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Building a Sustainable Internet of Things

Energy-efficient routing using low-power sensors will meet the need.

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The Internet of Things (IoT) is a framework built as a network of trillions of devices (called *things*) communicating with each other to offer innovative solutions to real-time problems. These devices monitor the physical environment and disseminate collected data back to the base station. In many cases, the sensor nodes have limited resources like energy, memory, low computational speed, and communication bandwidth. In this network scenario, sensors near the data collector drain energy faster than other nodes in the network. A mobile sink is a solution in sensor networks in which the network is balanced with node energy consumption by using a mobile sink in the sensing area. However, the position of the mobile sink instigates packet overhead and energy consumption. This article discusses a novel data-routing technique to forward data toward a base station using a mobile data collector, in which two data collectors follow a predefined path to collect data by covering the entire network. The proposed technique improves the network performance, including energy consumption and sensing area lifetime.

Autonomous tiny sensors are spatially distributed to monitor real-time environmental situations like emergency threats and temperature, pressure, sound, pollutants, light, humidity, and wind direction in wireless sensor networks (WSNs) and the IoT [1], [2]. In cyberphysical systems, such as smart cities, smart health, and smart agriculture, the IoT uses a substantial number of sensors with limited sensing, storage, computing,

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Digital Object Identifier 10.1109/MCE.2017.2776462
Date of publication: 8 February 2018

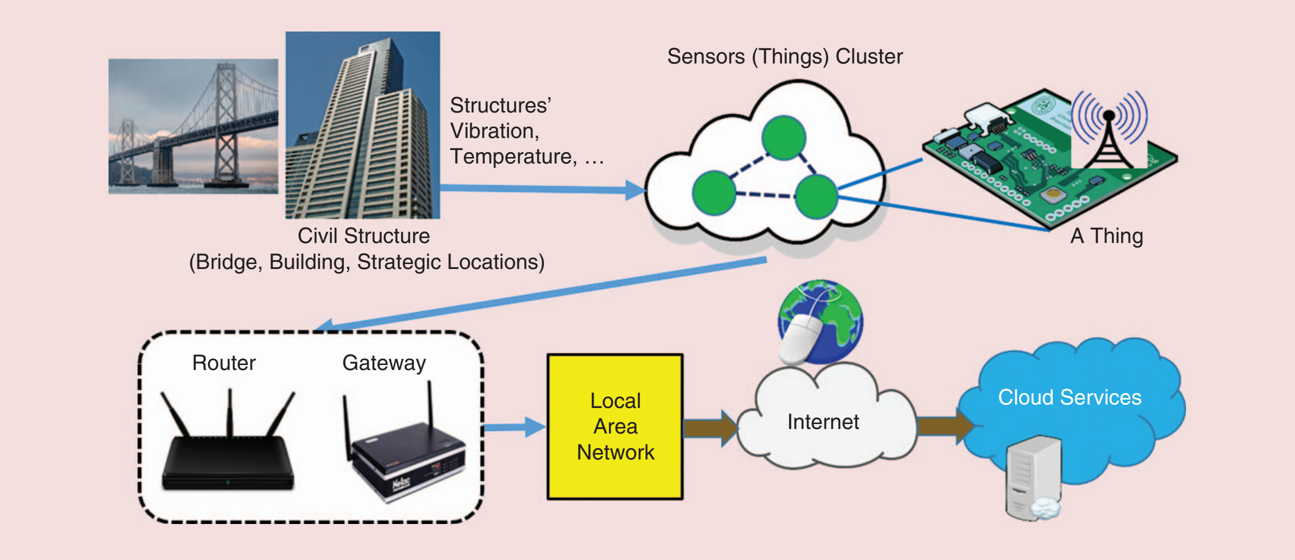

FIGURE 1. The IoT for smart structures in smart cities.

and wireless communication capabilities (Figure 1) [1]–[3]. IoT applications include target tracking, monitoring (e.g., environmental, weather, habitat, field), disaster management, and industrial process monitoring and control. It may be noted that, while sensor network (including WSNs) and IoT terms are used interchangeably in the existing literature, these are not the same things, as depicted in Figure 2 with a three-layer model of the IoT [4].

A sensor node has several parts, including a radio transceiver, a microcontroller, and a battery. A sensor node communicates with other nodes by receiving and transmitting data packets through radio-frequency (RF) signals within its transmission range [5]. The source node forwards the sensed data in two different ways: 1) by routing to the nearest sensor to reach the base station or 2) routing the data packets directly to the base station if the base station is within the sensor's radio range. There are several algorithms available in the existing literature to optimize routing data packets in a WSN from source sensors to the sink nodes or base station. Sensor nodes transmit the sensed data through an RF channel to the base station [6]. They have limited battery capacity, and battery replacement is challenging in hostile or remote environments.

Sensor nodes are usually static in the sensing area. The radio range of the sensor node is short, thus multihop communication is essential between source sensors and the base station. A data collector (i.e., a sink in sensor networks) plays a vital role in multihop data transmission toward the base station by collecting data from source-sensing devices. This is also known as a *device* for the fog-computing architecture [7], [8]. Nodes nearer to the data collector deplete their batteries faster than other nodes, which is known as the *energy-hole problem* [9]. This problem limits the delivery of the sensor data packets and affects the network lifetime. A mobile data collector is an alternate efficient solution to overcome the energy-hole problem [10]. Mobility of a data collector can maintain load balancing, which helps to attain uniform energy consumption and increase the network lifetime. A mobile data collector is able to access remote locations of the sensing area, which are unreachable by a static data collector [11]. However, a mobile data collector requires frequent advertisement of its own position in the network, causing more overhead, which needs to be minimized to reduce energy consumption. Depending on the application requirements, there are three types of data delivery models: 1) periodic, 2) event driven, and 3) query driven. In periodic sensing, sensors route the sensed data packets continuously in an interrupted interval. In the case of the event-driven data dissemination model, a sensor transfers data when an event occurs. For the case when it is query driven, a sensor reports data when a data collector requests the required data.

To address the aforementioned challenge, this article discusses a data-routing design by broadly dividing a sensing area into two equal parts, either horizontally or vertically, to form an elliptical path. There are two mobile data collectors that repeatedly rotate in each side of a sensor field in a predefined elliptical path. Mobile data collectors select some sensors to forward data packets from static sources. The data packets are forwarded to data collectors by adaptive neighbor detection and node selection. The mobile data collectors then

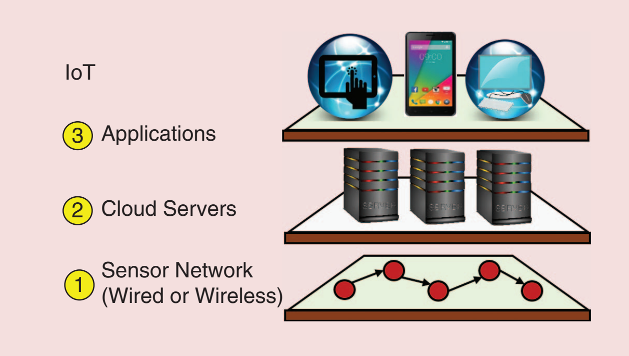

FIGURE 2. The WSN versus the IoT [10].

forward the collected data toward the base station. The elliptical path of the collector can be adjusted to maintain load balancing when more sensors are added to the sensing area.

STATE OF THE ART

WSNs with tiny (low-power) sensors for sensing and data forwarding (data routing) in the IoT for energy efficiency is addressed in this article. There are several data-routing protocols proposed for IoT and wireless networks in the existing literature. The traditional methods of data routing toward a base station include flooding and gossiping [12]. Flooding means repeated broadcasting, which is a simple and fast technique for data communication. In the gossiping routing technique, a sensor node randomly selects one of its neighbors to receive its data. After receiving the data, the neighbor node selects another neighbor, and the process repeats.

There are three types of data routing based on finding a route to the destination: 1) proactive, 2) reactive, and 3) hybrid. In a proactive routing protocol, all data dissemination routes to the destination are computed before it is required, while, in reactive routing protocol, data dissemination routes are computed when it is required. A hybrid routing protocol is the combination of both proactive and reactive protocols. The mobility model of sensors is classified into three major categories: controlled, predictable, and random. In random mobility, the data collector arbitrarily moves without depending on network conditions, i.e., network information is not required for mobility. In predictable mobility, the data collector's movement is based on a certain strategy. It does not require frequent updates of the collector's position information. In controlled mobility, the mobility of the data collector is managed based on a certain criterion, such as an event position, residual energy, and so on. The sink controls the mobility to reduce energy consumption and increases the lifetime of the network. Security plays a vital role in the IoT, as sensors are deployed in a hostile environment [13], [14].

Based on the mobility of the sink, the data dissemination protocol can be further classified into two types: 1) a data dissemination protocol with a mobile sink and 2) a data dissemination protocol with a static sink. In a specific protocol example, Railroad constructs a virtual rail structure in the middle of the sensor field [15]. The source node locally stores sensed data and then forwards the corresponding metadata to the closest rail node inside the rail, as shown in Figure 3. The sink sends a query message into the rail to collect the required data. Railroad increases overhead and consumes more energy as the query message travels through the rail until it obtains the metadata of the required data. In another protocol example, ring routing constructs a closed loop, taking sensor nodes with single-node width around the center of the sensor field, as shown in Figure 4 [16]. When the energy level of the ring node decreases, it selects another neighbor node as a ring node and constructs a new ring, i.e., the ring structure changes. The mobile data collector selects a neighboring node as an anchor node. After selection of the anchor node, position information for the anchor node is forwarded to the ring. When the source wants to send data to the sink, it sends a request message to the ring for the anchor node position information. Then the ring forwards a response message.

A PROPOSED DATA-ROUTING TECHNIQUE

Sensor nodes of the proposed technique play two parts: 1) the collector node and 2) the normal node. The data-forwarding node is the neighboring sensor node selected by the mobile data collectors while rotating in the predefined elliptical path. Except for the forwarding node, all of the sensors in the sensing area act as standard source sensor nodes. After the sensor node deployment, a path is discovered for the mobile data collectors, based on the concept of covering a maximum area of the WSN. In the proposed technique, the data collector repeatedly rotates in a predefined elliptical path to collect a portion of data from the source nodes through collector nodes and delivers it to the base station.

ASSUMPTIONS

Realistic assumptions have been made to design the routing technique. One of the assumptions was to position the base station at the center of the sensing area. A large number of

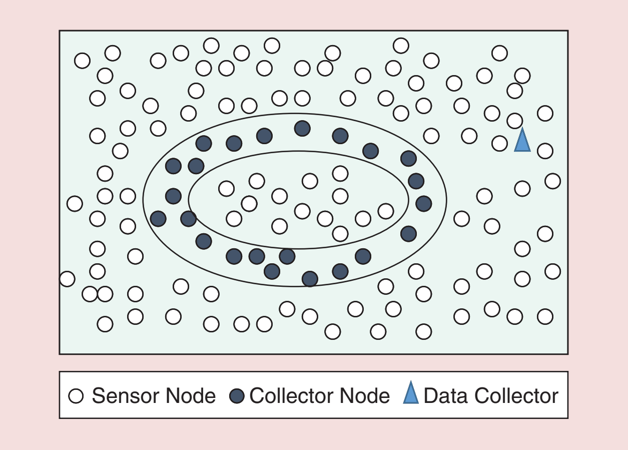

FIGURE 3. The data dissemination in railroad protocol.

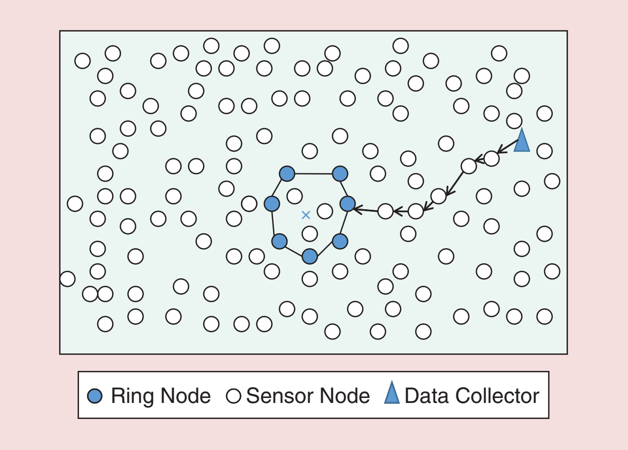

FIGURE 4. The data dissemination in ring-routing protocol.

sensors are randomly deployed to detect the sensing area. At the same time, uniform density is ensured such that the data-gathering rate of each sensor node in the sensing area is relatively the same. Two mobile data collectors are used to increase the data collection rate and to alleviate the energy-hole problem. The base station is always aware of the shape of the sensing area. The sensing area is divided into two equal parts, either horizontally or vertically. Each mobile data collector collects data from one of these two parts by rotating in a predefined elliptical path. In the case of a square field, an elliptical path can be constructed either horizontally or vertically from the sensor field center, where the base station is situated. Similar results are observed for both cases. However, in the case of a rectangular area of the sensor field, some calculations have to be performed before constructing the path for both the mobile data collectors.

PROTOCOL DESCRIPTION

The shape of the sensor field has to be found before deciding the elliptical path of the mobile data collector in the sensor field. The sensor field can be square or rectangular in shape. Initially, the base station has the information of the two diagonal points of the sensor field. The base station can find the shape of the sensing area.

A square sensor field is divided either horizontally or vertically to construct an elliptical path. However, in a rectangular sensor field, there are two possible cases: 1) the rectangle is divided horizontally, and 2) the rectangle is divided vertically. The new major axis and new minor axis are calculated for each case. The greater value of the new major and minor axes of the two cases are compared:

$$\begin{aligned}\text{new major axis } (M) &= \frac{1}{2} * majoraxis\\ \text{new minor axis } (m) &= \frac{2}{3} * majoraxis. \qquad (1)\end{aligned}$$

An elliptical path is constructed taking the major axis value M and minor axis value m. The maximum perimeter value of the ellipse is needed so as to cover the maximum area by maximizing the perimeter of the ellipse $P_{\max}$ on both sides of the sensor field:

$$P_{\max} \approx 2 * \pi * \sqrt{\frac{(M^2+m^2)}{2}}. \qquad (2)$$

An optimum elliptical path is then discovered for both the mobile data collectors where the base station is positioned at the sensing area center. Both the mobile data collectors are deployed in the opposite parts of the sensor field. These mobile data collectors start moving from the base station and collect data packets by rotating periodically. The proposed technique is divided into five parts: 1) the partition (horizontal or vertical), 2) the ellipse formation for data collectors, 3) the collector node selection, 4) the neighbor detection, and 5) the data transmission. These technical descriptions are as follows.

THE PARTITION (HORIZONTAL AND VERTICAL)

The elliptical path discovery for mobile data collectors is done either by dividing horizontally or vertically, as shown in Figure 5. The base station has the information of the two diagonal points of the sensing area. Thus, the base station has $X_{\max}$ and $Y_{\max}$, which are the maximum X and Y coordinate values of the sensor. If $X_{\max} \leq Y_{\max}$, then the sensor field is vertically partitioned; otherwise, there is a horizontal partition. The sensing area is thus divided equally into two parts. The sensor node determines its position from this partition information.

THE ELLIPSE FORMATION

After partitioning the sensing area, each mobile data collector is placed in a separate elliptical path constructed in different parts of the sensing area. The new major axis (M) and new minor axis (m) can be obtained using (1). For the ellipse formation in each partition, the major axis value M and minor axis value m are taken to find major radius and minor radius:

$$\begin{aligned}\text{major radius}\left(\frac{M}{2}\right) &= \frac{majoraxis(M)}{2}\\ \text{minor radius}\left(\frac{m}{2}\right) &= \frac{majoraxis(m)}{2}. \qquad (3)\end{aligned}$$

Then the focal point is calculated from the center of the ellipse, i.e., linear eccentricity (f) as

$$f = \sqrt{\frac{M}{2}^{2} - \frac{m}{2}^{2}}. \qquad (4)$$

The two focal points (i.e., F_1 and F_2) on the ellipse's major axis have an equal distance from the center of the ellipse ($F_1F_2 = 2f$). If any point on the ellipse is taken and the sum of the extension to those two focal points are calculated, then it always gives a constant value that is equal to the major axis (M) of the ellipse. An ellipse is constructed along both sides of the sensor field, as show in Figure 3, by taking the value of the major axis (M), the minor axis (m), and the value of f. Then,

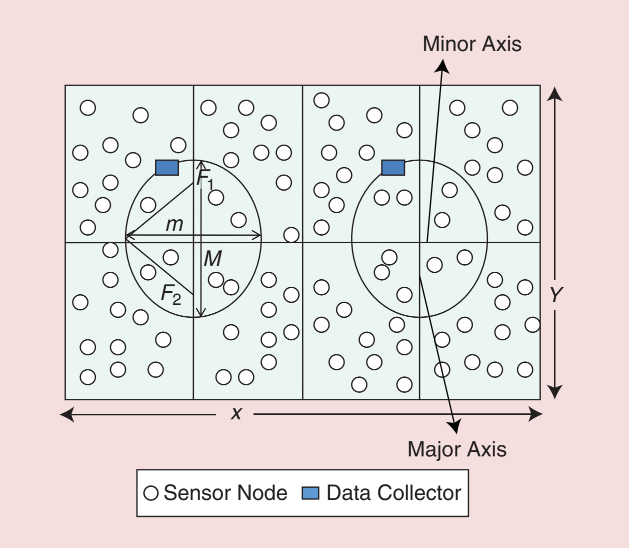

FIGURE 5. The elliptical path construction.

Algorithm 1: Ellipse formation and forwarding node selection.

```
1. if $X_{max} \le Y_{max}$
2.     vertically partition the sensing area
3. else
4.     horizontally partition the sensing area
5. end if
6. $M = \frac{1}{2} * majoraxis$ and $m = \frac{2}{3} * majoraxis$
7. linear eccentricity: $f = \sqrt{\frac{M^2}{2} - \frac{m^2}{2}}$
8. construct ellipse by taking the value from steps 6 and 7
9. if sensor $\in$ data collector neighbor
10.     set node as forwarding node
11.     include the node in forwarding node list
12. end if
```

the position of sensor nodes within or outside the ellipse is determined. After the ellipse formation, two mobile data collectors are placed in the opposite part of the sensor field. Both mobile data collectors rotate in their specified path and collect sensed data from the collector nodes. Algorithm 1 presents steps for ellipse formation and forwarding node selection.

THE DATA-FORWARDING NODE SELECTION

Data-forwarding nodes are the sensors closer to the mobile data collector path. These nodes receive data packets from source sensors through multiple paths. Mobile data collectors select data-forwarding nodes in the sensing area before collecting the sensed data from the data-forwarding nodes. Mobile data collectors rotate on the predefined path, send a beacon message to the neighboring forwarding nodes, and collect the sensed data from the forwarding nodes. Both of the mobile data collectors start moving in the elliptical path from the base station, and, on the first rotation in their assigned path, they select all of the neighboring sensor nodes within a one-hop distance of data-forwarding nodes, as shown in Figure 6. The forwarding node reports to the mobile data collector node with neighbor information. If the energy level of the mobile data collector node is lower than a threshold, then it selects one of the neighboring nonforwarding nodes (or an old forwarding node) that is within the range of the data collector as the new forwarding node.

THE NEIGHBOR DETECTION

According to the proposed technique, source sensors transmit the data packets to the forwarding node, followed by the data collector retrieving data from them by rotating in the predefined elliptical path. The sensor node has two main functionalities: 1) to ascertain the recipient of the data and 2) determine the direction in which the data is to be sent. Therefore, an important task for source sensors is to determine their neighbors to which they send sensed data.

Sensors have their own position information at the time of node deployment. These sensors determine whether they are within or outside the ellipse using their position information. If a sensor finds its position outside of the ellipse, then it sends data toward the ellipse center, whereas sensors send data away from the ellipse center of that partition if they have found their own position inside the ellipse. The clear data inward or outward flow is shown in Figure 7. Later, they find their neighbors after the partition of the sensing area. The neighbor detection in this technique has two different phases: 1) the set-up phase and 2) the data collection phase.

THE SET-UP PHASE

This phase consists of the procedures to partition sensor field, ellipse formation, and forwarding node selection. Data collectors send beacon messages to their one-hop neighbors to get to the forwarding node. Sensors respond to the collector node's beacon message if they have enough energy to participate and are also a one-hop neighbor from the elliptic path.

THE DATA COLLECTION PHASE

The source node forwards the sensed data to the nearest collector node based on its position. Forwarding nodes store the data packets and wait for the data collector's presence to forward

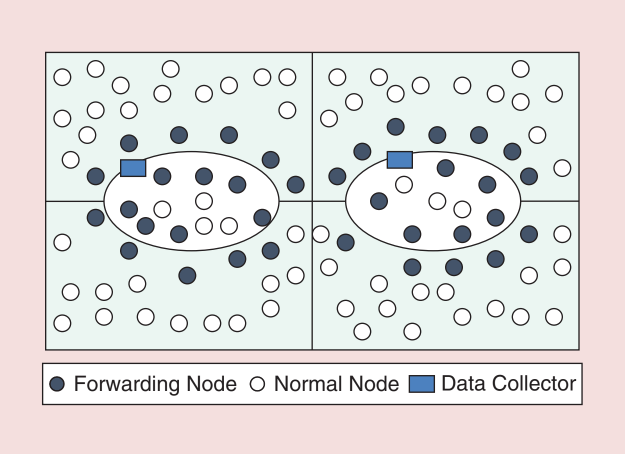

FIGURE 6. The data-forwarding node selection.

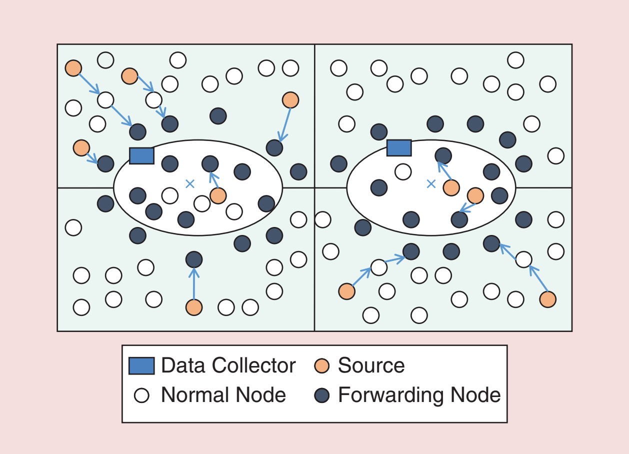

FIGURE 7. The data packets toward the forwarding node.

Algorithm 2: Collection of data from the forwarding node by mobile data collectors.

```
if node=collector node
    if data collector ∈ neighbor
        send data to data collector
    end if
else if node=normal node
    if collector node ∈ neighbor
        send sensed data to the collector node
    else
        if source is within ellipse
            send data away from the center of the ellipse to
            the nearest collector node
        else
            send data toward the center of the ellipse to
            the nearest collector node
        end if
    end if
end if
```

Table 1. Simulation parameters.

Simulation Parameters	Values
Simulator used	Castalia Simulator (version 3.2)
Network area	600 × 600 m^2
Number of nodes	200
Maximum radio transmission power	0 dbm
Sensibility	–95 dbm
Simulation time	600 s
Medium access control (MAC) protocol	Tunable MAC
Initial energy of nodes	1,000 mJ
Data collector speed	3, 6, 9, 12, 15 km/h
Number of data collectors	2

data. The collector node rotates on the predefined elliptical path and collects the stored sensed data from its neighboring forwarding nodes, as shown in Figure 7. The data collector is responsible for data forwarding to the base station based on the data sensitivity level or distance between them. In the worst case, the collector node delivers the aggregated collected data to the base station after one rotation.

THE DATA TRANSMISSION

Two mobile data collectors are placed in the predefined path by dividing the sensing area into two approximately equal parts. The mobile data collectors are deployed in either part with the base station always present at the center of the sensing area. Both of the mobile data collectors start moving from the base station to collect data packets from the forwarding nodes at the time of rotation. These collectors periodically rotate in the elliptical path to collect the data packets from the sensor nodes. After completing one rotation, the mobile data collectors aggregate the collected data and finally deliver the accumulation of the collected data back to the base station, as stated in the section, "The Data Collection Phase." A procedure for data collection is shown in Algorithm 2.

PERFORMANCE EVALUATION

Several simulation environments also exist for the IoT and WSNs [16]. The Castalia simulator in the Ubuntu platform was used to evaluate the performance of the proposed data-routing technique [17]. The simulation parameters used are shown in Table 1. The performance of the proposed routing technique is compared with ring-routing protocol [18].

AVERAGE CONTROL PACKET OVERHEAD

To manage the data collector mobility, sensors transmit the control packets for rendezvous region construction. Figure 8 shows the average control packet overhead with varying data collector speed. The proposed technique reduces the use of control packets as compared to the ring-routing protocol. In ring routing, the ring nodes always keep the location of the sink, which allows for easy retrieval of the sink location. However, as network operation progresses, there is always the need for a control packet exchange to repair the ring. An increase in the distance between the source and sink leads to higher energy consumption for the increased ring length.

AVERAGE ENERGY CONSUMPTION

The average energy consumption of a node is the energy consumed in transmitting and receiving data packets and control packets in a network. Energy consumption of routing protocols should be reduced to improve the network effectiveness. In this experiment, the average energy consumption was measured by varying the data collector speed from 3 to 15 km/h in increments of 3 km/h at a constant simulation time of 600 s. The average energy consumption for the proposed technique is less than the existing standard mobile sink

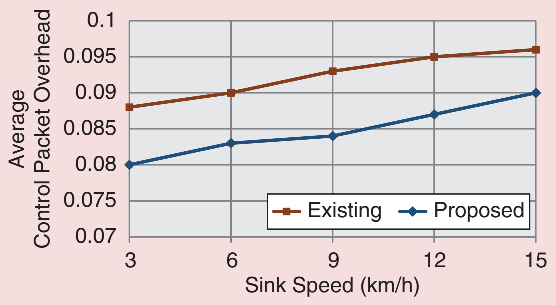

FIGURE 8. The variation of the average control packet overhead with the data collector speed.

protocol, as shown in Figure 9. Average energy consumption reveals an improved lifetime as a result of this technique.

END-TO-END DELAY

Finding the data collector's location and then forwarding the data packets to the collector node is a time-consuming task. End-to-end latency of the network of the proposed protocol in comparison with the existing protocol is shown in Figure 10. In the proposed model, source sensors forward data to the forwarding node, followed by the data collector gathering sensed data when the forwarding nodes are within its radio range. As a result, the end-to-end delay of the proposed technique is much less compared to the existing protocol. End-to-end latency of the network of the proposed protocol in comparison with the existing protocol is shown in Figure 10.

PACKET DELIVERY RATIO

The packet delivery ratio is the ratio of received packets to the packets delivered. This ratio is always counted in percentages, i.e., the number of packets delivered when 100 packets are sent from source sensors. The proposed technique needs less time to get the data collector's location when compared to ring routing. Ring routing introduces a delay while forwarding a data packet toward the base station. In that time, the data collector may change its location by selecting the next movement, causing data loss. In the proposed model, the data collector's location information is not required; when the sensor node senses data, it forwards that data to the forwarding node, decreasing packet loss. Therefore, the proposed technique has a better packet delivery ratio compared to other protocols. As shown in Figure 11, the packet delivery ratio performance of the proposed model is always efficient and better compared to the ring-routing protocol.

NETWORK LIFETIME

Network lifetime refers to the time taken until the first node dies in the network. Network lifetime plays a vital role when time sensors are used to sense the network. In a specific experiment, the network lifetime is measured by considering the number of nodes (200 nodes) that have died in the sensing network by varying the simulation time from 100 to 600 s. The result of the comparison between the existing and proposed technique for network lifetime is shown in Figure 12. The proposed technique has a longer network lifetime than the ring-routing protocol. The proposed protocol uses fewer control packets, resulting in load balance among the sensors and follows an optimum route for data packet dissemination.

CONCLUSION AND FUTURE DIRECTION

In the IoT, tiny sensors are deployed to sense networks within scenarios where the sensors have limited battery capacity and

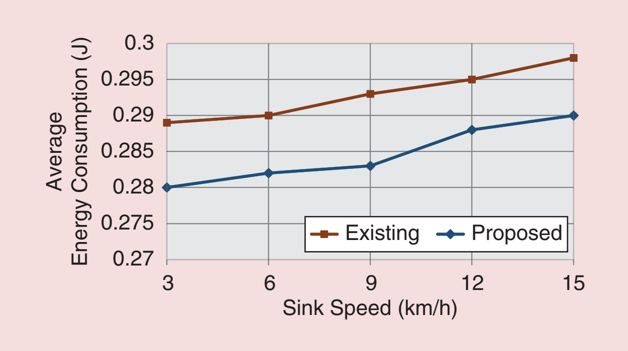

FIGURE 9. The variation of the average energy consumption with the data collector speed.

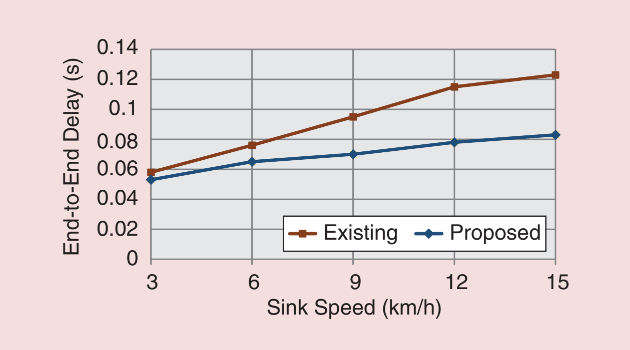

FIGURE 10. The variation of the end-to-end delay with the data collector speed.

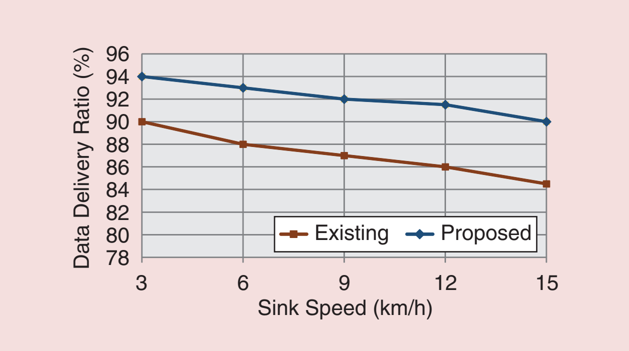

FIGURE 11. The variation of the packet delivery ratio with the data collector speed.

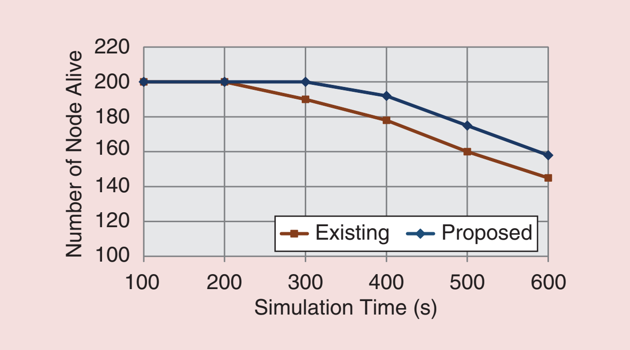

FIGURE 12. The variation of the network lifetime with the simulation time.

battery replacement takes effort. In such a situation, the main challenging issue is the better utilization of the limited energy of the sensor node to prolong the network lifetime. An energy constraint sensor was the major design focus of this article. In the proposed routing, two mobile data collectors were used to collect data from the sensor field, which was divided into two partitions. Mobile data collectors rotated on the predefined elliptical path, and they collected data from individual sensors, sent a beacon message to the neighboring forwarding nodes, collected the sensed data from the forwarding nodes, and delivered the collected data to the base station located at the center of the sensor field. The performance of the proposed routing was superior in terms of average control packet energy consumption, average energy consumption, data delivery latency, and low end-to-end latency. This routing technique solves the energy-hole problem and has great potential for IoT applications.

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