing the localization and the routing protocols in the proposed framework with the corresponding approaches in [39]. We assume this framework as an existing framework to compare with our proposed framework.

In the localization approach of this existing WSN management solution [39], the sink node acts as an origin that is located at the coordinate $(0, 0)$. One of the neighboring nodes, A, of the sink node is considered to be located on the positive side of the x-axis at the coordinate $(a, 0)$. Then, the sink node collects all neighbor tables that contain information of distances among sensor nodes. Using this information, the sink node selects a node, B, which is the neighbor of both the sink node and A. Authors assume that node B is at distance b_1 from the sink node and distance b_2 from node A and that node B is located at the positive side of the y-axis. Once the locations of the sink node, A, and B are determined, other nodes that receive the location information of these three nodes can localize themselves using triangulations. In this approach, whenever a node, C, is localized, it is considered as an anchor node. Thus, if there is any location error in C, this error will be propagated to localize other unlocalized nodes. This results in a large average localization error.

In the routing protocol of this existing approach, each node keeps an attribute, radio depth d_r (i.e., distance from the node to the sink node in terms of radio range). For instance, the sink node has $d_r = 0$, and all nodes within the radio range of the sink node has $d_r = 1$. Whenever a node, A, checks its neighbor table and finds the node m with the lowest radio depth, d_m, A sets its $d_r(A)$ as $d_r(A) = d_m + 1$. In routing towards the sink node, each node selects the upstream node with radio depth $d_r - 1$ as the next hop. However, this selection based on the least hop in terms of radio range does not guarantee the shortest path in Euclidean distance. This routing protocol considers the remaining energy of a node along with its d_r to balance energy network consumption.

5. PERFORMANCE EVALUATION

We simulate the proposed WSN management framework using the C programming language and evaluate its performance in terms of localization error, localization energy consumption, network energy consumption, and end-to-end data transmission delay. We use randomly connected UDGs on an area of 100×100 m as a network simulation model. The energy model used in the simulation is presented in the following section.

5.1. Energy model

Let E_{TX} and E_{RX} represent energy consumption for transmitting and receiving data of size *dataSize* to/from another

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Table I. Simulation parameters and their values.

Parameter	Value
Network size	100 x 100 m^2
Number of nodes	Maximum 200
Number of zones	4–12
Base station position	55 × 101 m
Transmission energy consumption (ε_{data})	50 nJ/bit
Energy consumption in free space/air (ε_{air})	0.01 nJ/bit/m^2
Initial node energy	2 J
Transmission speed	250 kB/s
Propagation speed	198×10^6 m/s

node at distance d and are denoted as

$$E_{TX} = dataSize \times \varepsilon_{data} + dataSize \times d^2 \times \varepsilon_{air} \quad (8)$$

$$E_{RX} = dataSize \times \varepsilon_{data} \quad (9)$$

In Equations (8) and (9), ε_{data} and ε_{air} represent the energy spent in transmitter electronics circuitry and in RF amplifiers for propagation loss, respectively.

The simulation parameters and their respective values are presented in Table I.

5.2. Simulation results

In the following subsections, we present simulation results and performance analysis.

5.2.1. Proposed localization approach, RELMA in the integrated framework.

We measure the performance of our proposed localization approach, RELMA, in the integrated network management framework. For this purpose, we build a new framework by replacing RELMA with the existing neighbor-information-based localization system (NBLS) approach in the proposed framework and then compare the proposed framework with this new framework. We vary the number of nodes between 100 and 160. We set the number of zones, the transmission range (R_c), and the sensing range (R_s) to four zones, 30 m, and 15 m, respectively. We use a single mobile anchor node that is attached to a vehicle and moves very slowly at a velocity of 5 cm/s. Thus, the unlocalized node obtains enough time to collect the anchor's position and compute its coordinate.

Figures 11 and 12 illustrate that both RELMA methods 1 and 2 outperform the existing NBLS approach in the integrated framework in terms of localization error and energy consumption. Figure 11 demonstrates that both RELMA methods 1 and 2 are identical in terms of localization error, which is also validated by Student's t-test. However, localization energy consumption for RELMA method 1 is lower than that of RELMA method 2 (Figure 12). This is because a large number of messages are transmitted in RELMA method 2 for determining the NS and the ND between anchor and unlocalized nodes, which is not the case for RELMA method 1.

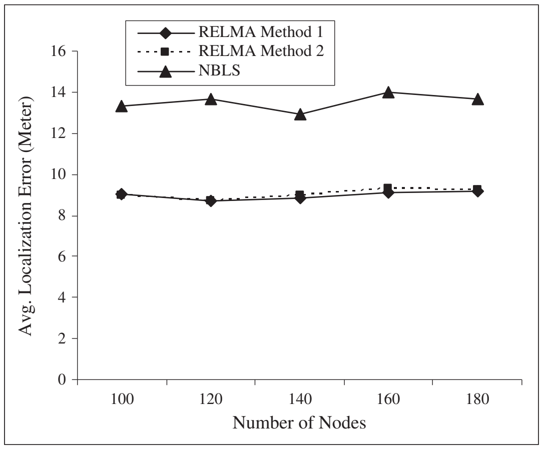

Figure 11. Localization error of range-free, energy-efficient localization technique using mobile anchor (RELMA) methods 1 and 2 and neighbor-information-based localization system (NBLS) in integrated framework.

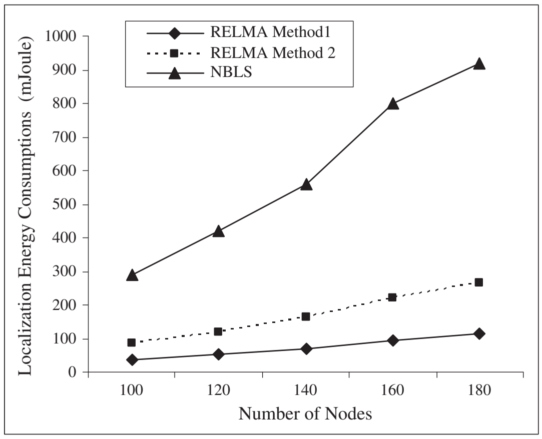

Figure 12. Localization energy consumption of range-free, energy-efficient localization technique using mobile anchor (RELMA) methods 1 and 2 and neighbor-information-based localization system (NBLS).

Similarly, Figures 13 and 14 demonstrate that the proposed RELMA localization approach outperforms NBLS in terms of localization error and energy consumption, varying the number of nodes. This is because the existing NBLS approach is very complex and works in three phases. In the first phase, it localizes nodes using the distance-vector-hop approach. These initial localized nodes are known as unexamined nodes. In the second phase, the unexamined nodes, which have localization error less than an error threshold, are selected as quasi-anchor nodes. These quasi-anchor nodes are used in the third phase to localize all other unexamined nodes using the neighbor-information-based approach. Thus, a large number of

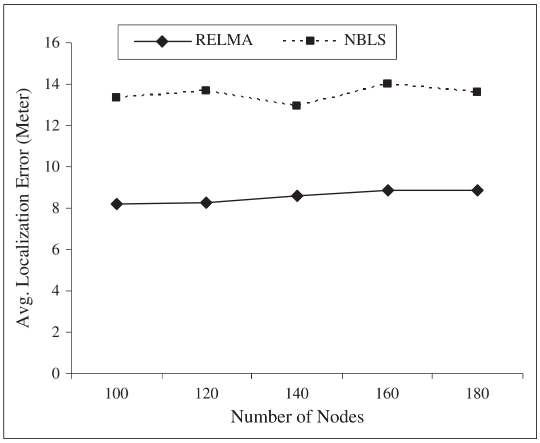

Figure 13. Localization error of range-free, energy-efficient localization technique using mobile anchor (RELMA) and neighbor-information-based localization system (NBLS) in an integrated framework.

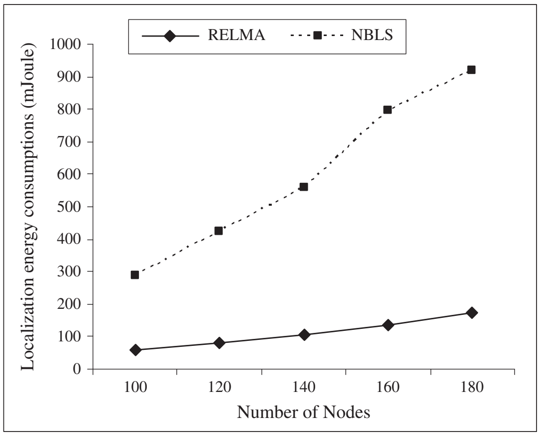

Figure 14. Localization energy consumption of range-free, energy-efficient localization technique using mobile anchor (RELMA) and neighbor-information-based localization system (NBLS) in an integrated framework.

messages are transmitted in the NBLS approach. Moreover, in the NBLS approach, static anchor nodes use R_c to transmit location information to unlocalized nodes, whereas the proposed RELMA localization approach uses R_s. Because R_s is much shorter than R_c, RELMA contributes lower localization energy consumption and error than NBLS. All these results are also validated using Student's t-test at 95% confidence level.

This framework works for a few number of mobile anchor nodes. If we include more anchor nodes, this is expected to increase the localization accuracy. However, increasing the number of anchor nodes will increase the number of data transmissions. Thus, each node will receive more data packets from anchor nodes and consume more energy. Thus, the network lifetime will be reduced. Because sensor nodes are an energy constraint, we use a

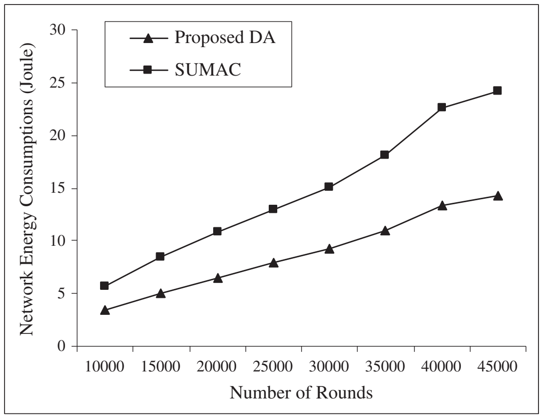

Figure 15. Network energy consumption of proposed data aggregation (DA) and Scalable and Unified Management and Control (SUMAC) approaches in the integrated framework, varying number of rounds.

few mobile anchor nodes to trade off localization error and energy consumption, that is, achieve sufficient localization accuracy (as is required by a WSN application) and also energy efficiency.

5.2.2. Proposed data aggregation approach in the integrated framework.

We also evaluate the performance of the proposed data aggregation approach in the integrated framework and compare it with the existing Scalable and Unified Management and Control (SUMAC) data aggregation approach in terms of network energy consumption, end-to-end data transmission delay, and network lifetime, varying the numbers of both rounds and zones. For this purpose, we again form a new framework by replacing the proposed data aggregation with the existing SUMAC in our integrated framework. We vary the number of rounds between 10 000 and 60 000. We set the number of nodes, zones, and R_s to 100 nodes, four zones, and 15 m, respectively.

Figure 15 demonstrates that the proposed data aggregation approach has better performance than SUMAC in terms of network energy consumption over a number of rounds. This is because the proposed data aggregation approach selects a minimum number of aggregating nodes. Moreover, special packets are transmitted to achieve fault tolerance, which also consume less energy. On the other hand, SUMAC requires a large number of aggregations switching among different levels of the network. This requires a large number of message transmissions and consumes much network energy, which is not the case for the proposed data aggregation approach.

Figure 16 illustrates that the proposed data aggregation approach has lower end-to-end data transmission delay as compared with the existing SUMAC approach because the proposed approach uses variable-length time slots at different levels using the TDMA scheme. Moreover, small-sized special packets take less time to be transmitted to the BS.

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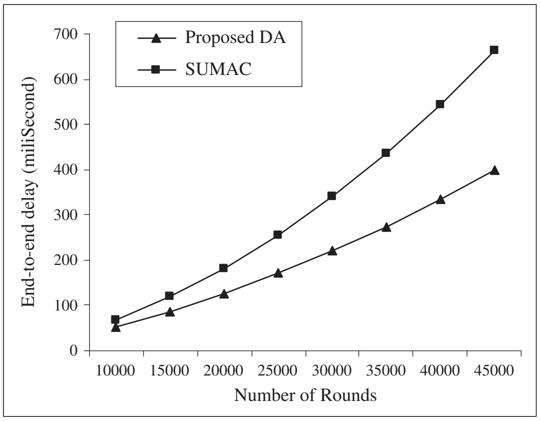

Figure 16. End-to-end data transmission delay of proposed data aggregation (DA) and Scalable and Unified Management and Control (SUMAC) approaches in the integrated framework, varying number of rounds.

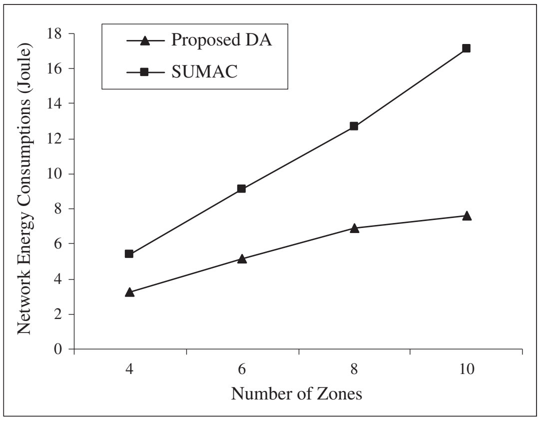

Figure 17. Network energy consumption of the proposed data aggregation (DA) and Scalable and Unified Management and Control (SUMAC) approaches in the integrated framework, varying number of zones.

Varying number of zones

We vary the number of zones between 4 and 10. We set the number of nodes, rounds, and R_s to 120, 10 000, and 15 m, respectively. We observe in Figures 17 and 18 that the proposed aggregation approach outperforms SUMAC in terms of network energy consumption and end-to-end delay. Possible reasons for this performance difference have already been explained.

5.2.3. Proposed framework versus existing framework.

We present the working principle of an existing solution or a framework in Section 4, which measures the performance of its localization approach in terms of normalized root mean square error by varying the signal-to-noise ratio and its routing protocol in terms of network lifetime by

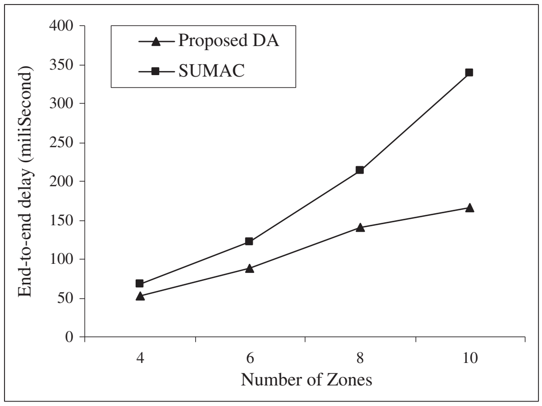

Figure 18. End-to-end transmission delay of proposed data aggregation (DA) and Scalable and Unified Management and Control (SUMAC) approaches in the integrated framework, varying number of zones.

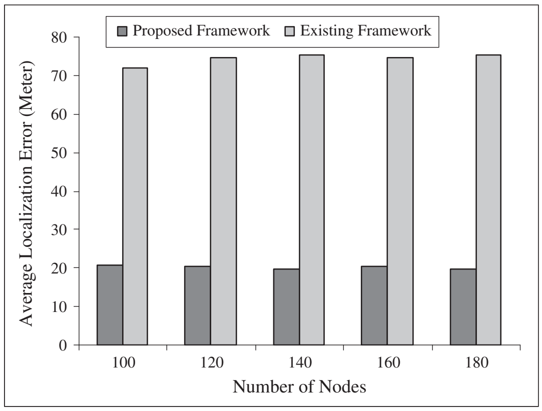

Figure 19. Localization error, varying number of nodes.

varying the radio range. Thus, we also simulate the existing approach to compare it with the proposed framework rather than using the results from the paper [39]. This is because we use different performance metrics in the proposed WSN management approaches and framework.

We vary the number of nodes between 100 and 160. We set the number of zones, rounds, and sensing range to four zones, 100, and 28 m, respectively. Figure 19 demonstrates that the average localization error of the existing approach is much higher than that of our proposed approach. This is because the existing approach considers a newly localized node as an anchor node. Thus, error in localizing a node will be propagated. Again, we illustrate the average localization error as

$$avgLocError = \frac{totalError}{numOfNodes} \tag{10}$$

Thus, the error remains almost the same for each approach even if we increase the number of nodes.

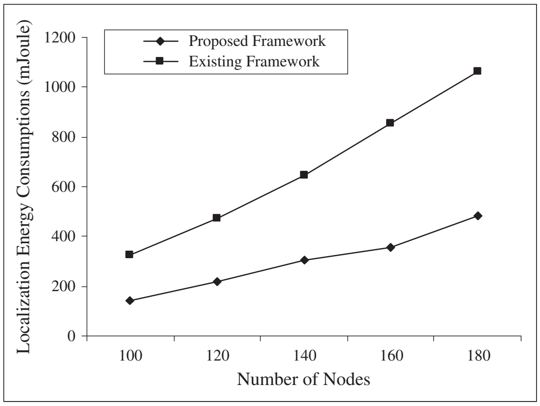

Figure 20. Localization energy consumption, varying number of nodes.

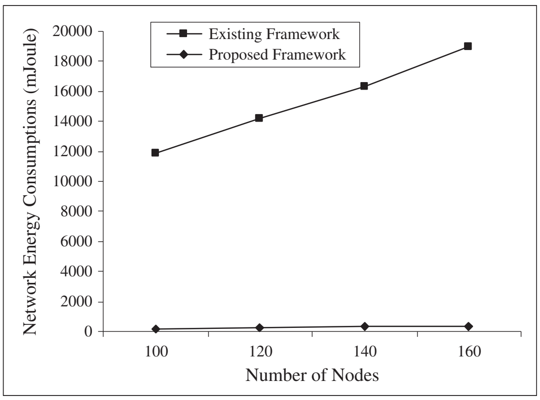

Figure 21. Network energy consumption, varying number of nodes.

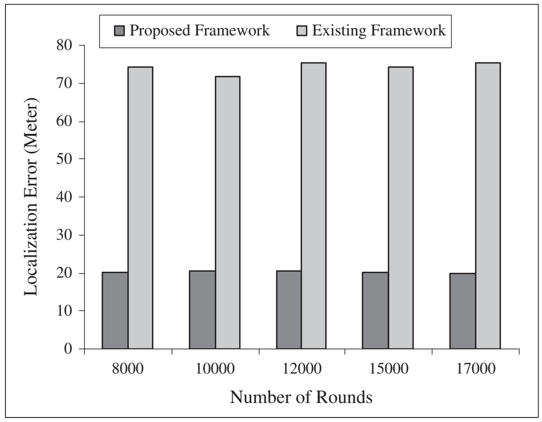

Figure 22. Localization error, varying number of rounds.

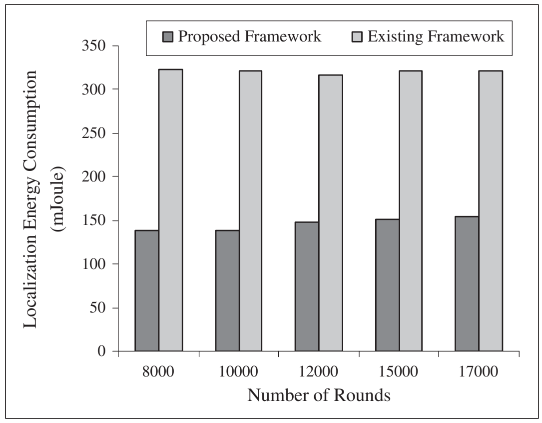

Figure 23. Localization energy consumption, varying number of rounds.

Figure 20 illustrates that the localization energy consumption of the proposed framework is much lower than that of the existing localization approach in [39]. This is because each node consumes much energy to compute its neighboring table (with distance information to each other) in the existing localization approach, whereas in the proposed approach, anchor nodes transmit their location information to the unlocalized nodes, which are at the smaller sensing range (R_s) apart.

Figure 21 demonstrates that the network energy consumption (which contains energy consumption for both localization and routing) in the proposed approach is much lower than that in the existing approach, varying the number of nodes. This is because each node broadcasts its radio depth to neighboring nodes, which consumes much energy in the existing routing protocol. Moreover, in the existing routing protocol, a sensor node transmits data to its neighboring node with the lowest radio depth. However, a neighboring node with the least radio depth does not guarantee the shortest Euclidian distance. Figure 21 also demonstrates that the differences in the network energy consumption between the existing and proposed frameworks are much more than the differences in the localization energy consumption between the existing and proposed frameworks in Figure 20. Thus, we can conclude that the energy consumption of the existing framework for data routing is much higher than that of the proposed framework, which results in larger differences in network energy consumption.

We also evaluate the performance of the proposed framework by varying the number of rounds while setting the number of nodes and zones to 100 and 4, respectively. Figures 22–24 demonstrate the performance results. In all cases, the proposed framework outperforms the existing framework. We have already explained the possible reasons for this. All these results are validated through statistical analysis (Student's t-test) at 95% confidence level.

5.2.4. Individual node energy dissipation.

We also evaluate the performance of the CRTCA protocol of the proposed framework having topology N_2 (a few more nodes are distributed to zones that are close to the BS) against that having topology N_1 (equal number of

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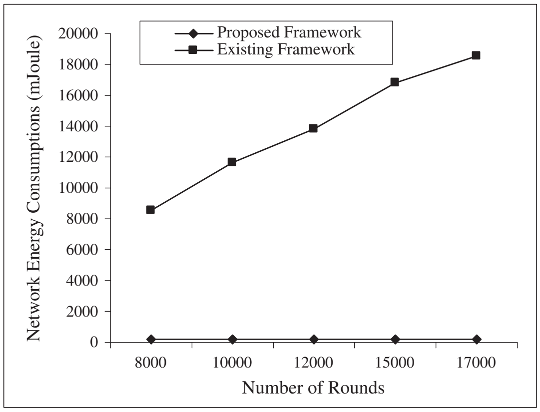

Figure 24. Network energy consumption, varying number of rounds.

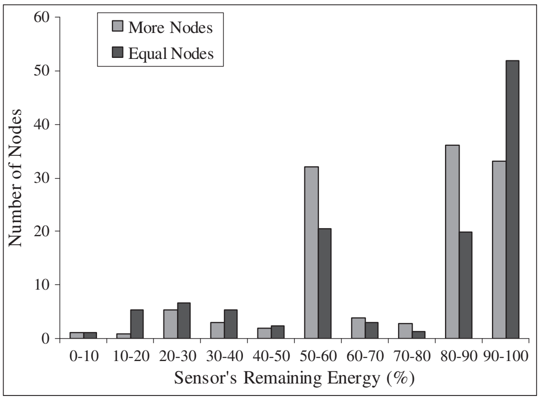

Figure 25. Remaining energy of sensor nodes in percentage for equal number of nodes and extra nodes distributed to zones that are close to the base station.

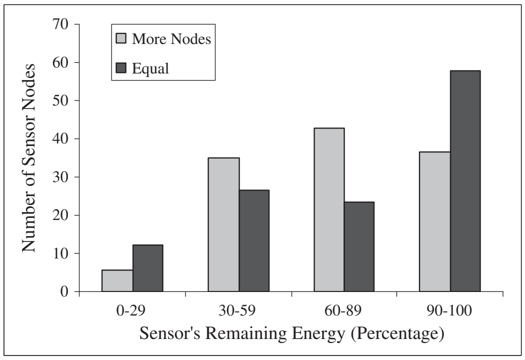

Figure 26. Remaining energy of sensor nodes in percentage for equal number of nodes and extra nodes distributed to zones that are close to the base station.

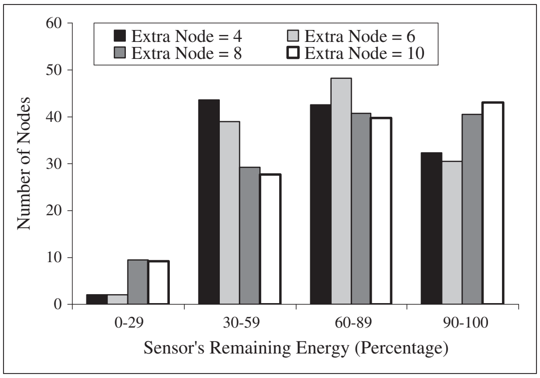

Figure 27. Remaining energy of sensor nodes in percentage, varying the number of extra nodes that are distributed to the zones that are close to the base station.

nodes are distributed to all zones) in terms of the remaining energy of individual sensor nodes for several energy groups (in percentage). This experiment is performed to illustrate whether the energy dissipation of individual sensor nodes is properly distributed.

Let us assume that S_n and Z_n are the number of sensors and zones, respectively, in the network and p is the number of more nodes that are distributed to the zones closest to the BS. If S_n is divisible by Z_n, S_n/Z_n, nodes are distributed to each zone of N_1. However, the number of nodes to the zones that are close to the BS of N_2 will be $(S_n/Z_n) + p$. For instance, in this simulation, we set the number of nodes and zones to 120 and 4, respectively. Thus, 30 nodes are distributed to each zone of N_1, whereas the number of nodes in the zones are 36, 36, 24, and 24 for N_2 because $p = 6$.

To evaluate the performance, we divide the sensor's remaining energy into 10 groups: 0–10%, 11–20%, ..., 90–100%. We run the simulation by varying the number of rounds and take the average of the remaining energy in different energy groups. Figure 25 illustrates that the number of nodes that lie in the lowest percentage groups (in the range 0–50%) is less in N_2 (i.e., more nodes) than in N_1 (i.e., equal nodes). Thus, N_2 has better performance than N_1 because it is highly expected to have less number of nodes in the lower percentage groups. This also reflects the network lifetime and energy dissipation of individual nodes of the network.

To better understand the energy dissipation of individual sensor nodes, we also divide the network remaining energy in four major percentage groups: 0–29%, 30–59%, 60–89%, and 90–100%. Then, we vary p from 4 to 10 for a fixed number of rounds and take the average of the remaining energy in four groups for a number of simulation runs. Figure 26 illustrates that the remaining energy of sensor nodes is properly distributed in each energy group. This also reflects the prolonged network lifetime because the number of nodes in the lowest remaining energy group (0–29%) is much less than in the other groups. Again, the lifetime of N_2, "more node," will be longer than that of N_1, "equal nodes," because the number of nodes of N_2 in the energy group 0–29% is much less than that of N_1. Similarly, Figure 27 illustrates the number of nodes that lie in different energy groups, with p varied between 4 and 10.

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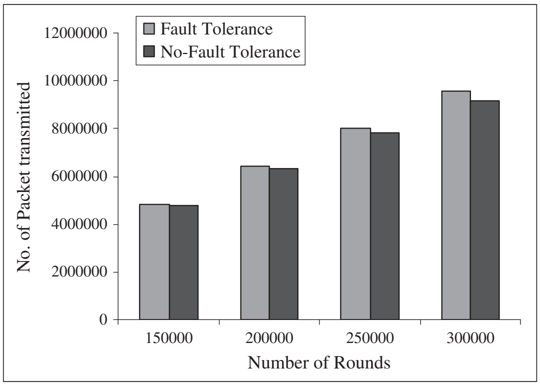

Figure 28. Number of packets transmitted for both fault-tolerance and without-fault-tolerance techniques, varying number of rounds.

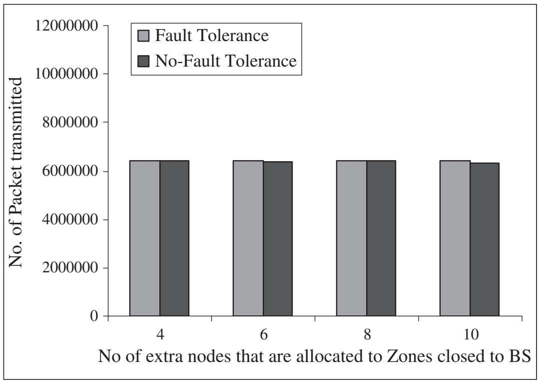

Figure 29. Number of packets transmitted for both fault-tolerance and without-fault-tolerance techniques for equal nodes and extra nodes distributed to zones that are close to the base station (BS).

Thus, we can conclude that the CRTCA protocol of the proposed framework balances individual node energy consumption as well as the overall network energy consumption. A few of the possible reasons are the following: (i) a few more nodes are distributed to zones that are close to BS because nodes in these zones receive and transmit more data packets as compared with nodes in other zones; (ii) each node sends its remaining energy information with the data packet that is transmitted to BS; thus, BS can reselect active nodes if the remaining energy of a current active node goes below a threshold value; and (iii) after a certain number of rounds, R_n, the setup phase is initiated, where R_n is calculated from the current network energy (Equation (4)).

5.2.5. Fault tolerance of the proposed framework.

Figures 28 and 29 illustrate the fault tolerance characteristics of the proposed framework in terms of the number of transmitted packets. Figure 28 shows that the number of transmitted packets for no fault tolerance (i.e., no fault tolerance mechanism is implemented) is less than that with fault tolerance (i.e., a fault tolerance mechanism is implemented). Thus, a number of packets are lost because of the link and/or node failures whenever no fault tolerance mechanism is implemented in the proposed routing protocol.

Figure 29 illustrates that only a small number of packets are lost for the number of extra node, $p = 6$ and $p = 10$, whenever no fault tolerance mechanism is implemented in the protocol. This result reflects that there is a probability of packet loss without taking any measures for fault tolerance. We also validate the simulation results using Student's t-test.

6. CONCLUSION AND FUTURE WORK

In this paper, we evaluate the performance of the proposed integrated WSN management framework that comprises components for sensor localization, data scheduling, routing, and data aggregation. Experimental results show that the proposed framework outperforms an existing approach [39] that comprises only localization and routing protocols in terms of localization energy consumption, localization error, end-to-end data transmission delay, packet loss ratio, and network energy consumption for varying number of nodes, zones, and rounds. The proposed framework achieves fault tolerance capabilities and balances individual sensor energy dissipations to prolong the network lifetime. We expect that this framework can be used as a basis for developing efficient and large-scale WSN management frameworks in future and also "Internet of Things."

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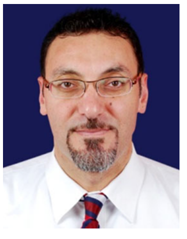

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