E^2R^2: Energy-Efficient and Reliable Routing for Mobile Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) are resource constrained. Energy is one of the most important resources in such networks. Therefore, optimal use of energy is necessary. In this paper, we present a novel energy-efficient routing protocol for WSNs. The protocol is reliable in terms of data delivery at the base station (BS). We consider mobility in sensor nodes and in the BS. The proposed protocol is hierarchical and cluster based. Each cluster consists of one cluster head (CH) node, two deputy CH nodes, and some ordinary sensor nodes. The reclustering time and energy requirements have been minimized by introducing the concept of CH panel. At the initial stage of the protocol, the BS selects a set of probable CH nodes and forms the CH panel. Considering the reliability aspect of the protocol, it puts best effort to ensure a specified throughput level at the BS. Depending on the topology of the network, the data transmission from the CH node to the BS is carried out either directly or in multihop fashion. Moreover, alternate paths are used for data transmission between a CH node and the BS. Rigorous simulation results depict the energy efficiency, throughput, and prolonged lifetime of the nodes under the influence of the proposed protocol. Future scope of this work is outlined.**

***Index Terms*—Energy efficiency, mobile base station (BS), mobile nodes, reliability, routing protocol, wireless sensor networks (WSNs).**

I. INTRODUCTION

Wireless Sensor Network (WSN) consists of several resource-constrained sensor nodes randomly deployed over a geographic region. These sensor nodes forward sensory data toward a resourceful base station (BS). Depending on the application type, the BS is located either far away from the sensor field or within the sensor field [1]. Such networks have wide range of applications in military and civil domains. Some application areas of WSN are as follows: combat field surveillance, target tracking in battlefields, intrusion detection, postdisaster rescue operations, smart home, monitoring and alarming systems for supermarkets, wildlife monitoring systems, and many safety and security related applications [1]. In the aforementioned applications, the sensor nodes generate sensory data from the environment of interest. The sensed data are finally forwarded toward the BS for further processing and decision making with regard to the control for meeting the objectives of the system in place. Depending on the application type, the sensor nodes and the BS can be static or mobile. In a typical WSN, the sensor nodes are highly resource constrained [1]. The sensor nodes are inexpensive, disposable, and expected to last until their energy drains out. Therefore, energy is a very limited resource for a WSN system, and it needs to be managed in an optimal fashion. Reliable and successful data delivery at the BS is desired. Energy efficiency is an important aspect of any application of WSN. Routing of data in WSN is a critical task, and significant amount of energy can be saved if routing can be carried out tactfully. Routing is an issue linked to the network layer of the protocol stack of WSN [1]. In multihop communication, the major issue may be the selection of the intermediate nodes in the route. The intermediate nodes are to be selected in such a way that the energy requirement is minimized. At the same time, the data are to be delivered at the BS reliably and successfully.

Hierarchical routing is considered to be an energy-efficient and scalable approach. There are several hierarchical routing protocols proposed for WSN [2]–[5]. All these protocols consider a WSN with static sensor nodes. Theses protocols are not suitable to handle mobility of the sensor nodes and the BS. Although dynamic source routing (DSR) [6], ad hoc on-demand distance vector (AODV) routing [7], destination-sequenced distance vector (DSDV) routing [8], temporally ordered routing algorithm (TORA) [9], and zone routing protocol [9] are some routing protocols that exist for mobile ad hoc networks, these are not well suited for WSN setup [10]. This is so, due to different features of WSN and the unique constraints WSN suffers from. Moreover, the WSN applications have different sets of requirements [10]. Routing in a WSN setup in which both the sensor nodes and the BS are mobile is a challenging problem.

Existing routing protocols reported in [11]–[13] do not consider the mobility in sensor nodes and in the BS, and therefore, these are not directly applicable to a mobile WSN. In a mobile WSN, the communication links may come up and fail very dynamically. Therefore, the routing protocol has to take care of the connectivity issue also in such a WSN setup. Data packets are to be routed taking this connectivity issue into consideration. Otherwise, there will be significant loss of data packets due to failed links apart from all other reasons such as frequent death of sensor nodes or noise of the wireless links [1].

In this paper, a novel routing protocol, which is called *Energy-Efficient and Reliable Routing protocol for mobile wireless sensor network (E^2R^2)*, is proposed. The proposed

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protocol is a hierarchical one. Our major goal is to achieve energy efficiency and to provide connectivity to the nodes. The mobility of the nodes is considered while routing decisions are made. The objective behind such routing is that the data packets need to move through suitable routes in spite of node mobility and in presence of subsequent link failures.

The rest of this paper is organized as follows. Section II describes the related work to the problem of energy-efficient and reliable routing in WSN, followed by Section III, in which the system model is described and the problem is formally stated. Section IV describes the proposed protocol in detail. A mathematical analysis with regard to the validity of the routes is presented in Section V. In Section VI, simulation results are reported along with an analysis. Finally, in Section VII, this paper is concluded, stating the future scope of this work.

II. RELATED WORK

In the literature, several energy-aware protocols have been proposed for WSNs [28]–[30]. Again, there are several routing protocols proposed for WSN, in which the main focus is on reliable data delivery [17]. However, they are designed keeping static sensor nodes and static BS in mind.

In the wired networks, the design emphasis has been on maximizing end-to-end throughput and minimizing delay. However, in wireless networks, apart from these two design objectives, there are two more dominating design issues. These are *energy constraints* and *signal interference*, which have attracted most attention from the researchers in the past decade. These have become important issues along with the growing popularity of the wireless consumer devices. Due to the unattended nature of the sensor nodes in the WSN applications, the energy efficiency issue has become extremely important.

Energy efficiency can be improved at various layers of the communication protocol stack of WSN. There are several results reported that focus on hardware-related energy efficiency aspects of wireless communications systems. For example, low-power electronics, power-off modes, and energy-efficient modulations [25] are hardware-based approaches. Significant energy efficiency can be also achieved at the software level. Tactful design of routing mechanisms, which is a network layer issue of the communication protocol stack, may lead to acceptable level of energy saving along with reliable routing service. Network-layer energy efficiency related studies are available in the literature, specifically for static sensor networks. Most of the proposed routing protocols for WSN do not consider mobile sensor nodes and mobile BS [11], [31]. Very limited work for mobile sensor networks is available. When the mobility is introduced in the sensor nodes, the topology becomes very dynamic, and the task of finding out the stable routes (i.e., reliable and long living) under such circumstances becomes challenging. Moreover, it is infeasible for the WSN nodes to cope up with the overhead of maintaining routing tables mainly due to onboard memory constraints. Therefore, different table-driven routing protocols for wireless networks are not directly applicable to WSN. Thus, DSR [6], AODV [7], DSDV [8], and TORA [9] are some representative routing protocols for mobile ad hoc networks, but these are not feasible for mobile WSN.

RAP [15], SPEED [16], and Multi-path and Multi-SPEED routing protocol (MMSPEED) [17] are some routing protocols designed for WSN, which can meet objectives such as timely delivery and/or reliable delivery of data packets. Low-energy adaptive clustering hierarchy (LEACH) [2], threshold-sensitive energy-efficient sensor network (TEEN) [3], adaptive TEEN [4], power-efficient gathering in sensor information systems [5], and hybrid energy-efficient distributed clustering [14] are some examples of energy-efficient and hierarchical routing protocol for WSN. However, all these protocols consider static WSN only. Hierarchical Information gathering protocol with Multiple Associated Leaders within A YArd (HIMALAYA) [18] is a hierarchical energy-efficient routing protocol for WSN, which considers the BS mobility but does not consider node mobility. BeamStar [19], energy-efficient clustering scheme [20], energy-aware routing protocol [21], Self Organizing Network Survivability routing protocol (SONS) [22], Directed Alternative Spanning Tree (DAST) [23], and energy-efficient routing algorithm to prolong lifetime [24] are some recent work reported, in the direction of energy-efficient routing. However, these protocols do not consider the issue of reliability in data delivery. Moreover, these protocols are designed for static WSN. In [33], the authors proposed energy-balanced routing protocol, in which the packets move toward the BS through dense energy area and thus protects the nodes with relatively low residual energy. It uses the concept of potential in physics and constructs a mixed virtual potential field in terms of depth, energy density, and residual energy. The protocol prolongs the lifetime of the network, but it does not consider the issue of reliable data delivery. Moreover, the protocol does not consider mobility of the sensor nodes and the BS. The modified LEACH (M-LEACH) [40] is an extension of the LEACH protocol, which can handle mobility of sensor nodes. However, M-LEACH, again, does not consider mobility in the BS. LEACH is also enhanced in [32] in order to support mobile sensor nodes. In [32], node mobility in the WSN is supported by adding membership declaration to the LEACH [2] protocol. It declares the membership of a cluster as they move and confirms whether sensor nodes are able to communicate with a specific CH node. This version also does not support mobility in the BS.

Thus, none of the existing protocols can achieve all the following goals at the same time:

1) guaranteeing reliability in an energy-efficient manner in presence of node and BS mobility;
2) managing mobility of the nodes and maintaining connectivity through alternate paths;
3) minimizing message overhead and overcoming less reliable wireless links.

Therefore, energy-efficient and reliable routing in mobile WSN environment is still an open issue.

In this paper, our contributions may be summarized as follows.

1) We consider the mobility of the sensor nodes and the BS while routing decisions are made.
2) The notion of deputy cluster head (DCH) is used, which increases the lifetime of the network.

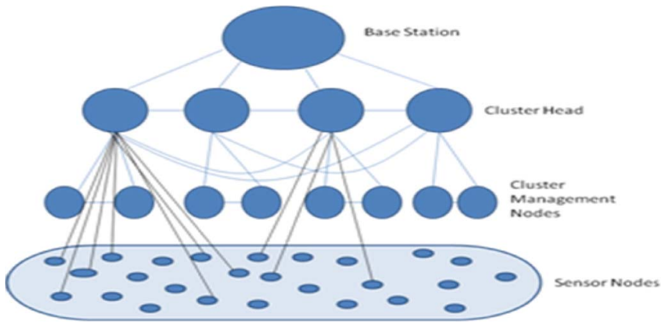

Fig. 1. WSN system architecture.

3) The notion of cluster head (CH) panel is used, which also increases the lifetime of the network.
4) The notion of feedback by the BS regarding data delivery in it is considered.
5) The protocol ensures reliability in terms of data delivery at the BS; this is achieved through the use of multiple routes and switching of the routes as decided by the BS.
6) We adapt a probability-based mathematical model that can be used for identifying the most suitable path for data forwarding.

III. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

In the system under consideration, it is assumed that the sensor nodes are all similar in hardware, software, and capabilities (i.e., computing and sensing). Initially, all the sensor nodes have equal amount of energy. After some time of operation, nodes may be left with unequal energy levels. The sensor nodes and the BS are mobile with medium mobility level. A medium mobility level indicates a speed range of the sensor nodes and the BS, which is neither very high nor very low. At the time of implementation, the range may be specified quantitatively. It is assumed that the sensor nodes know their mobility level. We consider three different mobility levels, i.e., high, medium, and low. The BS is highly reliable and resourceful. After deployment of the sensor nodes in the field, the field is logically partitioned into some clusters. The BS forms these clusters by executing some suitable clustering algorithm [36], [37]. Each cluster contains one CH node and two supporting DCH nodes. DCH nodes are also called *cluster management node*. Communication takes place in hierarchical fashion, e.g., Sensor Node $\rightarrow$ CH $\rightarrow$ BS. Again, communication between a CH node and the BS may take place in multihop fashion depending on the current network topology. Fig. 1 depicts the system architecture and shows the sensor nodes with different roles in the system. The selection of nodes for various roles, e.g., CH or DCH, is carried out at the BS. Each sensor node is assumed to be capable of operating in an *active mode* or in a *dormant mode* (i.e., low power). We assume that there exists some Geographic Position Systems (GPS)-free low-cost solution to know the geographic location of each node by itself [34], [35]. The energy source, i.e., the battery, of the sensor nodes cannot be refueled. In the system under consideration, it has been assumed that there exists only a single BS and that the BS is located away from the sensor field. Although the BS is mobile, it never moves across the sensor field.

B. Problem Statement

The major goal of this work is to design an energy-efficient and reliable routing protocol for a mobile WSN that operates in an unattended manner and, sometimes, in hostile environment. As the sensor nodes are resource constrained (*particularly limited energy and limited onboard storage capacity*), the routing protocol should consume low power and should not burden the nodes with storage overhead.

IV. PROPOSED PROTOCOL

Here, we propose a novel scheme for routing in a mobile WSN in which both the sensor nodes and the BS are mobile. The proposed protocol, which is called E^2R^2, achieves fault tolerance by offering some alternate routes to forward data in presence of any fault in the existing route. The main objective is to extend the lifetime of the sensor nodes in the network. The protocol offers some suitable alternate routes for packet forwarding in presence of node or link failure in the current route. This arrangement does not allow the throughput level at the BS, in terms of packet delivery, to degrade drastically. The protocol takes care of the energy efficiency and the reliability of the routes. The data packets are routed through multiple hops in order to minimize the transmission energy requirements at the sender nodes. In addition, some sensor nodes are intelligently scheduled for *dormant state*, which is a low-power state. Those nodes are scheduled for dormant state, whose services are not required at a particular instant in time. At a later stage, these nodes may perform state transition and again become *active* while needed. The state transition is dictated by the BS. This saves significant amount of energy at the nodes. Thus, the battery lives of the sensor nodes get prolonged.

After the deployment of the sensor nodes, the BS creates groups of different sensor nodes in order to form clusters. Each cluster contains a CH node and two DCH nodes. The BS selects a set of suitable sensor nodes from each cluster, which can act as CH or DCH at a later stage. This set of nodes is also called *CH panel*. The cluster members i.e., the sensor nodes, forward data to the respective CH node. The CH nodes do the data aggregation to remove redundancy and then forward the aggregated data toward the BS. The DCH nodes do several cluster management tasks that include mobility monitoring also. Other cluster management tasks are, for example, collecting location information of cluster members regularly and communicating this location information to the BS. They also remain ready to act as intermediate hop in presence of faults in some CH nodes. Therefore, the DCH nodes are also called cluster management nodes. The CH nodes do not transmit data directly to the BS, unless it is the nearest one to the BS. The communication pattern or the route for the CH nodes is determined by the BS and distributed to the respective CH nodes. Fig. 1 depicts the overall organization of the sensor network system. It is assumed that the BS has an idea about the expected number of data packets (i.e., the volume of data) to be arrived in it during a

Phase I: Self-Organization Phase
Phase II: Scheduling and MAC Information Computing Phase
Phase III: Operational Phase
Phase IV: Exception Handling Phase

Fig. 2. Overall protocol description of E^2R^2.

specified time interval. Therefore, the BS keeps on monitoring the actual volume of data arrived from different clusters in the network. If the BS observes less arrival of data packets from some clusters in comparison with a prespecified threshold level, then it informs the respective CH nodes to check their connectivity with their cluster members. The CH considers this as feedback from the BS and accordingly checks the current connectivity with its cluster members. If the connectivity status of the cluster members with the respective CH is very poor, the BS decides to shift the charge of cluster headship to another suitable member from within the CH panel. Depending on the connectivity scenario, the cluster headship may be transferred to one of the two DCH nodes also. The routing decisions are made at the BS and then communicated to the sensor nodes. Since the sensor nodes are resource constrained and, moreover, the nodes are also committed to data processing and communication apart from sensing activities, it is always advantageous to offload the routing decision making process from the sensor nodes. Therefore, this protocol exploits the resourcefulness of the BS by shifting routing and some cluster management activities to the BS. Fig. 2 describes the overall protocol in terms of its different phases.

A. Self-Organization Phase

After random deployment of the sensor nodes in the sensor field, the self-organization phase starts. It is the first phase of the protocol. During this phase, the clusters are formed. The CH set, the current CH, and the two DCH nodes are selected by the BS. Initially, the BS collects the current location information from each of the sensor nodes and then forms a *sensor field map*. The sensor nodes can discover their geographic location information through some GPS-free solutions [34], [35]. Based on the velocity of a sensor node, the BS can prepare a rough estimate of the zone in which the sensor node is going to be in the *next time interval*. The next time interval is a specific time period for which a particular setup of the network remains valid. The value of the next time interval can be set manually depending on the type of the application, and this value is critical because most of the computations, e.g., cluster setup validity period and *medium access slot*, are dependent on the next time interval. Using this information, the BS can compute the topology of the sensor network. Once the BS creates the sensor field map, it forms the clusters. The cluster formation approach is simple. The basic objective is to maintain geographically uniformly distributed clusters so that the coverage is uniform. It is also desired that the CH nodes are uniformly distributed over the entire sensor field. Therefore, the entire sensor field is geographically uniformly divided into n clusters, where n is approximately 5% of the total number of nodes N deployed in the field. These clusters may be formed by creating uniform logical partitions over the entire sensor field. On the other hand, some existing sensor field clustering algorithms, which are energy efficient, may be used to create the clusters [36], [37]. After formation of the clusters, the BS identifies a set of suitable nodes, i.e., CH panel, from within each cluster. The nodes in the CH panel can take the role of CH node and DCH node. This selection is based on the *cumulative credit point* earned from the three parameters, namely, residual energy level of the node, degree of the node (i.e., the number of neighbors), and mobility level of the node (high, medium, low). At the initial stage of the self-organization phase, each node broadcasts its three attributes, namely, *geographic location information*, *residual energy level*, and *mobility level* or *velocity*. This broadcast is intended for the BS so that the BS can utilize those for cluster formation and CH panel selection. The designer can use a suitable **normalization function** to compute the cumulative credit point earned by a node considering these three nonhomogeneous parameters. An ideal node suitable for CH role should have higher residual energy, higher degree (i.e., more numbers of neighbors), and low mobility. Such a method for calculating cumulative credit point was used in [41] for static WSN in order to select CH and DCH. Then, the BS prepares the CH panel consisting of nodes having a cumulative credit point above a threshold value. Again, this threshold value can be set manually at the time of implementation. Moreover, this value depends on the application of the WSN under consideration. On the other hand, the selection of the normalization function shall also influence the threshold value. Then, the node with highest cumulative credit point is selected as the current CH node. The next two nodes in the list with second and third highest cumulative credit points, respectively, are selected as DCH nodes for the same cluster. This set of nodes with different roles such as CH or DCH is valid for a given round. The duration of a given round is equal to the next time interval that is set initially. Thus, a particular cluster setup is valid for the next time interval. In other words, *cluster setup validity period* is equal to the next time interval. We describe the procedure with regard to computation of cumulative credit point in the following.

A node earns cumulative credit point from three parameters, namely, *residual energy level of the node*, *degree of the node (i.e., the number of neighbors)*, and *mobility level of the node (high, medium, low)*. These three parameters are nonhomogeneous, and therefore, a normalization method is required in order to compute the cumulative credit point. Ideally, a CH node should have higher residual energy, higher degree, and low mobility. In this paper, the following algorithm is used to compute the cumulative credit point of a node. It is important to mention that the algorithm gets executed by the BS for each cluster in the field.

Selection of w_1, w_2, *and* w_3*:* Three different criteria used at the time of selecting the CH and two DCH nodes are residual energy level of the node, number of neighbors, and mobility level of the node. Ideally, a CH node is expected to be equipped with maximum energy level, relative maximum number of neighbors, and minimum mobility level. Thus, one such parameter is not directly linked or correlated with the other parameters. All the three parameters are independent of each other.

Algorithm 1: to compute cumulative credit point of a candidate node

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Input:      d → degree of the node or number of one-hop neighbor,
            e → residual energy level of the node,
            m → mobility level (high/medium/low).
Output:     $C_p$ → cumulative credit point of the node
Variables:  N → the total number of candidate sensor nodes shortlisted by the BS
            $P_d, P_e, P_m$, CCP, $w_1, w_2, w_3$

Step 1: Calculate the percentile score ($P_d$) of a sensor node for degree-
        $P_d$ = {(number of candidate nodes who have lower degree (d) than the degree of the candidate node concerned, inside the cluster)$/N$} × 100
Step 2: Calculate the percentile score ($P_e$) of a sensor node for energy level-
        $P_e$ = {(number of candidate nodes who have less energy level (e) than the energy level of the candidate node concerned, inside the cluster)$/N$} × 100
Step 3: Calculate the percentile score ($P_m$) of a sensor node for mobility-
        $P_m$ = {(number of candidate nodes who have less mobility level than the mobility level (m) of the candidate node concerned, inside the cluster)/N} × 100
Step 4: Compute the cumulative credit point (CCP) for each node inside a cluster as follows:
        $CCP = (w_1)P_d + (w_2)P_e + (w_3)P_m$
        where $w_1$, $w_2$, and $w_3$ are weight factors given to different parameters, for example, degree, residual energy, and mobility, respectively, subjected to the following condition:
        $w_1 + w_2 + w_3 = 1$
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Now, when we talk about the priorities of these parameters, the priorities of the respective parameters actually depend on the characteristics of a specific application of the WSN. For example, according to our design principle, in the case of highly energy constrained network, residual energy level of the node gets the highest priority. Mobility level gets the second level of priority, and number of neighbors gets the third priority level. Mobility level determines the rate of change of topology, and this fact leads to recomputation of routes, hence more energy expenditure. Similarly, higher number of neighbors shows better connectivity in the network, and therefore, it leads to existence of multiple paths in the network. A CH node is expected to have maximum numbers of neighbors. Thus, in order to set weights w_1, w_2, and w_3 when calculating the cumulative credit point, the kind of WSN application, in particular, needs to be considered. These weights indicate the importance of each parameter. The optimization objective, e.g., energy efficiency, of the network may be useful in setting up of the weights.

During our simulation, we set $w_1 = 0.5$, $w_2 = 0.3$, and $w_3 = 0.2$. This is so because energy efficiency is our utmost priority, as explained earlier.

Role of CH Node: The CH node is responsible for gathering sensed data from the cluster members, aggregate those, and forward toward the BS either directly or in a multihop fashion. This part of data forwarding will take place according to the communication pattern or the route distributed by the BS.

Role of DCH Nodes: The DCH nodes keep monitoring the sensor nodes' mobility pattern. DCH nodes are also called cluster management nodes as they take a major responsibility of collecting current location information from the cluster members and communicating it to the BS. Based on this information, the BS computes the actual current topology. The initial state of the topology based on which the BS creates various clusters is an estimation only. Moreover, in the event of the immediate link or node failure in the route of the CH toward the BS, the CH may seek the aid of one of the two DCH nodes to forward the data toward the BS. The reason behind selecting two DCH nodes is the necessity to maintain connectivity inside the clusters. Ideally, the two DCH nodes are located in the opposite sides of each cluster. In such a situation, it is highly probable that the CH is connected to either of the DCH nodes all the time. Moreover, location information collection and dissemination to the BS is an energy-consuming task. In addition, such a task is too heavy for one node. Since this task is jointly carried out by the two DCH nodes, the work load in each of the two DCHs is less. Thus, energy expenditure is reduced by dividing the work load.

CH-BS Network Creation: Since the location information of each of the CH nodes is available with the BS, the BS computes different alternate multihop routes for each of the CH node. These routes are computed considering the CH nodes only, which are spread throughout the sensor network. Considering all the CH nodes in the field, a graph G showing the connectivity among the CH nodes can be constructed. The links in G are created based on the respective radio ranges and the geographic locations of the CH nodes. The BS then computes different spanning tree [10] based routes (from the graph G) for each of the CH nodes to the BS itself. The BS acts as the root of the tree. Thus, the BS computes a separate pool of multihop routes considering each CH. Then, the BS distributes the most energy efficient route for each of the CH nodes. The details regarding the energy efficiency of a route is given in the following.

Correlation Between Number of Cluster and Number of DCH: The number of clusters in the network is generally 5% of the total number of nodes in the network as per [2]. Now, we have decided to have one CH node and two DCH nodes inside each cluster. The reason behind selecting two DCH nodes has already been explained. Thus, if we try to establish a correlation between the number of clusters, for example, n, and the number of deputy heads within the cluster, then it can be done as follows.

Let us consider the number of nodes in the network as N and the number of clusters in the network as n. Then, $n = 5\%$ of N, $= 0.05$ N. The number of DCHs in each cluster is $\mathrm{d} = 2$. Therefore, the total number of DCHs in the network is $D = \mathrm{d} \times n$. Thus

$$D = \mathrm{d} \times (0.05 \times \mathrm{N}) = 0.05 \times \mathrm{d} \times \mathrm{N}. \tag{1.1}$$

Energy Efficiency of a Route: Each route from a CH node to the BS consists of some intermediate nodes and, therefore, some edges, i.e., $E_{u,v}$. $E_{u,v}$ signifies an edge connecting the nodes u and v. Thus, each route is a set of edges. The total energy expenditure involved in a route due to communication is a function of two parameters, and those are as follows:

1) the number of transmissions considering the source node and all intermediate nodes;
2) the number of receptions considering the intermediate nodes and the destination node.

Transmission expenditure for each bit is again dependent on the distance separating the sender–receiver nodes, as discussed in the following section.

The total energy expenditure of a route is the sum of energy expenditures due to different transmissions and receptions across the edges present in the route.

Let us consider there are n edges in a route R. Therefore, the total number of nodes involved in the route is $n+1$. Let u be the source node and z be the destination node in the route. Thus, the route may look like a set of nodes, i.e.,

$$R = \{u, v, w, \ldots, y, z\}. \tag{2.1}$$

Then, the total energy expenditure involved in R can be expressed as the sum of energy expenditures of each edge.

Therefore

$$\begin{aligned}\mathrm{EE}_R &= [E_{Tx}(k, d_{u,v}) + E_{Rx}(k)] + [E_{Tx}(k, d_{v,w}) + E_{Rx}(k)] \\ &\quad + \cdots + [E_{Tx}(k, d_{y,z}) + E_{Rx}(k)] \\ &= [E_{Tx}(k, d_{u,v}) + E_{Tx}(k, d_{v,w}) + \cdots + E_{Tx}(k, d_{y,z})] \\ &\quad + n \times E_{Rx}(k). \end{aligned} \tag{2.2}$$

It is assumed that the sensor nodes are homogenous. Thus, the most energy efficient route can be computed considering all possible routes between a pair of source and destination nodes and then comparing respective total energy expenditures of all the routes.

Transmission Expenditure and Energy Requirement of a Route: Energy expenditure for transmitting and receiving a data packet of size k bit between two nodes being separated by a distance of d unit can be respectively expressed as

$$E_{tx}(k, d) = k(E_{\mathrm{elec}} + \varepsilon_{\mathrm{amp}} \times d^{\gamma}) \tag{3.1}$$

$$E_{Rx}(k) = k \times E_{\mathrm{elec}} \tag{3.2}$$

where $\gamma = [2, \ldots, 4]$ is called path loss exponent; E_{elec} denotes the energy consumption caused by digital coding, modulation, filtering, and spreading of the signal; and $\varepsilon_{\mathrm{amp}}$ is the energy consumed by the transmitter power amplifier.

Let us consider $d_{u,v}$ to be the distance by which the nodes u and v are separated. The total energy expenditure for delivering a packet of size k bit at the node v that originated at u can be expressed as follows:

$$\begin{aligned}\mathrm{EE}_{u,v}(k, d_{u,v}) &= E_{Tx}(k, d_{u,v}) + E_{Rx}(k) \\ &= k\left(2E_{\mathrm{elec}} + \varepsilon_{\mathrm{amp}}[d_{u,v}]^{\gamma}\right). \end{aligned} \tag{3.3}$$

Thus, the physical distance separating two sensor nodes influences the overall energy consumption in transmitting data packets between the two nodes.

The route is also called *communication pattern*, and it is valid only for a specific *time duration* t. After this time duration t, the BS distributes another suitable and energy-efficient route to the CH. This is so because, if all data traffic keeps on traveling through the same route, the intermediate nodes in that route will deplete their energy very fast. Therefore, eventually, it may lead to network partition. The value of t can be determined by considering network-specific parameters such as data rate and energy level of the nodes in a route.

These alternate routes are selected from the pool of multihop routes computed initially. The condition for selecting a multihop route is as follows: a *multihop route* must incur less energy expenditure than a *direct route*. A little explanation on it is as follows.

Let us consider three nodes i, r, and j in a sensor filed. Node i (i is a transmit node) wishes to transmit information to node j (j is a receive node). We consider that the third node r may be used as a relay (or intermediate hop) while transmitting from i to j if necessary, and r is called relay node. The aim is to transmit information from i to j with minimum energy requirement. Now, the question is whether we shall use r or we do transmission directly from i to j. Let us denote the position of j by (x, y). According to our principle, r shall be used as a relay node provided the following condition is true:

$$R_{i \to r} = \left\{(x, y) | E_{i \to r \to (x,y)} < E_{i \to (x,y)}\right\}. \tag{4.1}$$

Here, R indicates need of relay, and E indicates energy requirement. Now, the presented equation can be interpreted as follows: there is a need of relay R via node r, for transmitting data from node i to node j, provided that the energy expenditure incurred for transmitting from i to j through the relay node r is less than that against direct transmission from i to j, where j is located at (x, y).

According to the first-order radio model, which was mentioned in [26], energy requirement is a power of the distance factor between the sender and receiver nodes.

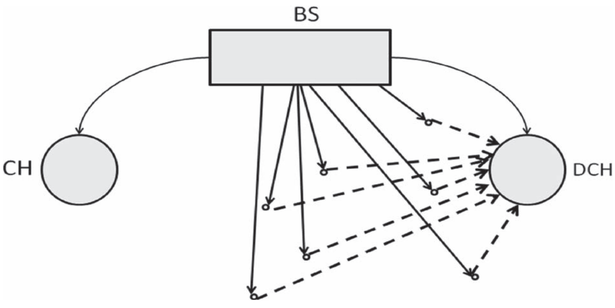

Fig. 3. Cluster headship gets shifted to DCH.

DCH-BS Network Creation: Similar to the CH-BS network creation process, the BS also creates the DCH-BS networks. In this situation, only the DCH nodes in the sensor field are considered. Alternate routes are also created for the DCH and switched intelligently by the BS.

Current Cluster Setup Cycle Length: An important and critical issue is how long a particular cluster setup will remain valid. Depending on the initial energy level of the sensor nodes and the kind of application, the optimal time duration is fixed. This optimal time duration is called as *cycle length*, and the current cluster setup remains valid until the end of the cycle length. However, exception may always occur. For example, due to mobility of the nodes, severe link failures may occur, and nodes may die out due to depletion of energy, which may together cause network partition. In such situations, current cluster validity time, i.e., cycle length, may become outdated, and reclustering may get initiated by the BS before expiry of the cycle length. Ideally, cycle length is the same as the next time interval aforementioned.

Use of the CH Panel: The CH panel is selected initially and remains valid until the end of the cycle length or until the reclustering process is initiated. If the current CH loses connectivity with most of its cluster members due to which throughput at the BS degrades, the CH may be asked to relinquish the charge of cluster headship. Even a CH node may drain out its energy below a threshold level and becomes useless; in this situation also, a new CH is necessary. Under such circumstances, the BS may give the charge of headship either to one of the two DCHs or to a node from within the CH panel. This saves a lot of cost and time involved in the process of selecting CH. An instance of shifting the charge of CH from CH to DCH is shown in Fig. 3. The BS also instructs the sensor nodes to join the DCH as their new CH.

B. Scheduling and MAC Information Computing Phase

The sensor nodes can be in either of the two states *active* and *dormant*. Some sensor nodes are scheduled for dormant state, which is a low-power state. A node in dormant state does neither any sensing task nor any relaying task. This approach is opted based on the observation that if two senor nodes are in close proximity, then there is a very high probability that they sense similar and redundant data from the environment. On the basis of the geographic locations and proximity of the nodes, the BS schedules some nodes into dormant state in such a way that the coverage of the network does not get affected. Again, at a later time, the node does state transition from its dormant state to the active state as signaled by the BS.

The BS distributes a time-division multiple access (TDMA)-based medium access time slot for each of the CH and DCH nodes in order to enable communication with the BS. It has been assumed that different CH nodes use different frequency bands so that they can communicate simultaneously. Again, the CH nodes distribute TDMA-based medium access slot to their cluster members, including the DCH nodes, for the communication with respective CH nodes.

C. Operational Phase

During this phase, actual sensory data transmissions take place. The sensor nodes forward data toward the CH node according to their respective medium access time slots. The CH nodes remove the redundancies in the data sent by the sensor nodes by the process of data aggregation and finally forward the aggregated data toward the BS as per the communication pattern distributed by the BS. DCH nodes do only cluster management tasks such as monitoring the mobility of the nodes and exception handling. Normally, they do not take part in data sensing and data forwarding tasks, but they do data forwarding under exceptional circumstances, which is described in the following. This phase, i.e., operational phase, has the longest time interval in comparison with the other aforementioned phases.

D. Exception Handling Phase

This phase is an occasional one. Due to the node mobility and the sudden death of some sensor nodes, the CH node may lose enough links with its cluster members. This may significantly degrade the throughput level in terms of packet delivery at the BS. Under this situation, the BS may send feedback to the CH, and the CH then checks the current connectivity with its cluster members. If there is significant loss of connectivity with its cluster members, then the CH is asked to relinquish the charge of cluster headship, and a new one is selected either from the CH panel or one from within the two DCH nodes already selected. If a DCH node becomes the CH (as shown in Fig. 3), another node from the CH panel is selected by the BS as the DCH. We consider this as the *first exception condition*. The *second exception condition* may be the link failure between the CH and the DCH. This link is not required all the time. However, if this link is not available at the time of need, either party, i.e., CH or DCH, informs the BS. Then, the BS checks and compares the geographic locations of both CH and DCH. The BS selects a new suitable DCH from within the CH panel if it finds that there is no chance of return of the current DCH node to the proximity of the CH node. The *third exception condition* is as follows: the CH may lose the link with the next hop in its communication pattern toward the BS. This is a critical situation, and the CH becomes unable to transmit data toward the BS. Then, the CH requests the DCH nodes to inform if it has a route available toward the BS. If such a route is available, then data packets follow the route through one of the two DCH nodes toward the BS. This process goes on until the next hop in the communication pattern of the CH becomes available or the BS distributes a new communication pattern to the CH for the next time duration (i.e., t). It is assumed that there is at least one such route always available toward the BS through either of the DCH nodes.

V. ANALYTICAL MODEL TO ANALYZE ROUTE VALIDITY

Here, we present an analytical model that can be adapted to find the probability of a route being valid. Since the nodes are mobile, the links are prone to break abruptly. Therefore, a route that is available and thus valid at the present moment may not be available after some time. The insight regarding route validity presented here may be helpful for the BS to identify the most suitable route from a CH node to the BS. Ideally, a suitable route is one that is energy efficient and remains valid after a time interval.

The link availability addresses the issue of prediction of the status of a link between two mobile nodes after a specific time period based on different network parameters. In [42], the probability of link availability is computed. Based on a random ad hoc mobility model, the authors computed the probability of link availability $A_{m,n}(t)$ between two mobile nodes m and n, after time t, as

$$A_{m,n}t \approx 1 - \varnothing\frac{1}{2}, 2, \frac{-4R_{eq}^2}{\alpha_{m,n}} \tag{5.1}$$

where

$$\alpha_{m,n} = 2t\frac{\sigma_m^2 + \mu_m^2}{\lambda_m}\frac{\sigma_n^2 + \mu_n^2}{\lambda_n}.$$

Here, $\varnothing\ (a, b, z)$ is the Kummer confluent hypergeometric function [42]. Moreover, R_{eq} is the effective communication radius; σ_i^2 and μ_i are the variance and mean speed of node i during each epoch, respectively; and t is the time. Again $1/\lambda_i$ is the mean epoch length for node i. An epoch is the duration while the node is moving during which its speed and direction remain constant.

In [43], the preceding equations for link availability are modified. In that work, it is assumed that all nodes have equal mean speed and variance during each epoch and that the mean epoch length is uniform over the network. Therefore, mean speed, variance, and epoch length are now considered as network parameters instead of node parameters. Based on these assumptions, the preceding equations are written as

$$A_{m,n}t \approx 1 - \varnothing\frac{1}{2}, 2, \frac{-4R_{eq}^2}{\alpha} \tag{6.1}$$

where

$$\alpha = \frac{4t}{\lambda}(\sigma^2 + \mu^2).$$

In [43], the probability of link validity $P_{\text{link-valid}}$ is calculated as

$$P_{\text{link-valid}} = 1 - \varnothing\frac{1}{2}, 2, \frac{-4R_{eq}^2}{\alpha} \tag{7.1}$$

where

$$\alpha = \frac{4t}{\lambda}\sigma^2 + \mu^2.$$

The probability of link validity is defined as the probability of a link that is valid at $t = 0$ will remain valid at $t = T$, where $T > 0$.

Then, the probability of route validity $P_{\text{route-valid}}$ is calculated. This is the probability of a route being valid after time $t = T$ that has been discovered at $t = 0$. The probability of route validity is expressed as

$$P_{\text{route-valid}} = 1\varnothing\frac{1}{2}, 2, {\frac{-4R_{eq}^2}{\alpha}}^{h} \tag{8.1}$$

where h is the number of links in the route. The parameter h acts as a decay factor since the probability of route validity decreases along with the increase in number of hops and, thus, links in the route. Thus, (5.1) can be used for estimating the validity of a discovered route. This model assists in identifying the suitable routes that are energy efficient, valid, and stable in spite of node mobility.

VI. SIMULATION RESULTS AND ANALYSIS

The effectiveness of the proposed routing approach is validated through simulation experiments. Here, we discuss various performance metrics used, simulator architecture, simulation environments, and the experimental results. The results of our approach are also compared with another routing approach, i.e., M-LEACH [40]. We identify M-LEACH as a relevant protocol for performance comparison due to the fact that this protocol can handle mobility of the sensor nodes.

A. Performance Metrics

The following metrics are used to understand the performance of our routing approach and to compare it with M-LEACH.

Average Communication Energy: It is the average of the total energy spent due to communication in the network over a particular time period and with respect to a specific data rate. If E is the total energy spent due to communication and N is the total number of nodes in the system, then E/N (i.e., energy per node) is the average communication energy. A protocol with lower average communication energy is desirable.

Throughput: It is the ratio between the actual numbers of packets transmitted by the nodes in the system to the numbers of successfully delivered packets at the BS. It reflects the percentage of packets lost during transmission. A protocol with higher throughput is desirable.

Lifetime: It is the time taken since the start of the network (*during the simulation*) for the first node to die. A protocol with larger lifetime is desirable.

Node Death Rate: It is a measure with regard to the number of nodes that died over a time period since the start of the simulation.

B. Simulator Architecture

We use simulator software developed by us using C++ language. We are motivated by the work in [27] to develop a simulator of this kind. The entire simulator is consisting of different modules such as Deployment Module, Topology Construction Module, Mobility Management Module, Medium

Access Control Module, Routing Module, Energy Expenditure Computing Module, and Throughput Computing Module. The various sources of energy expenditure at each sensor node are due to computing, sensing, transmitting, receiving, and idle listening. An agent for computing energy expenditure against each of these sources is implemented inside the Energy Expenditure Computing Module in the simulator. Similarly, different error sources such as transmission channel error, collision, buffer overflow, and miscellaneous (for example, link failure) are implemented inside the Throughput Computing Module.

C. Simulation Environment

In our experiment, we consider a sensor network of 50 sensor nodes randomly deployed over a field of dimension 210 × 210 m^2 area. The BS is located in the left side of the sensor field. The radio transmission range of the sensor nodes is 50 m. The sensor nodes move in random direction with a random value of speed in the range of 1–4 m/s. In our simulation, we compute the location of each of the nodes after a regular interval of 120 s. We run the simulation for a period of 1800 s. All nodes are assumed to have equal amount of initial energy. The initial energy in each sensor node is considered to be 10 J.

We use the same communication paradigm as described in [2] with respect to the energy expenditure against transmission and reception of data. It is considered that the sensor nodes use different power levels in order to transmit data packets across different physical distances.

The sensor nodes are considered to be constant bit rate source. In one set of simulation, the nodes generate report only at a single rate such as 1 or 2 report/s. Each report consists of 64 B or 512 b. We assume a packet drop probability in the range of 0.0–0.2 at each intermediate hop. We measure the throughput after every 300 s and finally compute the average throughput after 1800 s of simulation.

Some other parameters values used in the simulation are as follows:

Number of nodes: 50and 100
Number of clusters: 3 and 5 (*5% of number of nodes*)
Threshold energy value for the cluster head nodes: 5 J
Next time interval: 300 seconds
Weight parameters for calculating cumulative credit point:
w_1=0.5, w_2=0.3, and w_3=0.2
(w_1 to residual energy, w_2 to mobility level, w_3 to neighborhood degree)

The mobility of the sensor nodes may be described through a random waypoint mobility model [39]. Each sensor node picks its direction at random from $(0, 2\pi]$ and moves in that direction from its current position to a new position for a distance d with a speed v from within a range, for example, $[s\min, s\max]$, where d is exponentially distributed. If the node hits the boundary, then the node is reflected at the boundary [32].

D. Experimental Result

Here, we present some results obtained through simulation. We also provide an analysis of the results. We compare the performance of the proposed protocol with that of M-LEACH in terms of throughput and lifetime against different data rates. LEACH has been designed keeping static sensor nodes in mind. Therefore, in our simulation, we considered extended version of LEACH, i.e., M-LEACH, which is applicable for mobile sensor networks. We also analyze the performance of the proposed protocol with respect to different data rates.

TABLE I
ROLE SELECTION

Node ID	Role (Cluster Head/Deputy Cluster Head)	Cluster ID	Residual Energy (J)	Mobility (low/medium/high)	Location (210×210 square meter)
5	Cluster Head	C1	9.1	low	(190,160)
7	Deputy Cluster Head	C1	9.0	low	(150,180)
12	Deputy Cluster Head	C1	8.9	low	(180,50)
6	Cluster Head	C2	9.2	low	(140, 110)
41	Deputy Cluster Head	C2	9.0	low	(90,30)
36	Deputy Cluster Head	C2	8.8	low	(40,90)
21	Cluster Head	C3	9.2	low	(41,170)
29	Deputy Cluster Head	C3	8.9	low	(42,190)
36	Deputy Cluster Head	C3	8.8	low	(95,200)

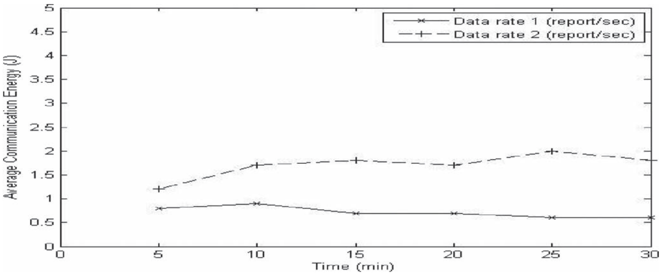

Fig. 4. Average communication energy against time.

The CH and two DCH nodes are selected by the BS based on the parameters such as geographic location information, residual energy level, and mobility level or velocity. Based on Algorithm 1 (*to compute cumulative credit point*), which is given in Section IV, the BS selects the CH and two DCHs for each cluster. In our simulation, for a setup of 50 nodes, the selected nodes as CH and DCHs are as presented in Table I.

Fig. 4 depicts the behavior of the proposed protocol in terms of average communication energy expenditure with respect to data rates of 1 and 2 report/s, respectively, throughout the simulation time. The average communication energy expenditure is higher when data rate is 2 report/s than when it is 1 report/s. It is observed that, while data rate is 2 report/s, the average energy expenditure gradually reduces after 25 min of simulation. It is due to the death of nodes, which actually leads to lesser traffic. Fig. 5 depicts the number of nodes that died after different time intervals over the entire simulation time. While the data rate is more, the node death rate increases. This is so because, along with the increase in data rate, the nodes need to communicate more data packets, which lead to more energy expenditures. In Fig. 6, the proposed protocol outperforms M-LEACH in terms

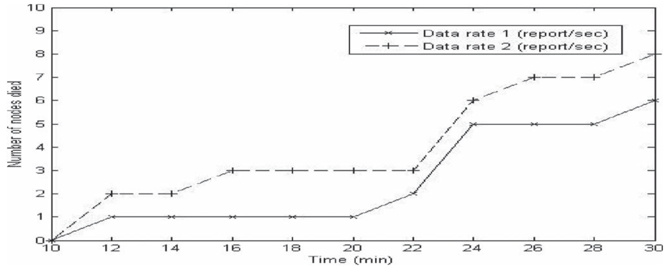

Fig. 5. Node death rate (over simulation time).

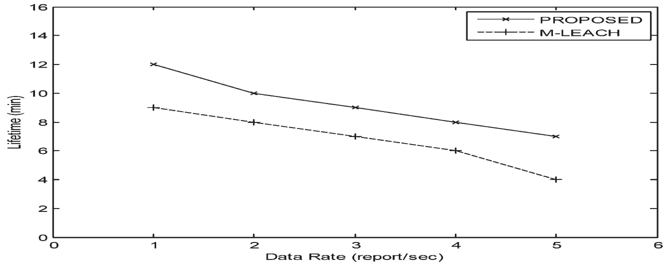

Fig. 6. Comparison of the proposed protocol with M-LEACH (lifetime versus data rate).

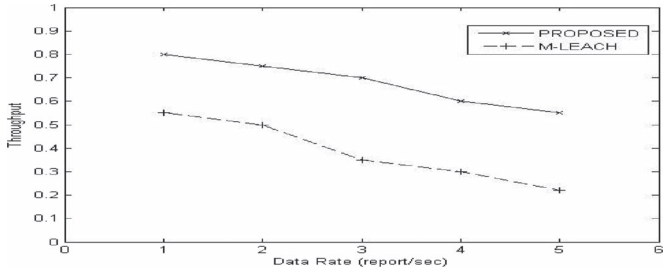

Fig. 7. Comparison of the proposed protocol with M-LEACH (throughput versus data rate).

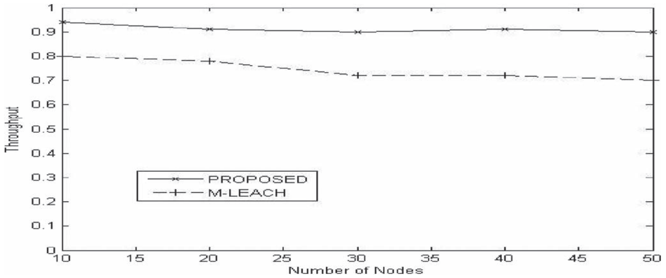

Fig. 8. Throughput analysis I with respect to network size.

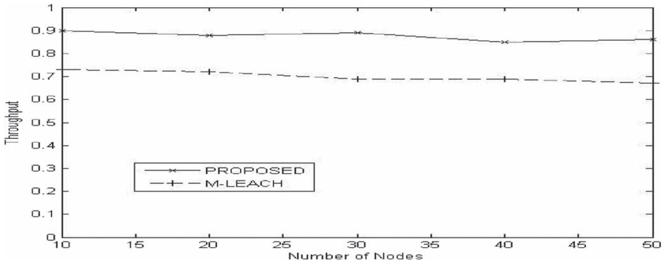

Fig. 9. Throughput analysis II with respect to network size.

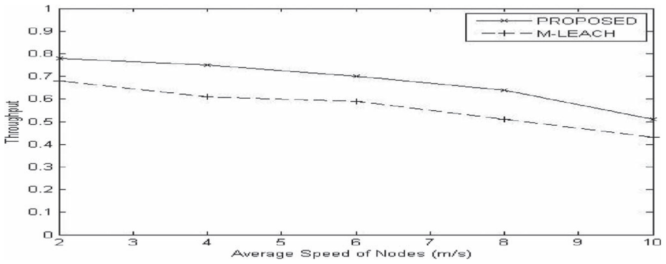

Fig. 10. Throughput versus average speed of nodes.

of lifetime. It is also observed that lifetime decreases along with the increase in the data rate in the case of both the proposed and M-LEACH protocols. The reason is straightforward, and this is because of the fact that, at a higher data rate, the nodes need to handle more data packets. Thus, more energy expenditures incur, and this leads to reduced lifetime.

It has been observed in Fig. 7 that the throughput decreases along with the increase in the data rate for both the proposed and M-LEACH protocols. However, the proposed protocol outperforms the M-LEACH protocol in terms of throughput also. Even for the proposed protocol, the throughput decreases significantly, whereas the data rate is increasing beyond 4 report/s. In fact, 4 report/s is a very high data rate under the current scenario, and therefore, the amount of data traffic is also very high. This leads to higher amount of packet drop in the intermediate hops. In addition, this is mainly due to limited buffer in the nodes. Therefore, the expected level of throughput at the BS is also decided keeping this fact in mind. Moreover, a single link failure in the case of higher data rate causes significant data loss. This is another reason of lesser throughput at higher data rate.

Figs. 8 and 9 depict throughput analysis under the influence of the proposed protocol while the network size in terms of the number of nodes deployed in the field is varied.

For throughput analysis I and II (see Figs. 8 and Fig. 9), the data rate is fixed at 16 B/s, and the network size is increased from 10 to 50 nodes at a step of 10, whereas the other parameters are kept fixed as before (as from Figs. 4–7). Moreover, for throughput analysis I, a random error (for link and node) of 2%–4% and, for throughput analysis II, a random error (for link and node) of 5%–7% are considered. In both analyses, the proposed protocol E^2R^2 improves the throughput level at the BS in comparison with that of M-LEACH. It has been observed that the average improvement in the throughput level of the proposed protocol is approximately 15% over M-LEACH. A graceful degradation in the throughput level is observed for both protocols with an increase in the error level (link and node error). The improvement observed in the throughput level of the proposed protocol is mainly due to the roles played by the DCHs. The mobility of the nodes leads to link failure, but still the system works well under the influence of the proposed protocol for its capability to handle such faults through DCH nodes.

The performance of the proposed protocol in terms of throughput against different mobility levels or speeds of the nodes is compared with that of M-LEACH, as shown in Fig. 10. The proposed protocol outperforms M-LEACH. However, the

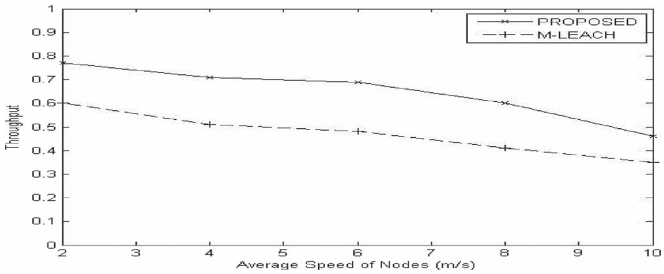

Fig. 11. Throughput versus average speed of nodes while node fault is considered.

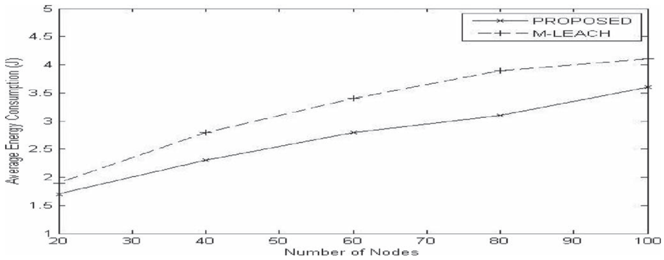

Fig. 12. Average energy consumption versus number of nodes at low mobility level (0–5 m/s).

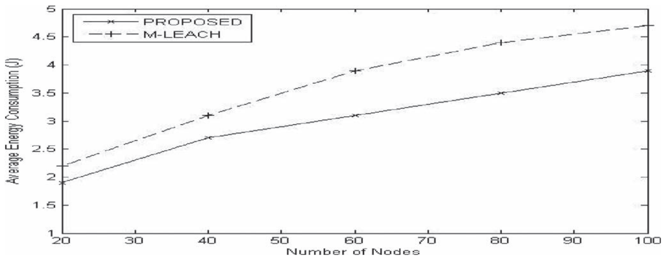

Fig. 13. Average energy consumption versus number of nodes at high mobility level (5–15 m/s).

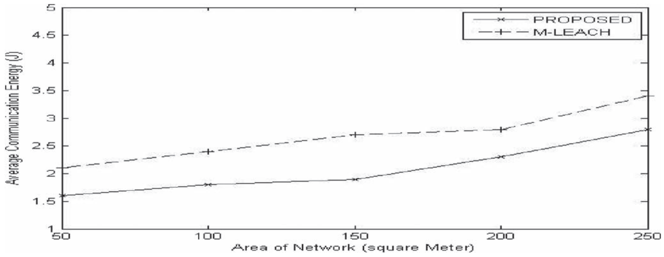

Fig. 14. Average communication energy versus network area.

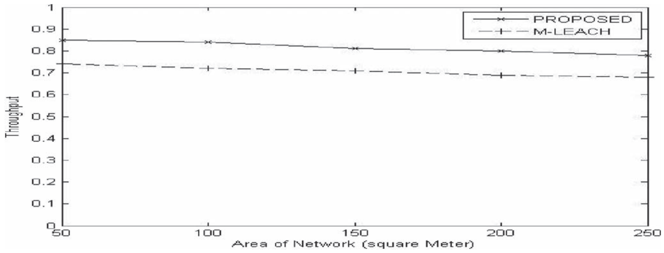

Fig. 15. Throughput versus network area.

throughputs of both protocols degrade along with the increase in speed. This may be due to the fact that more number of link breaks at higher speeds.

Throughput levels of both protocols are compared with respect to varying speed of the nodes and in presence of faulty nodes. The results are shown in Fig. 11. It is considered that 10% of the nodes are faulty. During simulation, the faulty nodes are arbitrarily selected, and under such situation, the throughput is measured. The proposed protocol outperforms M-LEACH. The degradation in the throughput level along with the increase in speed may be due to the increase in number of link breaks at higher speeds.

Average energy consumption is the average of the total energy spent due to communication and computation in the network over a particular time period. If E indicates the total energy expenditure due to communication and computation and N indicates the total number of nodes in the system, then E/N indicates the average energy consumption per node. Thus, the average energy consumption of the proposed protocol is compared with that of M-LEAH, as shown in Fig. 12. Here, we consider low mobility level (0–5 m/s) of the nodes. The proposed protocol outperforms M-LEACH. However, the energy consumption increases along with the increase in number of nodes deployed in the field. This increase in energy consumption is due to the fact that the number of packet exchange increases along with the increase in number of nodes, and this leads to more energy expenditure.

The average energy expenditure of the nodes under the influence of the proposed protocol and M-LEACH, in a high-mobility environment, is analyzed in Fig. 13. The high-mobility environment indicates that the nodes move with a higher speed (5–15 m/s). The proposed protocol outperforms M-LEACH. However, the energy expenditures for both protocols increase along with the increase in number of nodes deployed in the field. This is again due to the increase in the number of packet exchanges along with increased number of nodes. Average communication energy expenditures of the proposed protocol and M-LEACH, for networks of different sizes in terms of geographical area, are compared in Fig. 14. In this setup, we considered a network of 50 nodes. The proposed protocol outperforms M-LEACH. Again, average communication energy increases along with the growth in the area of network. This is because of the fact that long-distance communication incurs more energy expenditure.

Throughput levels of both protocols are compared with respect to varying network sizes in terms of geographic area, and the results are shown in Fig. 15. Here, we considered a network of 50 nodes. The proposed protocol performs better than M-LEACH and produces higher throughput. The throughput levels of both protocols degrade insignificantly along with the growth in the network size. This degradation is due to the fact that the number of intermediate hops increases along with the increase in network area. Thus, packets need to traverse through more number of links toward the sink. This leads to a higher probability of packet loss and that is why the throughput is low for a large network area.

VII. CONCLUSION

In this paper, we have proposed an energy-efficient and reliable routing protocol for mobile WSNs. The proposed protocol E^2R^2 is hierarchical and cluster based. Each cluster contains one CH node, and the CH node is assisted by two DCH nodes, which are also called cluster management nodes. We analyze the performance of the proposed protocol through simulations and compare with M-LEACH. The proposed protocol outperforms M-LEACH in terms of lifetime and throughput. In the proposed protocol, the throughput improvement is 15% *on average* over M-LEACH. Such a routing protocol is useful when the sensor nodes and the BS are mobile. This work can be extended to improve the throughput even in the high-data-rate situation, where the sensor nodes generate data at a very high constant rate. The proposed protocol can be also tested under the influence of highly mobile sensor nodes.

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