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Design of a novel routing architecture for harsh environment monitoring in heterogeneous WSN

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Abstract: Wireless sensor network (WSN) has proved to be a hardcore desideratum for the continuous monitoring of hostile areas suffering from devastating forest fires, sudden volcanic eruptions, floods and many more. It can be contemplated by reviewing the state-of-the-art routing strategies, network instability and the delay incurred in data reception at the user end may lead to deplorable circumstances. In this study, a design of a novel routing architecture is proposed for harsh environment monitoring in heterogeneous WSN. It aims to ameliorate the stability period and network lifetime by shortening the communicative distance of nodes from the gateway node and by mitigating the hot-spot problem in the network. This architecture comprises of a network with multiple gateway nodes (MGNs) (four in this case), placed at equidistant from each other, outside the monitoring area. MGN is enriched with unlimited resources of energy, computation and coverage capabilities. The proposed MGN-based routing architecture (MRA) also improves the cluster head selection by incorporating node density factor along with energy and distance. Simulations show that MRA outperforms the state-of-the-art protocols, i.e. threshold-sensitive energy-efficient delay-aware routing protocol, Stable and Energy Efficient Clustering Protocol (SEECP), and Distance based Residual Energy-Efficient Stable Election Protocol (DRESEP) for two different cases of 'nodes and energy' fractions at various performance metrics.

1 Introduction

A wireless sensor network (WSN) consists of various nodes capable of sensing and communicating the data in any monitoring area [1]. The numerous applications of WSN have brought revolution in almost every field of human civilisation. The primary objective of emerging information technology, i.e. Internet of things (IoT) is to render the energy efficient [2], bit error free [3] and secured routing [4] services by using battery-limited sensor nodes. Even smartphones that are widely used across the globe are equipped with different sensors [5].

The evolution of sensor network has been possible due to the desideratum of the monitoring devices for their applications in the remote areas, where human intervention is not possible [6]. These applications include forest fire detection, earlier detection of a volcanic eruption, landslide detection, flood detection etc. Forest fire detection has great significance among the aforementioned detection and monitoring activities.

Here, are some real statistics related to the forest fire that makes it a paramount concern to be dealt with significant considerations as it is a fatal threat to the world:

a. It is noted that huge areas, i.e. a large number of hectares are destroyed due to forest fires every year. It is reported that around 2000 wildfires occurred in Turkey and more than 100,000 across the globe [7].
b. In the most recent report, one of the most devastating wildfires took place in Oregon's Columbia River Gorge. It devoured the natural resources to a large extent, i.e. flaming almost 2 million acres of land [8].

These wildfires are very frequent all across the world causing heavy devastation [9]. From the above data analysis, it is evident that it does not need any other evidence to prove forest fire to be fatal for human civilisation. Therefore, in order to quickly report about the wildfire, the data from the network must reach to any gateway node that alarms the user as early as possible. It is possible only if the routing among the nodes that are deployed for the same purpose is strategically an appropriate one. Routing in WSN follows the main objective of energy saving for the maximum running duration of the sensor network due to the fact that sensor nodes are wireless and battery of these nodes is irreplaceable [10].

Among three routing techniques, i.e. flat, hierarchical and location-based routing, the hierarchical routing is the most energy balanced and energy efficient [11]. In it, the architecture of sensor network follows single-hop cluster-based routing as shown in Fig. 1. The cluster head (CH) in each cluster collects data from the cluster members and aggregates the collected data from the network. After that data is forwarded to the gateway node that can also be termed as a sink. The selection of CH is a crucial concern in clustering.

Mostly for the selection of CH, energy and distance parameters are used extensively by the researchers. However, the node density factor has been rarely used for the CH selection. The incorporation of this parameter will reduce the communicate distance of CH from the cluster member nodes and will help reducing the energy consumption in intra-cluster communication.

For inter-cluster or from cluster to gateway node communication, clustering can be done in single-hop or multi-hop manner. In case of multi-hop communication, the nodes placed nearby to the gateway node relays the data from the far-placed nodes. It leads to the energy depletion of those relaying nodes to a greater extent, and eventually they consume all their energy leading to the hot-spot around gateway node, and this problem is termed as a hot-spot problem [12, 13], whereas for a large area network, the single-hop communication employed with one gateway node will lead to long-haul data transmissions between the gateway nodes and the far-located nodes [14, 15].

Therefore, to avoid long-haul data transmissions and hot-spot problem, there is a need of placing the multiple gateway nodes (MGNs) outside the network pertaining to the hostile applications. In such scenarios, MGN can collect data from each side of the network through single hop, thereby reducing the delay in data delivery. Consequently, the network scenarios using MGN proves to be a boon for helping with the early detection of catastrophic events such as forest fires.

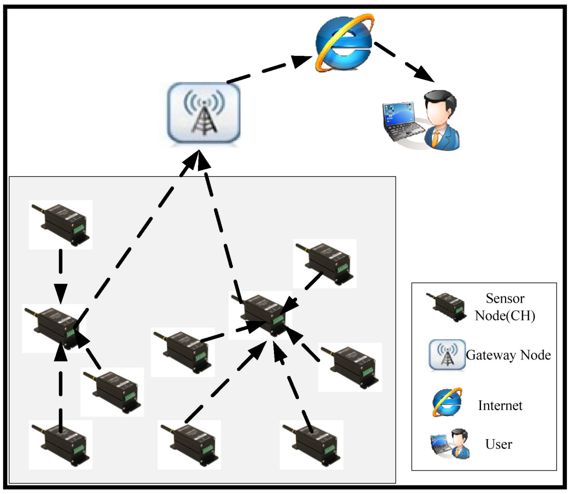

Fig. 1 *Architecture of WSN following cluster-based routing*

1.1 Main contribution

In this paper, we use the cluster-based routing technique in which three levels of energy-heterogeneous nodes are deployed. Our main contribution can be listed as follows:

a. A novel routing architecture MGN-based routing architecture (MRA), for hostile applications (forest fire in particular) is proposed that employs MGN (four gateway nodes in this work) outside of the network, placed at equidistant to each other. It helps in mitigating the hot-spot problem and shortens the delay in data delivery by reducing the communicative distance of each node from the gateway node. The term 'architecture' is used in MRA in place of 'protocol' to emphasise on the proposed architectural design applicable to real-time application scenario for harsh environment monitoring specifically meant for forest fire detection.
b. In MRA, CH selection is improved by incorporating the additional factor, i.e. node density, along with energy and distance. It helps in acquiring energy-efficient routing by shortening the effective distance of CH from the cluster member nodes in the network.
c. The performance evaluation of MRA is done against the state-of-the-art heterogeneous routing protocols with two different cases of nodes and energy fraction at different performance metrics. The reason for comparing an architecture with the existing protocols is the absence of any such architecture in the literature dealing with similar objectives as that of MRA.

The organisation of the rest of this paper is as follows: Section 2 discusses the related work, Section 3 describes MRA and Section 4 presents the simulation results and discussion. Section 5 reports the conclusion and future scope of the work. After that, the references are listed.

2 Related work

The plethora of research has proposed energy-efficient routing techniques for energy preservation of nodes [16, 17]. However, it is the application that matters for which the particular routing protocol is designed [10]. In this paper, the main concern has been to impact with hostile applications that work in extreme environments. Therefore, in this paper, the literature review basically focuses on following aspects; the advancements in heterogeneous protocols meant for above-discussed applications; routing techniques for data dissemination in smart cities; routing techniques using multiple sinks; and finally some forest fire detection techniques.

2.1 Advancements in heterogeneous routing protocols

There have been numerous heterogeneous routing protocols that focus on the enhancement of the stability period and network lifetime [18]. In Table 1, the comparison of some essential heterogeneous routing protocols has been done, focusing on their characteristics and the method for the selection of CH incorporated by them. The discussion about the protocols considered in Table 1 are as follows. Smaragdakis *et al.* [19] proposed the first ever heterogeneous protocol named as stable election protocol (SEP) that utilised the energy heterogeneity at two levels. It incorporated the factor of 'initial energy' of the node for its selection as CH. The protocols, namely design of a distributed energy-efficient clustering (DEEC) algorithm [20], developed DEEC (DDEEC) [22], worked on two levels of energy heterogeneity by utilising the residual energy of a node for CH selection. Energy-efficient heterogeneous clustering (EEHC) [21] and enhanced developed DEEC (EDDEEC) [23] worked for three levels of energy heterogeneity. Balanced energy-efficient network integrated super heterogeneous (BEENISH) protocol [24] worked for four levels of energy heterogeneity for the first time, so as to acquire network stability period. Kashaf *et al.* [25] presented threshold-sensitive SEP (TSEP), the event triggered protocol for a heterogeneous protocol that worked on the basis of some threshold value. However, the CH selection method was energy inefficient. Mittal and Singh in [26] emphasised on the CH selection based on distance and residual energy of the node. The authors improved the CH selection and made it worthy of the reactive applications. Furthermore, Mittal *et al.* [27] extended their work and proposed SEECP that focused on the stability enhancement by changing the criteria for dual hop communication. In SEECP, the authors fixed the number of CHs, and they defined the circular radius by physical geometry. Simulation analysis showed that SEECP outperformed DRESEP [26] and TSEP [25] comprehensively. Mittal *et al.* in [29] optimised the threshold-based threshold-sensitive energy-efficient delay-aware routing protocol (TEDRP) by utilising the Boolean differential evolution-based clustering algorithm for WSNs. The simulation showed that the author's scheme outperformed DRESEP and SEECP protocols. Naranjo *et al.* [28] proposed prolonged stable election protocol in which selection of CH is done randomly, and no preference is given to advanced nodes for CH selection.

Although the proposed approach in this paper aims for enhanced stability period and network longevity but for optimal network performance, quality of service (QoS), quality of experience (QoE), quality of information and fault tolerance can be considered [30–32].

2.2 Routing techniques for data dissemination in smart cities

The visionary aim of routing of WSN is to acquire green networking that fosters the minimum energy consumption of nodes. It is not only the outer residential areas, where WSN has been promising in rendering reliable data dissemination but also within the residential areas or within the city. A city is a smart city when it is acquainted with smart transportation, smart energy, smarty technology, smart infrastructure and smart healthcare system [33]. To avail an energy-efficient data dissemination in the smart city, a network of smart nodes following a strategical routing is required. The vision of a smart city was first presented in [34]. Since then, the role of IoT has been leaving a great impact on acquiring green computing (minimal energy consumption of sensor nodes involved in routing of data) in a smart city. Zanella *et al.* in [35] reported a comprehensive survey for urban IoT with its constituents, namely enabling technologies, protocols and its architecture. Talari presented a review of a smart city that basically focused on IoT concepts [36]. Al-Turjman *et al.* in [37] introduced a delay tolerant framework that works for integrated RSNs (radio-frequency identification sensor networks) in IoT. The proposed framework effectively reduced the delay and packet loss. Al-Turjman in [38] proposed adaptive routing approach decides the routes among the heterogeneous IoT nodes. A pricing mechanism is also introduced to investigate the exchange of monitoring cost by intermediate nodes so as to utilise their relaying resources. Al-

Table 1 Methods of CH selection in heterogeneous WSN

Study reference	Name of Protocols	Heterogeneity level	No. of sink/ gateway node	Reactive/ Proactive	Mode of Communication	Hot-spot Problem	No. of CH fixed	CH selection based on						Research Gap
								Initial Energy	Residual Energy	Total Energy	Average Energy	Distance	Node Density	
Smaragdakis et al. (2004) [19]	SEP	2	1	Pro-active	single hop	No	×	✓	×	×	×	×	×	Not suitable for multi-level
Qing et al. (2006) [20]	DEEC	2	1	Pro-active	single hop	No	×	×	✓	×	✓	×	×	Penalization of high energy nodes
Kumar et al. (2009) [22]	EEHC	3	1	Pro-active	single hop	No	×	×	×	×	×	×	×	Energy of nodes is not considered for CH selection
Elbhiri et al. (2010) [21]	DDEEC	2	1	Pro-active	single hop	No	×	×	✓	×	✓	×	×	Not suitable for multi-level heterogeneity
Javaid et al. (2013) [23]	EDDEEC	3	1	Pro-active	single hop	No	×	×	✓	×	✓	×	×	Not suitable for multi-level heterogeneity
Qureshi et al. (2013) [24]	BEENISH	4	1	reactive	single hop	No	×	×	✓	×	✓	×	×	Penalization of high energy nodes
Kashaf et al. (2012) [25]	TSEP	3	1	reactive	single hop	No	×	×	×	×	×	×	×	Energy factor not included for CH selection
Kumar et al. (2015) [26]	DRESEP	3	1	reactive	dual hop	Yes	×	×	✓	×	×	✓	×	Pre-fixed circular radius in random deployment scenario
Kumar et al. (2016) [27]	SEECP	3	1	reactive	dual hop	Yes	✓	×	✓	×	✓	×	×	In-efficient selection of circular radius for dual hop comm.
Paola et al. (2017) [29]	P-SEP	2	1	Pro-active	single hop	No	×	×	×	×	×	×	×	Selects CH randomly, No preference to advanced node
Kumar et al. (2017) [28]	TEDRP	3	1	reactive	dual hop	Yes	×	×	✓	×	×	×	×	Hot-Spot Problem exists
Proposed work	MRA	3	4	reactive	single hop	No	×	×	✓	×	✓	✓	✓	--

Turjman in [39] proposed cognitive energy-efficient algorithm as routing protocol. It considers the remaining energy of the next node to whom data is to be forwarded with a condition that its (next hop node) energy must be more than half of the energy taken initially. To acquire successful data delivery in cognitive information-centric sensor network (ICSN), two techniques, namely learning data delivery A and cumulative-heuristic accelerated learning were proposed in [32]. Cognitive caching approach for the future fog is proposed that considers the value rendered by the ICSNs [40]. It can be comprehended from the above discussion that the successful data delivery with no delay with adaptive routes is a desideratum for smart city applications.

2.3 Routing techniques using multiple sinks

One of the important concerns is that it is not given any consideration in most of the research work, is the application that does not allow the placement of the sink or gateway node inside the network. This creates the desideratum of a routing protocol in heterogeneous WSN that deals with the sink placement outside the network and also avoiding the hot-spot problem in the network. In the direction of avoiding hot-spot problem, the multiple data sinks were employed in some of the research work done toward lifetime enhancement in WSN [41, 42]. It is further observed that the work done in these papers does not focus on the routing strategies among the nodes rather it generates the optimal way by using which the sink nodes can be placed inside or outside the network. Till now, the research work that employs multiple data sinks in the heterogeneous network has contributed to only two routing schemes [14, 42]. However, these techniques did not focus on the enhancement in-network lifetime besides the placement of sink. As we know, the applications such as forest fire detection cannot afford any procrastination in data delivery [43]; these will be highly benefitted from the multiple sink scenario in the network.

2.4 Forest fire detection techniques

The forest fires have been causing a heavy devastation across the globe over the recent times [7]. Some of the comprehensive reviews focusing on forest fire detection are as follows. Bahrepour *et al.* in [44] surveyed three important aspects that include fire detection for residential areas, forests and the role of WSN in forest fire detection. Shahid *et al.* in [45] discussed the characteristics of outlier detection techniques for WSNs, particular for operation in harsh environments. Alkhatibin [46] reported the summarised discussion of techniques for forest fire detection. Three genres of forest fire detection techniques that employ different systems, namely human-based observation satellite system, optical cameras and WSNs were discussed comprehensively. The tabular analysis of different techniques used for forest fire detection [7, 47–50] is given in Table 2. The methods along with key findings and research gap are discussed for each technique. It is discerned from the techniques discussed in Table 2 that CH selection is not being given much importance and in many of techniques multi-hop routing is taken into consideration that eventually leads to energy-hole problem [47, 49, 50]. So, after contemplating the above-discussed research work, it becomes evident that there is a desideratum of some energy-efficient routing techniques that work for heterogeneous WSN for forest fire detection or any other early detection for the natural calamities.

3 MGN-based RA

It is comprehended from the literature that most of the heterogeneous routing protocols are missing out the node density factor for CH selection. For large area network applications, the techniques have incorporated multi-hop communication that led to the repercussion of hot-spot problem. Furthermore, it is contemplated that the reactive protocol TEDRP [29] has performed magnificently for the reactive applications. However, the protocol has not utilised node density factor for the CH selection.

Therefore, to impact with the aforementioned problems, MRA is proposed. In MRA, the CH selection is incorporated with node density factor along with energy and distance factors. Furthermore, the network of MRA is acquainted with MGNs which are placed outside the network at equidistant from each other. The communication is made single hop so as to mitigate the hot-spot problem. The network assumptions, radio energy model and working process of MRA are discussed as follows.

3.1 Network assumptions

To operate MRA, few network assumptions are adopted which are discussed below:

a. The routing architecture is proposed for monitoring of the extreme environment, so the proposed work, i.e. MRA has framed for hostile applications mainly forest fire detection. MRA deals with the routing involved in the considered region; however, the other radio interferences or any physical obstruction are not taken into consideration.
b. The deployment of heterogeneous sensor nodes (three-level energy heterogeneous) is done randomly in a monitoring area which is assumed to be rectangular shaped with dimensions $100\ \mathrm{m}^2$. The gateway nodes which act as a sink are deployed around each periphery of the network at around 10 m away from the monitoring region just to compensate any hostile circumstances. These gateway nodes are assumed to have no constraints on their energy resources. Furthermore, these gateway nodes are synchronised with each other, so that the alarming message can be sent to the concerned user in case of any inevitable single gateway node failure.
c. Among heterogeneous nodes, super nodes have the largest energy, advanced nodes have lesser energy than super nodes, and normal nodes have the least energy. These nodes cannot be recharged pertaining to their deployment in the extreme regions for monitoring of the extreme environment. Therefore, an energy saving of these nodes becomes a concerned issue.
d. Once the deployment is done, the MGN placed outside the network broadcasts *HELLO* message which is then acknowledged by all nodes by *HELLO_id* message according to the received signal strength indicator (RSSI) value. This acknowledged message comprises the unique id and the status of energy. Then, that message is broadcasted throughout the network by corresponding gateway node, so that every node is made aware of the status, i.e. ids and energy information of neighbouring nodes.
e. The sensor nodes used have the capability of fusing the data packets that are received from the other nodes and can generate one single packet for further processing.
f. The energy consumption of every node follows the fundamental radio energy model that decides the amount of energy consumed for data transmission, reception and aggregation. The radio energy model is discussed in the following section.
g. The proposed work is directed to enhance the network performance by enhancing the stability period, network lifetime and remaining energy. However, the QoS, QoE and fault tolerance are not taken into consideration in this work. Furthermore, it is to be noted that the security aspect of the proposed architecture is beyond the scope of this paper.

3.2 Radio energy model

MRA utilises radio energy model for computations of energy consumed while transmission and reception of data packets as followed in various hierarchical routing protocols [52]. The radio energy model used for MRA is discussed below.

To transmit data packets in any network, the fundamental equations for determining the energy consumption is given by (1)–(4). The energy consumption while transmission of g bit message at a distance d is given by the following equation:

$$E_{\mathrm{tx}}(g, d) = g \times E_{\mathrm{tx}} + g \times E_{\mathrm{efs}} \times d^2 \quad \text{for } d \le d_{\mathrm{o}} \tag{1}$$

$$E_{tx}(g, d) = g \times E_{tx} + g \times E_{amp} \times d^4 \quad \text{for } d > d_o \tag{2}$$

Here, E_{efs} and E_{amp} represent the parameters for energy consumed in transmission amplification in free space and in multi-path transmission, d_o is the threshold distance that decides for the extent of energy consumption while data transmission.

On receiving the g bit data, the energy consumed by a node is given by the equation below:

$$E_{rx}(g) = g \times E_{elec} \tag{3}$$

The process of data aggregation also consumes energy, (4) calculates the energy consumed during data aggregation of g bit data

$$E_{dx}(g) = g \times E_{da} \tag{4}$$

Here, E_{da} is the per bit energy consumed in the process of data aggregation of 1 bit data and E_{dx} represents the energy expenditure during data aggregation of g bit data.

MRA is based on clustering, and it follows the same steps of working as followed by the existing heterogeneous routing protocols.

Table 2 Methods of forest fire detection in heterogeneous WSN

Study reference	Name of technique	Method used	Key findings	Research gap
Yu *et al.* [47]	neural network method	• cluster header collects data from the nodes, forwards to sink and then it is sent to the manager node • neural network is applied for in-network processing method is used for data processing among nodes	• average communication load is reduced on nodes with the proposed method • threshold factor is varied for inspecting behaviour of communication load at different values of the threshold	• selection of CH is inefficient as it only considers and energy and node density factor • approach is not suitable for large area network as the hot-spot problem will counter the network performance
Zhang *et al.* [48]	Zigbee-based WSN	• employed Zigbee-based WSN • CC2430 chip is used to design the hardware circuitry	• information regarding temperature and humidity can be collected from any part of the network at any given time	• concern of energy consumption, the location of nodes and requirement of synchronisation questions the reliability of the proposed system
Hefeeda and Bagheri [49]	distributed randomised k-coverage algorithm	• it employs fire weather index (FWI) to model the fire detection system by investigating its (FWI) different parameters • K-coverage ($k \geq 1$) problem is used to model fire detection problem proposed distributed algorithm to relieve the network from desideratum of global positioning system enabled nodes	• activate near-optimal number of sensors • proposed algorithm converges faster than other algorithms, network longevity, unequal monitoring is achieved • error estimation is minimised that estimates the spread direction of forest fire	• selection of CH is done only on the basis of remaining energy which can be improved further • multi-hop communication may lead to energy-hole problem
Aslan *et al.* [7]	general forest fire detection framework	• develops its own custom simulator using C# and Microsoft Visual Studio 2008 development environment • proposed technique works for developing an approach for strategical deployment of sensor nodes, proposes an architecture for forest fire detection and design an intra-cluster and intra-cluster communication protocol	• focuses on efficient energy consumption along with the earliest detection of a forest fire • simulation results show the tremendous improvement in saving time for data delivery and reducing the energy consumption of nodes in the network	• remaining energy is considered for CH selection but the distance and node density factors are not taken into consideration • regular or deterministic deployment adds complexity to the network
Koga *et al.* [50]	improved maximise unsafe path routing protocol (MUP)	• priority fire detection data is selected and thereafter parent election is done for a node to whom data is to be forwarded • after collecting priority data, it is sorted in buffer with respect to its priority	• improves MUP by decreasing the dropped rate and end-to-end delay of high priority data	• multi-hop transmission among nodes will exert burden on relaying nodes that eventually lead to an energy-hole problem
Jan *et al.* [51]	sybil detection method	• RSSI-based and residual energy-based sybil attack detection techniques are used • main focus is to avoid the participation of sybil identities for CH selection • false negative alerts are avoided	• high stability period and network lifetime are achieved by the proposed technique as compared with LEACH[a], SEP and PASCCC[b]. • fake alerts were masked so as to reduce data delivery of genuine alerts	• there is computational complexity in CH selection. Overheads are too many that lead to energy consumption. On demand, query is a crucial concern which is not incorporated in proposed work

[a] Low Energy Adaptive Clustering Hierarchy

[b] Priority-based Application-Specific Congestion Control Clustering

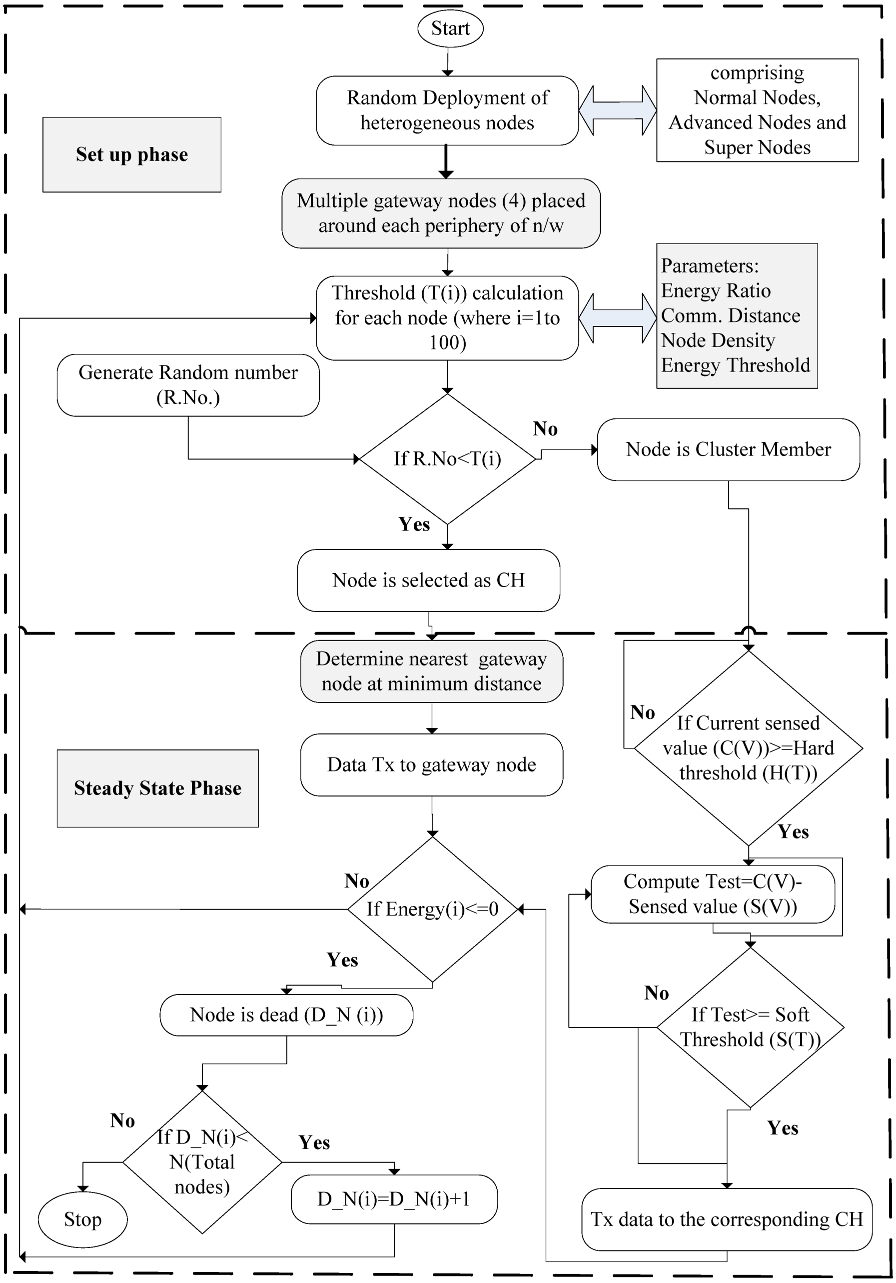

Fig. 2 *Flowchart of the working process of MRA*

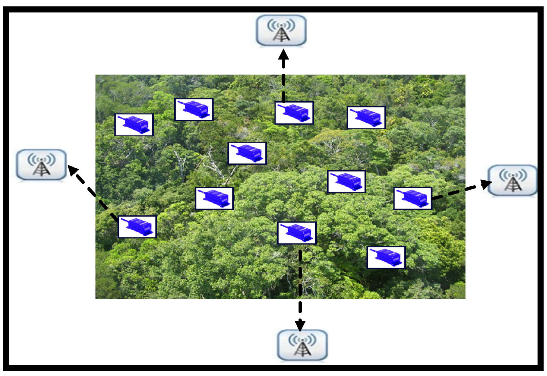

Fig. 3 *Demonstration of network scenario of MRA*

3.3 Working process of MRA

The working process of MRA is categorised into two phases; set-up phase and steady-state phase that are explained as follows and is demonstrated in the flowchart in Fig. 2.

3.3.1 Set-up phase: The set-up phase includes the network model and CH selection. The working operation of MRA starts by framing the network model which is discussed as follows.

Network model: In this work, the heterogeneous nodes are randomly deployed inside the network and MGN strategic placement (equidistant from each other) is done outside the network as shown in Fig. 3. The nodes used are of three levels of heterogeneity, i.e. normal nodes, advanced nodes, and super nodes. Super nodes have maximum energy out of three, normal nodes have the least energy for their operation and the energy of advanced nodes lies in between normal and super nodes.

After network formation, the process of clustering is done by following the distributed approach of CH selection. In Fig. 3, the demonstration of nodes deployment and MGN placement is shown; the nodes connected to the gateway nodes are CH nodes which are responsible for data forwarding. The clustering process demonstration is shown further in the Section 4.

The number of normal, advanced and super nodes is determined by (5)–(7). In these equations, N_{SUP}, N_{ADV} and N_{NRM} represent the number of super nodes, advanced nodes and normal nodes, respectively [26]

$$N_{\mathrm{SUP}} = n \times m \tag{5}$$

$$N_{\mathrm{ADV}} = n \times b \tag{6}$$

$$N_{\mathrm{NRM}} = n \times (1 - m - b) \tag{7}$$

The parameters n, m and b represent the total number of nodes, fractions of a number of super nodes and a fraction of the number of advanced nodes, respectively. The super nodes and advanced nodes are α times and β times higher in energy as compared with the normal nodes, respectively. The energy computations for each type of nodes are given in the following equations [26]:

$$E_{\mathrm{SUP}} = E_{\mathrm{O}} \times (1 + \alpha) \times n \times m \tag{8}$$

$$E_{\mathrm{ADV}} = E_{\mathrm{O}} \times (1 + \beta) \times n \times b \tag{9}$$

$$E_{\mathrm{NRM}} = E_{\mathrm{O}} \times (1 - m - b) \times n \tag{10}$$

In the above equations, E_{SUP}, E_{ADV} and E_{NRM} represent the total energy of super nodes, advanced nodes and normal nodes, respectively. The initial energy of a normal node is given by E_{O}. The total energy of the network is given by E_{TOTAL} and is computed by the equations below [26]:

$$\begin{aligned} E_{\mathrm{TOTAL}} = E_{\mathrm{O}} \times (1 + \alpha) \times n \times m + \ E_{\mathrm{O}} \times (1 + \beta) \times n \\ + E_{\mathrm{O}} \times (1 - m - b) \times n \times m \end{aligned} \tag{11}$$

$$E_{\mathrm{TOTAL}} = n \times E_{\mathrm{O}} \times (1 + \beta \times b + m \times \alpha) \tag{12}$$

After the network is established, the clustering is done among the nodes and selection of CH is done. Thereafter, the information about the selected CH is declared to the nodes and on the basis of the RSSI. Then, the nodes join the respective CH and are termed as cluster member nodes. CH collects data from the cluster member nodes, and after performing data aggregation, it transmits data to the nearest gateway node in a single-hop communication. The selection of CH is done by the following method.

CH selection: The CH selection is done by following the same steps as in SEP [19]. First, the probability of a node to become CH is computed. Afterwards, the threshold value is computed for each node which is eligible for becoming CH. The probability of a node for becoming CH depends on various parameters which are stated as follows:

a. The ratio of residual energy of a node to the average energy of the network.
b. The communicative distance of a node from the gateway node.
c. Node density factor to favour the CH selection in a node dense area.
d. Energy threshold to avoid penalisation of high-energy nodes to become CH frequently (see (13))

$$P(i) = \begin{cases} \dfrac{P_{\mathrm{opt}} \times E_{\mathrm{r}} \times N_{\mathrm{D}}}{((1 + m \times \alpha + \beta \times b) \times C_{\mathrm{dis}} \times E_{\mathrm{avg}})} & \text{for normal nodes if } E_{\mathrm{r}} \geq E_{\mathrm{TH}} \\ \dfrac{P_{\mathrm{opt}} \times E_{\mathrm{r}} \times (1 + a) \times N_{\mathrm{D}}}{((1 + m \times \alpha + \beta \times b) \times C_{\mathrm{dis}} \times E_{\mathrm{avg}})} & \text{for advanced nodes if } E_{\mathrm{r}} \geq E_{\mathrm{TH}} \\ \dfrac{P_{\mathrm{opt}} \times E_{\mathrm{r}} \times (1 + \beta) \times N_{\mathrm{D}}}{((1 + m \times \alpha + \beta \times b) \times C_{\mathrm{dis}} \times E_{\mathrm{avg}})} & \text{for super nodes if } E_{\mathrm{r}} \geq E_{\mathrm{TH}} \\ k \times \dfrac{P_{\mathrm{opt}} \times E_{\mathrm{r}} \times (1 + \beta) \times N_{\mathrm{D}}}{((1 + m \times \alpha + \beta \times b) \times C_{\mathrm{dis}} \times E_{\mathrm{avg}})} & \text{for all nodes if } E_{\mathrm{r}} < E_{\mathrm{TH}} \end{cases} \tag{13}$$

In the above equation, the symbols used are defined as follows. P_{opt} is the optimum probability of the number of CHs, E_{r} is the residual energy of the node and E_{avg} is the average energy of all nodes. The communicative distance of the current node from the gateway node is given by C_{dis}. The energy fractions of advanced nodes and intermediate nodes are given by α and β, respectively. The symbols m and b represent fractions of the number of advanced nodes and number of super nodes. The threshold energy value for nodes is represented by E_{THS} and optimal constant value is denoted by k. The value of C_{dis} for each node is computed by using the Euclidean distance formula as given in the equation below:

$$C_{\mathrm{dis}}(i) = \sqrt{(\mathrm{node}(i).x - \mathrm{GN}.x)^2 + (\mathrm{node}(i).y - \mathrm{GN}.y)^2} \tag{14}$$

The notations $\mathrm{node}(i).x$ and $\mathrm{node}(i).y$ represent the x and y coordinates of the node, respectively. $\mathrm{GN}.x$ and $\mathrm{GN}.y$ represent the x and y coordinates of the gateway node, respectively. The average energy, i.e. E_{avg} is computed by (15), where E_{TOTAL} is the total energy of the whole network and n is the total number of nodes in the network

$$E_{\mathrm{avg}} = \frac{1}{n} \times (E_{\mathrm{TOTAL}}) \tag{15}$$

The node density factor, i.e. N_{D} is computed in the following way. First of all, the average distance of each node in a cluster from the other cluster nodes is computed and is denoted by A_C_{DIS}. Thereafter, the A_C_{DIS} is fractionalised by dividing the value by 100. Then, it is subtracted from 1 to give the preference to high dense nodes (i.e. of least distance) to become CH. By considering the above-discussed steps N_{D} is computed as follows:

$$N_{\mathrm{D}} = 1 - \frac{(A\_C_{\mathrm{DIS}})}{100} \tag{16}$$

The probability value $P(i)$ computed in (13) is used further to compute the threshold $T(i)$ for each type of node [19]

$$T(S(i)) = \begin{cases} \dfrac{P(i)}{(1 - P(i)(r \bmod (1/P(i))))} & \text{if } S(\mathrm{i}) \in G \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

In (17), $S(i)$ is the current node under threshold computation, and the threshold value is given in the equation only if it belongs to the group G, i.e. group of nodes which are yet to become CH. However, $T(S(i)) = 0$ for the nodes which no longer belong to the group G. After threshold computation in (17), the calculated threshold value is compared with the randomly generated number that lies between 0 and 1. In case of any node, if the random number is less than the threshold value, then that node is selected as CH; otherwise, it stays as cluster member node. Subsequently, data transmission starts in the steady-state phase.

3.3.2 Steady state phase: This phase deals with the inter-cluster and intra-cluster communication. In intra-cluster communication, the cluster nodes send data to the selected CH, where data is aggregated and forwarded to the nearest gateway node. The data transmission inside the cluster occurs according to the Time Division Multiple Access scheduling [53], which provides an individual time slot to each node in the cluster. It is to be noted that MRA is reactive, i.e. it activates its functioning in achieving a hard threshold [$H(t)$] as shown in Fig. 2. If that hard threshold for a particular parameter, for example, temperature is achieved, i.e.

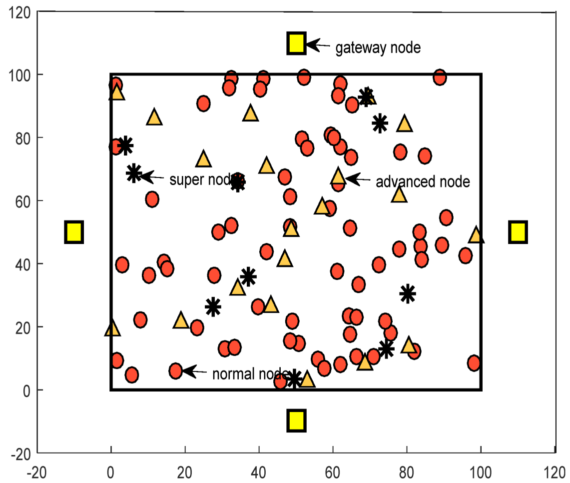

Fig. 4 *Network scenario of MRA*

when sensed value $C(V) >= H(t)$, then the data packet is transmitted from the cluster member nodes to the CH.

The proposed probability $P(i)$ (where $i = 1$ to 100) of each node is computed as follows.

After that, the very next round transmission depends on the soft threshold $S(t)$, for that, a test value (T) is computed, if it is greater than the soft threshold [$S(t)$], then only data packet is transmitted to the gateway node; otherwise, it waits till [$S(t)$] is achieved. The energy consumption for the data transmission takes place according to the radio energy consumption model discussed in the above section. The energy of each node is checked, if it becomes zero, the node is said to be dead node denoted as D_N and D_N is incremented and checked if it is equal to the total number of nodes denoted by N. When D_N becomes equal to the N, the whole network is said to be dead, and it stops functioning else it is incremented by 1.

However, if the energy of a node is not equal to zero, it is considered for operation for the next round, and the same process is followed for all nodes.

It is evident that due to the employment of MGN, the CH forwards the data to the nearest gateway node in a single hop, so there is no inter-cluster communication involved. It benefits the network at a great level as it avoids the hot-spot problem that could lead to the heavy energy drainage of relaying nodes.

4 Results and discussion

In this section, the simulation analysis of MRA is discussed on the benchmark of different performance metrics. The simulation settings for MRA are discussed as follows.

4.1 Simulation settings

MRA is simulated in MATLAB Software version 2016. The simulation is performed for ten times under some simulation parameters which are given in Table 3. The best acquired results are reported from the repeated simulations. The rectangular shaped monitoring area of 100 m × 100 m is considered and three-level energy-heterogeneous nodes are deployed. MGN (four in numbers) are placed around the periphery at the equidistant from each other. MGNs are placed at coordinates (50,110), (110, 50), (50, −10) and (−10, 50) in a network of (100 × 100) m^2 as shown in Fig. 4. The radio parameters values used for the simulation are given in Table 3.

Moreover, the placement of MGN is made at 10 m distance across each periphery due to its applicability in extreme environments. The total nodes are 100 in numbers that comprise of normal nodes (least in energy, i.e. 1 J), advanced nodes (with energy two-fold to that of normal nodes) and super nodes with the highest energy among three (with energy three-fold to that of normal nodes). To have a better insight into the performance validation of the proposed protocol, two cases, i.e. Case A and Case B of different fractional values for a number of advanced and super nodes and the fractions of their energy are taken into consideration. In Case A, the value for a number of nodes' fractions for advanced and super nodes are given as $m = 0.2$ and $b = 0.1$, respectively, and the energy fractions for advanced nodes and super nodes are given as $\alpha = 1$ and $\beta = 2$, respectively. In Case B, the value of nodes' fractions for advanced and super nodes are given as $m = 0.3$ and $b = 0.2$, respectively, and the energy fractions of advanced and super nodes are given by $\alpha = 0.5$ and $\beta = 1$, respectively.

Table 3 Simulation parameters

Parameter	Value
network coverage	(100, 100)m^2
placement of MGN	(50, 110), (50, −10), (−10, 50), (110, 50)
total nodes	100
initial energy (quantity)	1 J
E_{elc}	50 nJ/bit
E_{efs}	10 pJ/bit/m^2
E_{mp}	0.0013 pJ/bit/m^4
d_0	87 m
E_{da}	5 nJ/bit/signal

It is to be noted that the total energy of the network considered for Case A is 140 J, whereas the total network energy for Case B is only 67.5 J. The simulation parameters along with fractional values remain same as that of TEDRP in case of Case A. However, Case B is made to operate under the condition of reduced network energy by incorporating low-energy nodes. Basically, it is done so to compensate the expenses occurred by employing multiple data sinks around the network.

4.2 Simulation analysis

MRA is evaluated for its performance under following performance metrics against the existing reactive routing protocols.

First node dead (FND) or stability period: It is defined as the number of rounds completed until any first node, out of all nodes is drained out of its energy. It is the most important benchmark that decides the reliability of the network.

As the proposed work is done for the extreme environments, so the complete information transmission becomes a crucial concern. FND is also termed as the stability period as after the death of the first node; the network no longer remains stable. The loss of data packets gradually enhances with the increase in the number of dead nodes. Therefore, simulation analysis of MRA is done for inspection of stability period.

For Case A, FND for MRA is achieved after covering 6675 rounds, whereas in case of TEDRP, SEECP and DRESEP it is 5063, 4620 and 4534 rounds, respectively, as shown in Fig. 5. The alive nodes versus rounds graph is shown in Fig. 6 which shows the more number of alive nodes remaining over the passage of rounds.

For Case B, FND for MRA is achieved after covering 4099 rounds, whereas in case of TEDRP, SEECP and DRESEP it is 2523, 2302 and 2133 rounds, respectively, as shown in Fig. 7. The alive nodes versus rounds graph is shown in Fig. 8 which shows the number of alive nodes remaining over the passage of rounds.

Such enhancement is due to the reduced communicative distance of nodes from the gateway nodes. Moreover, the CH selection is also being improved by introducing the node density factor. While doing so, the energy of the network is preserved and the stability period is enhanced tremendously.

Half node dead (HND): When half of the network is dead due to the energy depletion of 50% nodes in the network, it is said to be HND. It signifies the network efficiency as more number of rounds are covered before 50% nodes are dead in the network.

For Case A, the HND in MRA is achieved at 12,354 rounds, whereas in case of TEDRP, SEECP and DRESEP it is 8503, 4620 and 9873 rounds, respectively, as shown in Fig. 7. The graph of dead nodes versus rounds is also shown in Fig. 8 that shows the

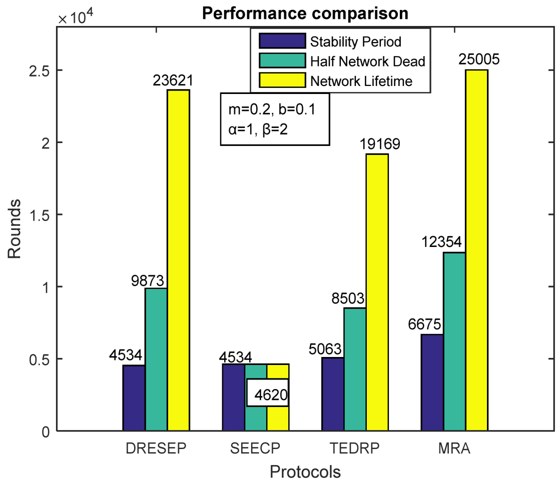

Fig. 5 *Performance validation of MRA against the other protocols for Case A*

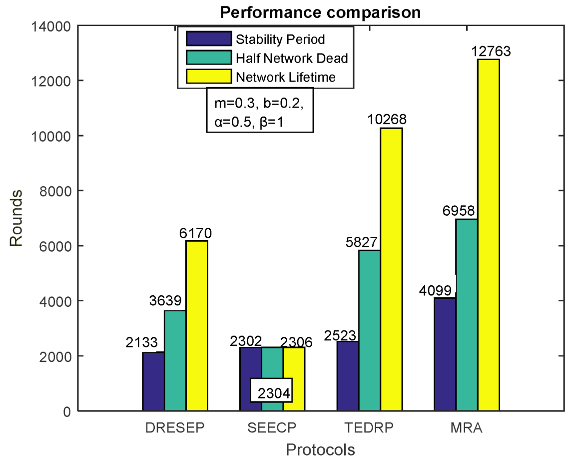

Fig. 7 *Performance validation of MRA against the other protocols for Case B*

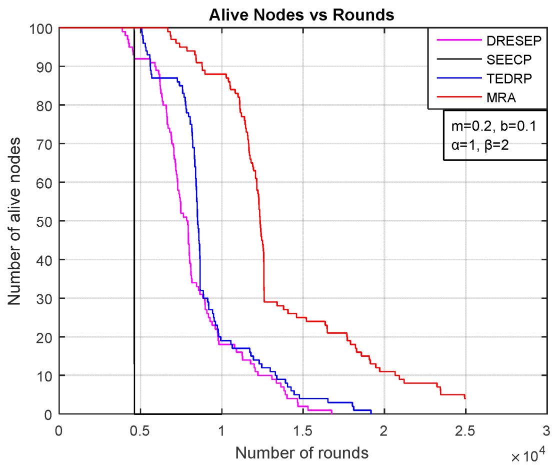

Fig. 6 *Alive nodes versus rounds comparison of MRA against other protocols for Case A*

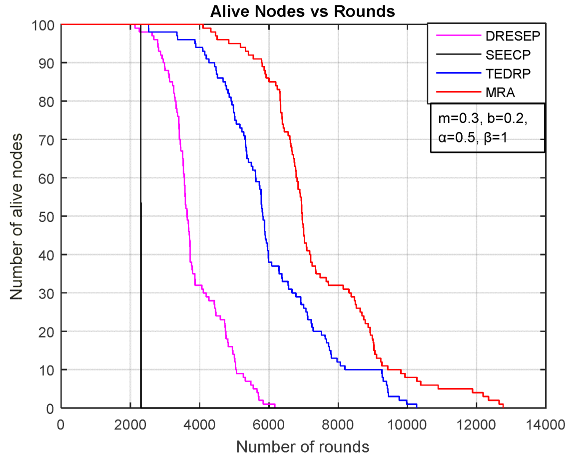

Fig. 8 *Alive nodes versus rounds comparison of MRA against other protocols for Case B*

coverage of more number of rounds by the MRA as compared with other protocols, before any number of nodes are dead.

For Case B, the HND in MRA is achieved at 6958 rounds, whereas in case of TEDRP, SEECP and DRESEP it is 5827, 2304 and 3639 rounds, respectively, as shown in Fig. 7. The graph of dead nodes versus rounds is also shown in Fig. 8 that shows the coverage of more number of rounds by the MRA as compared with other protocols, before any number of nodes are dead.

Such improvement is due to energy-efficient CH selection that rotates the role of CH among all the eligible nodes efficiently.

Network lifetime: It is the number of rounds completed till all nodes are dead or drained of its energy. It is another parameter that depicts the longevity of the network.

The network longevity is highly important when the information dissemination is indispensable for any particular application. In MRA, this parameter holds importance in a way that the forest fire detection or any other extreme application the user wants its network to run till it replaces the dead network with the energy enriched nodes.

For Case A, MRA achieves network lifetime at 25,005 rounds, whereas in the case of TEDRP, SEECP and DRESEP it is 19,169, 4620 and 23,621 rounds, respectively, as shown in Fig. 9.

For Case B, MRA achieves network lifetime at 12,763 rounds, whereas in case of TEDRP, SEECP and DRESEP it is 10,268, 2306, and 6170 rounds, respectively, as shown in Fig. 10.

The reason behind such network longevity is ascribed to the placement of MGN due to which the node preserves its energy and network runs for a longer period. In addition to this, the load balancing is also achieved in the network due to single-hop communication involved among the CHs and MGN (Table 4).

Network's remaining energy: The network's remaining energy signifies the way the energy consumption is occurring in the network.

For Case A, the total energy of the network is 140 J, as the data transmission proceeds, the energy depletion takes place (Fig. 11). Similarly, for Case B, the total energy of the network is 67.5 J which gets reduced gradually (Fig. 12).

It is observed that network's remaining energy, in the case of MRA, is preserved to cover a number of rounds as compared with the TEDRP, SEECP and DRESEP protocols as shown in Fig. 10. It is basically due to the energy-efficient routing technique based on MGN and energy-efficient CH selection in the network.

It is evident from the results and discussion in the above section, MRA has improved TEDRP, SEECP and DRESEP protocol by a significant amplitude of rounds. The aggregated improvement regarding a number of rounds and percentage is shown in Table 3, MRA has outperformed the state-of-the-art reactive protocols, namely TEDRP, SEECP and DRESEP meant for unattended applications (Fig. 12).

With such improvement rendered by the proposed architecture, it becomes highly favourite for the market which deals with harsh environment monitoring. The proposed architecture is the novelistic approach that not only provides energy-efficient routing but also helps in mitigating the hot-spot problem.

In addition to it, with the proposed architecture it becomes easy to deliver data packets with very less delay as compared with the existing techniques for harsh environment monitoring. The placement of data collecting platform, i.e. MGN is done outside the network in MRA; otherwise, if these were placed inside the network, could have suffered from harsh environmental or surrounding conditions for an example forest fire. These stock of characteristics make the proposed architecture grabbing a

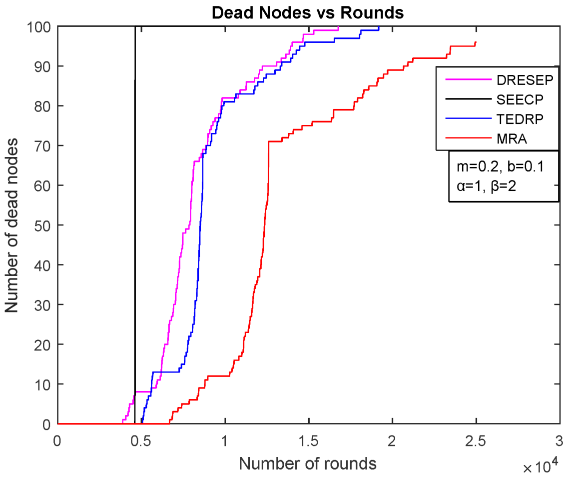

Fig. 9 *Dead nodes versus rounds comparison of MRA against other protocols for Case A*

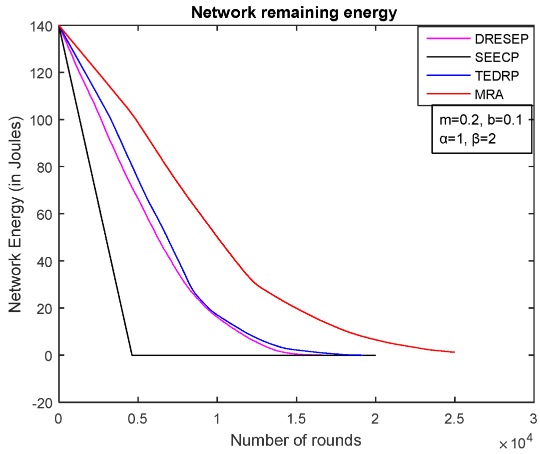

Fig. 11 *Network's remaining energy comparison of MRA against other protocols for Case A*

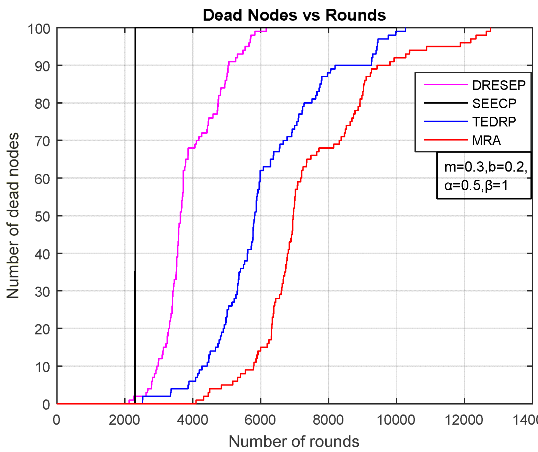

Fig. 10 *Network lifetime comparison of MRA against other protocols for Case B*

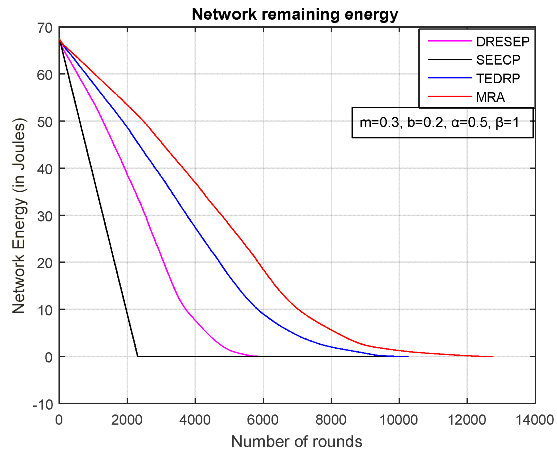

Fig. 12 *Network's remaining energy comparison of MRA against other protocols for Case B*

Table 4 Performance comparison (in rounds) by MRA against the other protocols

Protocols	Stability period				HND				Network lifetime			
	Case A		Case B		Case A		Case B		Case A		Case B	
	Rounds	% imp.	Rounds	% imp.	Rounds	% imp.	Rounds	% imp.	Rounds	% imp.	Rounds	% imp.
MRA	6675	—	4099	—	12,354	—	6958	—	25,005	—	12,763	—
TEDRP	5063	31.84	2523	62.47	8503	45.29	5827	19.41	19,169	30.44	10,268	24.3
SEECP	4620	44.84	2302	78.06	4620	167.4	2304	202	4620	441	2306	453.47
DRESEP	4534	47.22	2133	92.17	9873	25.13	3639	91.21	23,621	5.86	6170	106.86

Case A: $m = 0.2$, $b = 0.1$, $\alpha = 1$, $\beta = 2$; Case B: $m = 0.3$, $b = 0.2$, $\alpha = 0.5$, $\beta = 1$; '%' and 'imp.' are abbreviated for 'percentage' and 'improvement', respectively.

significant attention from the market dealing with harsh environmental monitoring.

5 Conclusion

In this paper, MRA is proposed that not only play a crucial role in avoiding hot-spot problem but also helps in enhancing network stability and its lifetime enhancement. The two cases of different nodes and energy fractions are considered. In Case A, the simulation results show that MRA improves stability period by 31.84, 44.48 and 47.22% as compared with the TEDRP, SEECP and DRESEP protocols, respectively. Moreover, the network lifetime in MRA is ameliorated by 30.44, 441 and 5.86% as compared with TEDRP, SEECP and DRESEP protocols, respectively. The network's remaining energy also covers a number of rounds as compared with the aforementioned protocols. The comprehensive improvement is achieved for Case B as well. Such significant improvement is due to the shortening of the communicative distance of each node from the data collecting gateway node that is the consequence of placement of MGN outside the network. Moreover, intra-cluster routing is improved by introducing the node density factor for CH selection along with the energy and distance. It is evident from the simulation analysis that MRA can be suitably implemented for various hostile applications. In future, the placement of MGN can be optimised to increase the network efficiency.

6 References

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