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NMR inspired energy efficient protocol for heterogeneous wireless sensor network

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Abstract

This paper presents a naked mole rat (NMR) inspired energy efficient protocol for heterogeneous wireless sensor network. NMR uses strategic deployment among three types of nodes i.e. normal nodes, advanced nodes and super nodes. It takes into consideration that nodes near the base station consumes more energy as they have to act as both data originators as well as data router, therefore nodes near the base station have been provided with maximum amount of energy. Moreover, it is seen that normal nodes in heterogeneous network dies out first. So, in order to increase the stability period, advanced nodes have been associated with normal nodes which add to the energy of the normal nodes as advanced nodes don't participate directly in the communication. Another addition is introduction of new weighted probability based on heterogeneity parameters of network for cluster head selection. Furthermore, a very important energy consumption parameter i.e. energy consumed in sensing has been taken into consideration. The simulation outcomes show that NMR based protocol is more proficient than existing protocols in terms of stability, lifetime and throughput of the network.

Keywords Wireless sensor networks · Naked mole rat · Strategic deployment · Heterogeneous network · Energy efficiency

1 Introduction

The energy and computationally constrained units whose task is to sense or collect the data from an area of interest may be referred to as Sensode. This term Sensode is similar to anode or cathode devices in electrochemistry whose task is to act as a medium of electron transfer in an electrical device. Correspondingly, Sensode may be referred to as a device which acts as a medium of information or data transfer from the area of interest. A Sensode can be data originator or data router, further, it is capable of sensing, computation, and communication. The basic architecture of wireless sensor network can be explained pictorially as in Fig. 1.

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WSNs are getting in blood and vein of our lifestyle due to their smart, easy and cheap availability. These networks are making their presence felt in public domains such as healthcare, agriculture, environmental monitoring, habitat monitoring, forest fire control, landslide detection, public safety and military, automation industry, transport, inventory management, retail, smart spaces, archaeological purposes and flood detection, etc., [1].

Routing protocols may be classified on the basis of node's computation capabilities or battery energy levels. Thereby, networks, where all the Sensodes have same computational capabilities, priorities and energy level, are known as homogeneous networks, while those networks which have different energy levels, computational capabilities or priorities are known as heterogeneous networks. This paper considers heterogeneous sensor network where Sensodes of the network have a different amount of initial battery levels but same priorities, computational and communication capabilities.

1.1 Motivation

Animal groups like the school of fishes, flocks of birds, swarms of locusts, herds of wildebeest show a variety of

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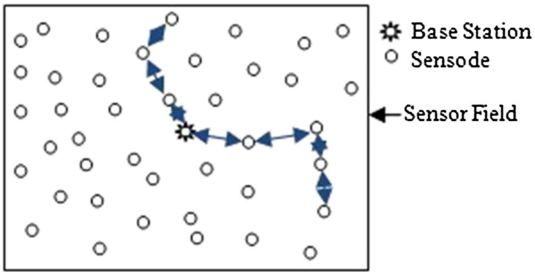


Fig. 1 Basic architecture of wireless sensor network

behaviors known as biological laws of collective motion. These laws of collective motion govern activities like swarming about the food source, milling around a central location, migration over a large distance in aligned groups, etc. Bio-inspired algorithms are usually inspired from collective animal behavior (CAB) [2]. Collective animal behavior can be perceived from the concept of individual organization. The key convention of an individual organization is the simple repeating interactions between individuals which can produce complex behavioral patterns at group levels. Such indirect communication among individuals through changes in the surrounding environment is known as stigmergy. The fundamental behind this form of emergent cooperation is the trace left in the environment by an action stimulates the performance of the next action by the same or different agent.

In this paper, naked mole rat [3] also known as desert mole rat has been identified as a rodent whose eusocial behavior motivates the development of the heterogeneous protocol in wireless sensor networks. NMR (biological name Heterocephalus glaber) [4–9] is a cold-blooded, herbivorous mammal which is found in the deserts of Africa. The general appearance is that of 3 inched, wrinkled, pink, blind and bald animal weighing somewhere between 30 and 70 g with overlarge front teeth. NMR is eusocial in the sense that they live in colonies which can have members ranging from 20 to 300 in a colony sized as large as 3 kms. Each adult individual in the society has working roles.

1.2 Our contribution

The current work studies the behavioral pattern in the society of naked mole rat and based on inspiration from the same, proposes a heterogeneous energy efficient protocol which implements heterogeneity in terms of eusocial attributes of the NMR society. The strategic deployment of the nodes has been done on the basis of foraging behavior of the mole rats in their society. Later, a new weighted probability based on heterogeneity parameters of the network for cluster head selection has been defined which address the problem of improving stability period of heterogeneous network. Further the work has been compared with existing protocols [10–12] and the results suggest that the proposed protocol presents a better lifetime, increased throughput and reduced energy consumption per round. In addition to this, a very important energy consumption parameter i.e. energy consumed in sensing has been taken into consideration which is usually ignored during analysis of the network lifetime.

1.3 Paper organization

The work in this paper has been presented in the following manner:

Section 2 details the literature domain of biological animal behavior mapping into computer networks along with current scenario of clustering in a heterogeneous wireless sensor network. Section 3 describes the used radio energy dissipation model. Further, Sect. 4 elaborates the NMR inspired energy efficient protocol which includes basic assumptions, network deployment strategy, energy distribution among nodes, clustering hierarchy, data transmission policy along with the arithmetic illustration for above. Later, comparative simulation outcomes have been discussed and analyzed in Sect. 5. Section 6 concludes and paves way for future study.

2 Related work

In Lin and Kernighan [13] introduced a highly effective heuristic procedure for generating an optimum/near-optimum solution for symmetric traveling salesman problem based on a general approach to heuristics for wide applicability in combinatorial optimization problems.

Dorigo et al. [14] proposed a new approach for stochastic optimization and problem solving without getting trapped in local minima. This technique was a combination of distributed computation, positive feedback and constructive greedy heuristic. Further, the quality of solution improved with increase in number of ants engaged in scenario. In Dorigo [15] proposed ant system, a model algorithm applied on travelling salesman problem. The main attributes of solution were positive feedback, distributed computation, constructive greedy heuristics. This solution was applicable on optimization problems like asymmetric travelling salesman problem, quadratic assignment and job scheduling problems. This considered visibility on the basis of distance and measure of trail present on connecting edge forming tabu-list and thereby finding shortest path and clearing tabu-list item on traversal. In Dorigo [16] further introduced the ant colony system which emphasized on local and global trail updating. This added that volume of pheromone trail present on a particular edge is inversely proportional to the tour length, thereby artificial and could know the proximity of a particular destination. Later in Dorigo et al. [17] specified a distributed, multi-agent based monte-carlo system called ant net, and introduced stigmergy in social insects. It focused on irregular topology, connectionless network on simple transport layer. Maniezzo and Colorni [18] evaluated the quality of proposed system by comparing the results achieved using different classical instances of ant system applied on quadratic assignment problem with evolutionary heuristics. Later, Dorigo and Blum [19] presented a survey "ant colony optimization theory", which summarized efforts in development of theory of ACO. The work highlighted the connection between ACO and the stochastic gradient ascent along with cross-entropy technique within the model based search scenario. Then in Dorigo et al. [20] introduced ACO as metaheuristic influenced by foraging habits of biological ants. It further suggested the use of ACO as an architectural framework for solving sequential ordering problems, resource-constrained project scheduling problems and open shop scheduling problems.

Biological systems [21] are the earliest large-scale complex systems which are evolving over billions of years and are continuously adapting to the changing environment. These systems motivate research in computer networks due to similar fundamental properties with WSNs which include the absence of centralized control, increase in complexity with growth in system size, an interaction of a large number of entities and self-governing components.

Meisel et al. [21] highlighted the taxonomy of bio-inspired research in the domain of computer network that motivates for thinking in use of biological behaviors in our networks. Changan et al. [22] proposed a global optimization algorithm named as Wolf Colony Algorithm based on the predatory behavior of wolf colony according to the assignment rule of the pack. WCA emphasizes on cooperation and coexistence of wolves in the colony thereby presenting good generalization as a solution to optimization problems.

In Cuevas et al. [2] introduced a meta-heuristic algorithm for global optimization based on collective animal behavior. Here searcher agents emulate a group of animals which interact among themselves based on biological laws of collective motion. Later in the same year, Taherdangkoo et al. [23] proposed a blind, naked mole-rats algorithm. Basically, it was a novel meta-heuristic algorithm for numerical function optimization, based on the social behavior of the blind naked mole-rats colony for foraging and defense against a foreign attack. This succeeded in dealing with the problem of getting stuck in local minimums or low scale of convergence. According to the algorithm, the mole rat society was divided into 3 groups as queen with a small group of males to carry out reproduction, employed workers engaged in food collection alongwith nest maintenance and soldiers answerable for cleanliness and security. Further, the society had a higher number of soldiers as compared to employed workers in addition to fixed regularities. The search for food started in a random manner from the center which is the residence for queen and its kids towards different food sources in the vicinity. The number of individuals in the society was twice that food sources which are the part of the solution in the problem space. Total 8 directions were considered around the food source separated at 45^{o} from each other.

In Xing and Gao published a book [24] named innovative computational intelligence as a guide to a large number of clever algorithms. The text presented the domain of innovative computational intelligence ranging from biology, physics, chemistry, mathematics-based CI Algorithms to biological animals like bats, bees, naked mole rat, cuckoo, luminous insects, invasive weeds, fishes, frogs, fruit fly, swarm intelligence in cats, biogeography-based optimization, group search optimization, music, imperialist competition, teaching-learning process, etc. These algorithms for illustration in biology based CI algorithms have taken inspiration from bacterial foraging, bacterial colony chemotaxis, bacterial colony optimization and viral system. Likewise, bats' intelligence or predatory behavior too have been explored as of how almost blind during the day, can spatially orient itself for food collection. It uses the continuous echolocation signals in the auditory system to identify their surroundings and locate preys. Further, numerous enhancement too has been done on these algorithms which have been justified on the application in different optimization problem domains and validated by different Benchmark functions.

Recently, Sendra et al. [25] presents a comprehensive review of recently proposed bioinspired mechanisms which could be used as protocols in the domain of WSNs. Here, they have analysed the mechanisms from two perspectives i.e. development of new systems and improvement of existing ones. In addition to bioinspired systems, the authors have also suggested for works inspiring from other biological behaviors including genetic algorithms, immune systems, bacteria and artificial plant optimization algorithms.

Coming to the current scenario of data transmission by clustering in wireless sensor networks, LEACH [26] uses as a pre-determined percentage of nodes which have to be cluster head in a particular round. For homogeneous case, LEACH assures that every node shall be cluster head (CH) exactly once in an epoch. It implies that the specific number of nodes is selected as the cluster head for the initial probability to be CH. At the beginning of an epoch, all the nodes belong to a set G. Nodes are removed from G as soon as they become CH, this increases the probability of becoming cluster head among members of G after each round, thereby maintaining a steady number of CH. The choice of a node s to be CH is done on the basis of a random number selected from the closed interval [0,1]. If the random number is less than threshold T(s), then node becomes CH for the given round:

$$T(s) = \begin{cases} \dfrac{p_{opt}}{1 - p_{opt}(r mod \dfrac{1}{p_{opt}})} & s\epsilon G \\ 0 & else \end{cases} \quad (1)$$

where r is the current round number. LEACH also concludes that optimal probability of being CH is a function of spatial density in a uniform distribution.

On application of LEACH for a heterogeneous uniform deployment scenario [10], for two types of nodes (i.e. normal and advanced). It is expected that the stability period is as long as that in a homogeneous scenario. In fact, the first node to die shall be a normal node, moreover, the probability of death of a normal node is higher as compared to the advanced node, even, the last nodes remaining alive in the later stages of the network operation shall be advanced nodes. This suggests a generous instability period due to the unstable selection process of CH formation leading to the idle state of advanced nodes because of no CH to whom the data can be forwarded further. SEP boosts the quality of information assessment from the sensor field by operating in the heterogeneous scenario. It increases the stability period for the network with $\alpha \times m$ times additional energy. The epoch is updated to $\frac{1}{p_{opt}}(1 + \alpha \times m)$, making each advanced node CH exactly $1 + \alpha$ times. Moreover, the extra energy of advanced nodes is used in sub-epochs of a given epoch. SEP assigns following weight of: $p_{opt} = \frac{Initial\ Energy\ of\ Node}{Initial\ Energy\ of\ Normal\ Node}$

$$p_{nrm} = \frac{p_{opt}}{1 + \alpha \cdot m} \quad (2)$$

$$p_{adv} = \frac{p_{opt}}{1 + \alpha \cdot m}(1 + \alpha) \quad (3)$$

where p_{nrm} and p_{adv} are weighted probabilities for normal and advanced nodes. Then Eq. (1) has been updated accordingly to select nodes as cluster heads.

Later Heterogeneity in node energies has been extended to level 3 (i.e. nodes have three types of nodes with increasing amount of initial energy) and multi level where initial energy of nodes is distributed within $[E_o, E_o(1 + \alpha_{max})]$. This implies that all nodes have different amount initial energy, but this seems inapplicable to design and deploy a network with large number of different energy levels.

Qing et al., DEEC [11] deliberate 2 level and multi-level heterogeneity in wireless sensor networks. It assigns a node to be CH based on probability from the ratio between residual energy of each node and the average energy of the network. Epoch for cluster head selection is based on initial and remaining energy.

Kumar [27] proposed two clustering based protocols particularly single hop energy efficient clustering protocol (S-EECP) and multi-hop energy efficient clustering protocol (M-EECP) to maximize the lifetime of the heterogeneous wireless sensor network. S-EECP used single hop to transmit data directly to BS through CH selected based on weighted probability from the ratio of the residual energy of each node and the average energy of the network but this consumed high amount energy from nodes far away from the BS. So, M-EECP solved this single source shortest problem using a greedy approach to find the shortest path from each CH to BS.

Singh et al. [12] use a single parameter to characterize heterogeneous network model. It further improves and implements DEEC on the proposed model for 1, 2 and 3 levels of heterogeneity as hetDEEC-1, hetDEEC-2, and hetDEEC-3.

3 Radio network model

A typical sensor node has a sensor system, A/D conversion circuitry, DSP and a radio transceiver as shown in Fig. 2. The process of information dissipation from sensor field to the base station includes energy consumption by each of these subsystems. All the subsystems except data communication consume approximately same amount of energy due to standard hardware available. Moreover, data communication (radio transceiver) consumes maximum amount of battery power. Therefore, the aim is to minimize the energy consumption in data communication, so as to maximize the network lifetime.

For analysis, the first-order energy dissipation model has been assumed as in [26] described as under:

The energy consumed in sending a packet of m bits over a one hop wireless link can be expressed as:

$$E_L(m, d) = \{E_T(m, d) + P_T T_{st} + E_{encode}\} + \{E_R(m) + P_R T_{st} + E_{decode}\} \quad (4)$$

where E_T is the energy used by transmitter circuitry and power amplifier, E_R is the energy used by receiver circuitry, P_T is the power consumed of the transmitter circuitry, P_R is the power consumed of the receiver circuitry, T_{st} is the startup time of the transceiver, E_{encode} is the energy used to encode, E_{decode} is the energy used to decode at transmitter and receiver end respectively.

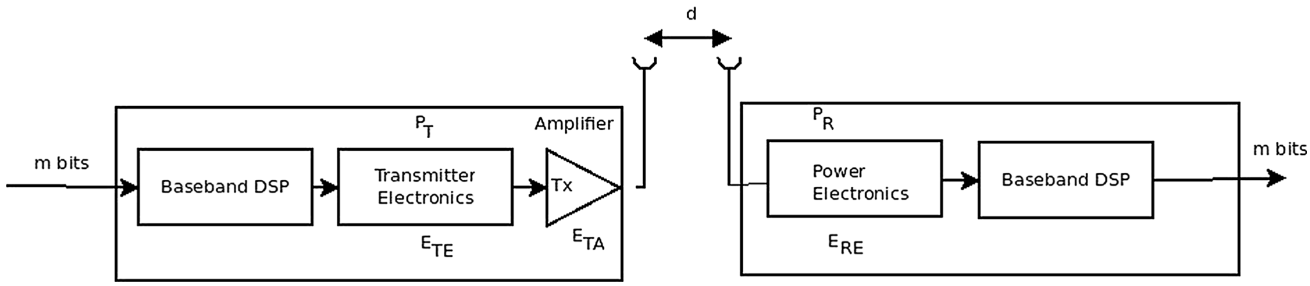


Fig. 2 Radio energy dissipation model

Assuming a linear relationship for the energy spent per bit at the transmitter and receiver circuitry E_T and E_R respectively, for communicating m bits of data over distance d can be written as:

$$E_T(m,d) = m(E_{TE} + E_{TA} d^{\alpha}) \quad (5)$$

$$E_R(m) = m(E_{RE}) \quad (6)$$

where E_{TE} is energy dissipated to run radio electronics of transmitter, depends on parameters like digital coding, modulation, filtering and spreading of the signal, E_{TA} is amount of energy dissipated to run power amplifier, depends upon distance d between two communicating entities and allowed error per bit; likewise E_{RE} is amount of energy dissipated to run receiver radio electronics and α is the path loss component whose value varies between 2 (for free space propagation) and 4 (for multi path propagation) depending on threshold d_o.

The effect of the transceiver startup time T_{st} will greatly depend on the type of MAC protocol used. To minimize power consumption, it is desirable to have the transceiver in sleep mode as and when possible. However, constantly turning the transceiver on/off to carry out transmission and reception too consumes considerable amount of energy in long run.

Considering a linear sensor array as a scenario of data transfer from an originator node n to the base station, depicted in Fig. 3.

Focusing only on the energy consumption due to actual communication process, ignoring energy consumed in encoding, decoding as well as on the transceiver startup as these energies are very small as compared to communication energy. The initial assumption is that there is one packet being relayed from the node farthest from the sink node towards the sink. The total energy utilized by the linear array to relay a packet of m bits from n_{th} node to the base station is given by:

$$E_{linear} = m\left\{\sum_{i=2}^{n}[E_{TE} + E_{RE} + E_{TA}(d_i)^{\alpha}] + [E_{TE} + E_{TA}(D_1)^{\alpha}]\right\} \quad (7)$$

E_{linear} will be minimum when all the d_i's are made equal to D/n, i.e. all the distances are equal [28]. Moreover, the sensor farther away from the base station consumes most of their energy by transmitting over long distances whereas sensors closer to the base station consume a large amount of energy in relaying packets from the upstream sensors towards the base station.

Hereby generalizing Eqs. (5) and (6) for the energy consumed in transmission and reception as under:

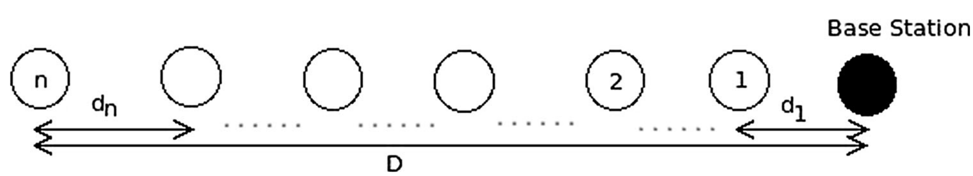
$$\begin{aligned} E_{transmission}(m,d) &= E_{TE}(m) + E_{TA}\cdot d^{\alpha}(m,d) \\ &= \begin{cases} m\cdot E_{elect} + m\cdot E_{fs}\cdot d^2 & for \quad d < d_o \\ m\cdot E_{elect} + m\cdot E_{mp}\cdot d^4 & for \quad d \geq d_o \end{cases} \end{aligned} \quad (8)$$

$$\begin{aligned} E_{Reception}(m) &= E_{RE}(m) \\ &= m\cdot E_{elect} \end{aligned} \quad (9)$$

Here $d_o = \sqrt{\frac{E_{fs}}{E_{mp}}}$ obtained by equating two expressions in Eq. (8) at $d = d_o$ and E_{elect} is the energy consumed to communicate 1 bit of data in transmitter or receiver circuitry, while E_{fs} is the energy consumed for free space propagation and E_{mp} is the energy consumed for multi path propagation, depending on the distance d between transmitter and receiver as depicted in Eq. (8).

The work also takes into consideration the energy consumed in the sensing process E_{sens} [29], so as to make a better estimate of energy consumption:

Fig. 3 Linear array of Sensodes



$$E_{sens} = V_{sup} \times I_{sens} \times T_{sens} \quad (10)$$

where V_{sup} is the supply voltage to the sensor, T_{sens} is the time duration for which sensor has carried out sensing task and I_{sens} is the amount of current utilized in sensing activity.

4 NMR inspired energy efficient protocol

4.1 Assumptions

For stationary, non-rechargeable nodes in ever data producing area of interest, propagation delay has been ignored for a symmetric radio channel. Data sensed by the nodes is send to the base station via different cluster heads in TDMA pattern of multiplexing so as to avoid collision. Further, nodes have same computation, communication capabilities and priorities. They consume energy on the basis of role assigned to them as data originator, data router or cluster head. In addition to this, nodes know their peer nodes in the network based on the received signal strength indicator (RSSI). Moreover, any node can directly communicate with the base station just by dissipating energy based on distance between the communicating entities (as discussed in radio energy model).

4.2 Network deployment

Before actual deployment of the network, let's understand some more interesting features of naked mole rat which inspire this animal as an entity for research are as under:

NMR are sensory specialists, senses through their skin/whiskers as they show *extreme efficiency in spatial orientation*. They can *run forward and backward direction at same speed*. They are insensititve to chemical irritants like acids, even spicy ingredients like chilli or pepper, even insensititve to cancer and pain due to their elastic skin, modelling them as *robust and fault tolerant*. Further, they show *no biological aging*, they can live from 22 to 32 years in its natural terrain and 17–27 years even in lab environment. In addition to this, they are poop eating which points to the idea of *energy scavenging* in case of emergency.

Social organization of NMR is as under:

Society has fixed location for sleeping, feeding and communal defication at the centre of the colony where queen lives with the young ones who donot contribute to any work but also donot consume any energy as they feed on poop at times. The task in the society is to collect the food at centre location from the nearby places by digging the tunnels in labyrinthine fashion. Three types working members exist in the society as diggers, sweepers and volcanoers. *Diggers* search for the food, take it till or around centre location say Base station, iff no sweeper is available to take it. *Sweepers* associated with some digger, takes the food searched by the diggers to the volcanoers. *Volcanoers* located around the base station or centre location, drags the food collected by diggers or sweepers to the base station.

On similar grounds, the work assumes a 100 × 100 m sensing field as an area of interest. Considering collected information as food, which is taken to the center location, so assuming base station at the center. The work divides the energy level of nodes in the field on the basis of the number of tasks to be done, i.e. the nodes around base station have to do data forwarding from far away nodes along with its own data sensing and communication, so they have been given more energy (*super node*). Likewise, *normal nodes* sense and collect the data, which is further forwarded by *advanced nodes*. The energy levels and deployment strategy of the above normal, advanced and super nodes have been detailed as under:

4.2.1 Deployment strategy

The 100 × 100 m sensor field consists of a single stationary base station at the centre (50, 50). This sqaure shaped area of interest has a circular subsection which divides the sensor field into two areas as shown in Fig. 4. The radius of this circle is approximately one hop distance (analysed in Fig. 5).

The available three types of nodes are deployed in uniform random fashion at different locations in the area of interest. Super nodes are deployed inside the circular subsection, while normal nodes are deployed outside the circular area but inside the field. Further, advanced nodes are deployed in vicinity of randomly selected normal node such that a normal node may not have more than one

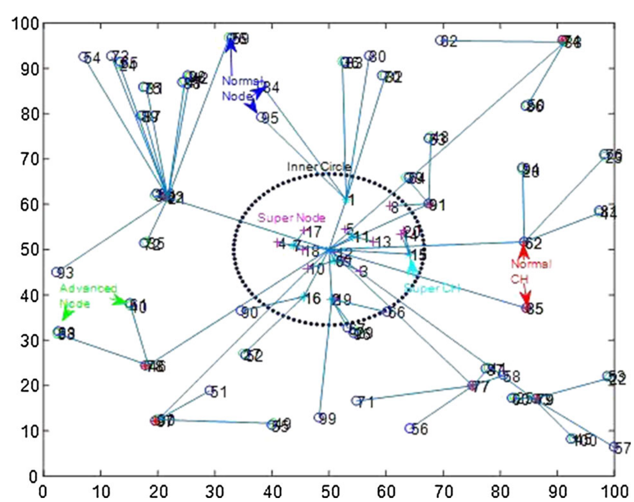


Fig. 4 NMR field deployment

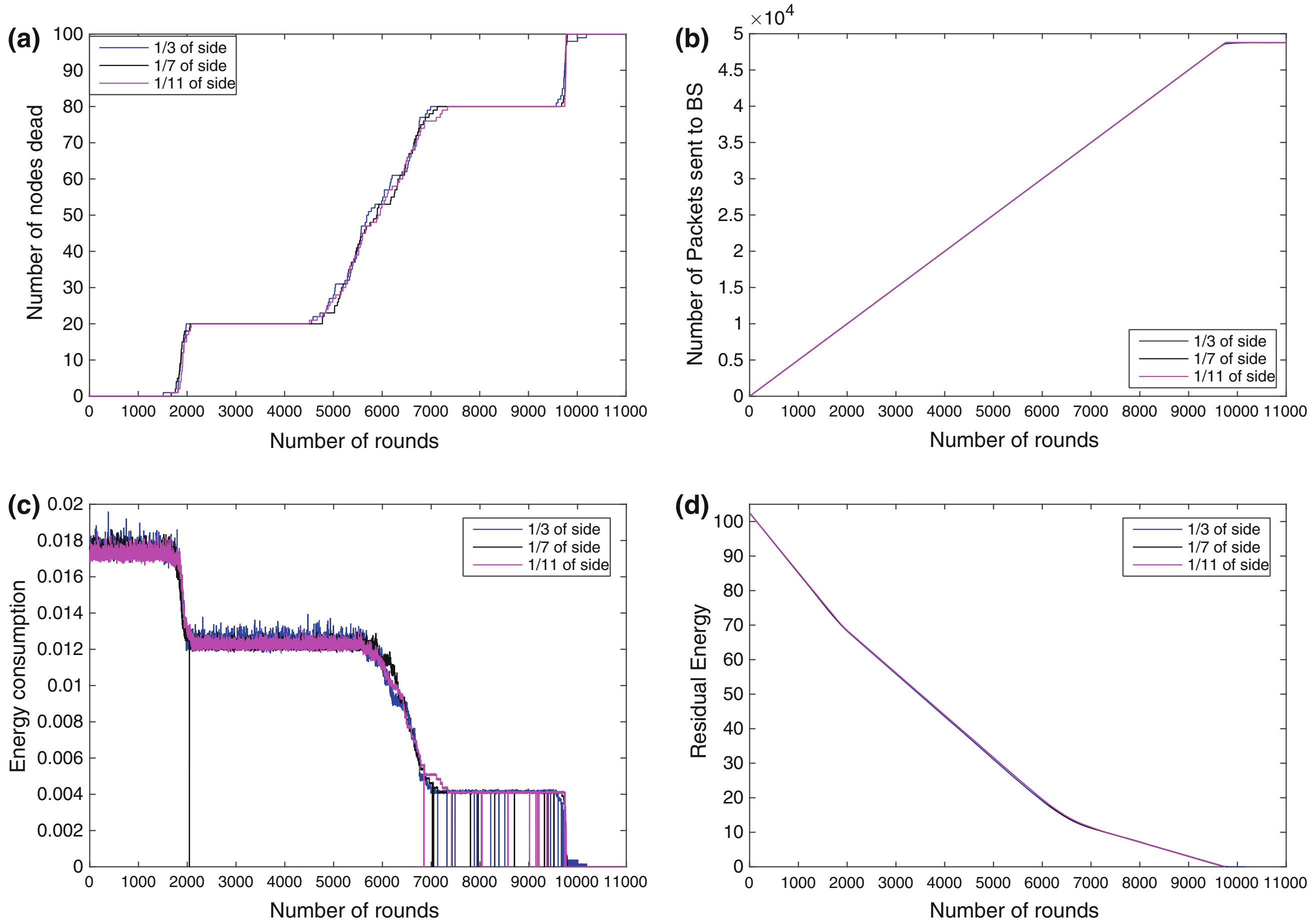


Fig. 5 Analysis for radius of inner circle in sensor field. (Top-down, left-right) **a** number of nodes dead per round, **b** Number of packets sent to base station per round, **c** energy consumption per round, **d** total residual energy per round

associated advanced node. Here, this is to be noted that densities of nodes deployed are as under:

For super nodes $(\rho_{sup}) = \frac{Number\ of\ super\ nodes}{Area\ of\ circular\ subsection} = 0.0229$ nodes/m^2

For normal nodes $(\rho_{nrm}) = \frac{Number\ of\ normal\ nodes}{Area\ of\ square\ field - circular\ subsection} = 0.0055$ nodes/m^2

For advanced nodes $(\rho_{adv}) = \frac{Number\ of\ advanced\ nodes}{Area\ of\ square\ field - circular\ subsection} = 0.0033$ nodes/m^2

4.2.2 Energy model

The sensor network considered here is heterogeneous in terms of initial energy of nodes. Sensodes in the network are divided into three energy levels [30] i.e. normal nodes (diggers), advanced nodes (sweepers), super nodes (volcanoers) summarized in Table 1 and explained as under.

Suppose N Sensodes are to be deployed in the sensor field with E_o as the initial energy of normal nodes. Then, taking mth fraction of total number of nodes N which have some extra energy and m_o is a percentage of $N \times m$ nodes which have β times more energy than normal nodes called super nodes. Leftover $N \times m \times (1 - m_o)$ nodes have α times extra energy as compared to normal nodes known as advanced Nodes and the rest of the nodes are known as normal Nodes.

It implies that total energy of the network is:

$$\begin{aligned} E_{Tot} = &\ \text{total energy of super node} \\ &+ \text{total energy of advanced node} \\ &+ \text{total energy of normal node} \end{aligned}$$

$$\begin{aligned} E_{Tot} &= N \times m \times m_o \times E_o \times (1+\beta) + N \times m \times (1-m_o) \\ &\quad \times E_o \times (1+\alpha) + N \times (1-m) \times E_o \\ &= N \times E_o \times [1 + m \times (\alpha + m_o \times (\beta - \alpha))] \end{aligned} \tag{11}$$

This suggests that network has E_{extra} amount of surplus energy as compared to homogeneous network of N nodes with initial energy of nodes as E_o.

Table 1 Energy distribution of the network

Node type	Number of nodes	Energy of a single node	Total energy
Super node	$N \times m \times m_o$	$E_o \times (1+\beta)$	$N \times m \times m_o \times E_o \times (1+\beta)$
Advanced node	$N \times m \times (1-m_o)$	$E_o \times (1+\alpha)$	$N \times m \times (1-m_o) \times E_o \times (1+\alpha)$
Normal node	$N \times (1-m)$	E_o	$N \times (1-m) \times E_o$
Total energy of network: $N \times E_o \times [1 + m \times (\alpha + m_o \times (\beta - \alpha))]$			

$$E_{extra} = N \times E_o(m \times (\alpha + m_o \times (\beta - \alpha))) \tag{12}$$

4.3 Clustering hierarchy

As an improvement to the weighted probability in Eqs. (2) and (3), the probabilities of the normal node and super nodes have been defined as under, further there is no modified probability for advanced nodes as they don't directly participate in the process of cluster formation.

$$p_{nrm} = \frac{p_{opt} \times (1+\alpha)}{(1 + \alpha \times m)} \tag{13}$$

$$p_{sup} = \frac{p_{opt} \times (1+\beta)}{(1 + \beta \times m \times m_o)} \tag{14}$$

Threshold to choose cluster head amongst normal nodes and super nodes is retrieved by substituting p_{nrm} and p_{sup} from Eqs. (13) and (14) in p_{opt} of Eq. (1). Therefore, threshold for normal nodes have been specified as:

$$Theshold(s_{nrm}) = \begin{cases} \dfrac{p_{nrm}}{1 - p_{nrm} \times \left(r mod \dfrac{1}{p_{nrm}}\right)} & \text{if } s_{nrm} \epsilon s' \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

while, the threshold for super nodes have been specified as:

$$Theshold(s_{sup}) = \begin{cases} \dfrac{p_{sup}}{1 - p_{sup} \times (r mod \dfrac{1}{p_{sup}})} & \text{if } s_{sup} \epsilon s'' \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

where r is the round number under consideration, *S'* and *S"* is the set of nodes which have not been able to be CHs for last $\frac{1}{p_{nrm}}$ and $\frac{1}{p_{sup}}$ rounds respectively in a epoch. The average number of cluster heads per round is the sum of cluster heads selected among normal or advanced nodes and number of cluster heads selected among super nodes.

4.3.1 Data transmission

The network considered in this work has two levels of hierarchy and three types of nodes [30]. The above two levels of hierarchy implies data is transmitted from the sensor nodes to the respective cluster head which can be a cluster head amongst the normal, advanced nodes or a cluster head amongst super nodes, then from this cluster head, the data is transmitted to the base station. Further, E_{extra} in Eq. (12) suggests that the network has $m \times (\alpha + m_o \times (\beta - \alpha))$ surplus energy as compared to homogeneous network of the same size and strength of nodes having all nodes with initial energy E_o. In other words, virtually the network has $m \times (\alpha + m_o \times (\beta - \alpha))$ more nodes whose initial energy is equal to initial energy of normal nodes i.e. E_o.

The energy utilization among the nodes in the network is in sensing the information from the area under sensing range, simple computation and communication. Normal nodes utilize their energy for communication only iff it has no advanced node associated to it or the associated advanced node has already utilized all its energy, else advanced node's energy is used for communication. As concluded for heterogeneous sensor network [10], normal nodes are first to die. This strategy is equivalent to providing extra energy to normal node, which shall help in extending the stability period.

4.4 Arithmetic illustration

Considering 50% of nodes as normal nodes implies remaining 50% have some extra energy ($m = 0.5$) and super nodes be 40% of nodes which have β times more energy ($m_o = 0.4$). Super nodes have 400% more energy than normal nodes ($\beta = 3$), while advanced nodes have 250% more energy than normal nodes ($\alpha = 1.5$). If the total number of nodes n be 100, for a 100×100 m square sensor field with initial energy of normal nodes be 0.5 joules, then the network has 50 normal nodes, 30 advanced nodes with initial energy as 1.25 joules and 20 super nodes with initial energy of 2 joules.

For uniformity, the work assumes that initially 10% of total number of nodes can be cluster heads (i.e. $p_{opt} = 0.1$) in a particular round. The extended heterogeneous epoch is equal to $\frac{1+\alpha \times m}{p_{opt} \times (1+\alpha)} = \frac{1}{p_{nrm}} = 7$ rounds, and each sub epoch is equal to $\frac{1+\beta \times m \times m_o}{p_{opt} \times (1+\beta)} = \frac{1}{p_{sup}} = 4$ rounds.

Further, other numerical values for different attributes used in this study are given in Table 2:

5 Quality of service policy

The quality of service parameters used to evaluate the performance of this protocol has been defined as under:

- *Stability period* is the measure of time elapsed from the beginning of the network till the first sensode dies. This region is depicted as stability region and is a clear indicator of the reliability of the network.
- *Network lifetime* is the time elapsed from the beginning of the network operation till the last sensode dies. This indicates the period of time till which nodes are able to send the information about sensor field to the base station.
- *Number of nodes alive per unit time* is the momentous measure of the number of total nodes which are providing information to the base station. This accounts to the number of normal, advanced and super nodes.
- *Residual energy* is the amount of total remaining battery energy in the network at a moment of time irrespective of the node type. This is an indicator of available energy in the network at a period of time.
- *Energy consumption per round* is the measure of energy utilized in a given round. This is a measure of energy use in the network with available resources at a given instant of time.
- *Throughput* the measure of data transfer in the network from nodes in terms of the number of packets transmitted to the base station. It is the indicator of the amount of information being sent to the base station per unit time.

6 Simulation outcome

For given area of interest, which is divided into two parts as illustrated in Fig. 4. Super nodes are deployed inside circular subsection whose radius from the base station is within the range $\frac{1}{3}$ to $\frac{1}{11}$ times length of side of square shaped sensor field (analysed in Fig. 5). Normal nodes are deployed outside circular area within sensor field, while advanced nodes are deployed in vicinity of randomly selected normal nodes such that no normal node has more than one advanced node and no advanced node is shared by more than one normal node, aiming to provide additional energy to normal node, in order to extend stability period of the network.

Table 2 Numerical value assumptions

Attribute	Value
Transmitted packet size	4000 bits
Transmitter/receiver electronics	50 nJ/bit
Transmitter amplifier energy, for $d < d_o$	10 pJ/bit/m^2
Transmitter amplifier energy, for $d \geq d_o$	0.0013 pJ/bit/m^4
Data aggregation energy, E_{DA}	5 nJ/bit/signal
Supply voltage to Sensode, V_{sup}	2.7 V
Time duration for sensing, T_{sens}	0.5 ms
Current for sensing, I_{sens}	25 mA
Vicinity radius for advanced node	0.5 m

Figure 5 shows that altering the radius of existence of high energy super nodes does not significantly effect the network lifetime. Figure 5 shows the existence of a tradeoff in extension of stability period and death of last nodes in the network. Moreover Fig. 5b–d. show that number of packets sent to the base station, energy consumption per round and residual energy per round are not significantly affected by change radius of inner circle. It implies that there exist a load balancing among normal and super nodes which demonstrate almost same number of packets sent to base station and energy consumption.

For comparative analysis, SEP 2 level (as 2lvlSEP), SEP 3 level (as 3lvlSEP), DEEC 3 level (as 3lvldeec) [10, 11], hetDEEC-3 (as hetDEEC-3) [12] protocol with similar attributes in MATLAB i.e. with the same amount of total energy of the network as well as the same number of nodes and network size have been considered. Further, the presented results are averaged values for 100 scenarios.

The network lifetime may be defined as the time elapse from the beginning of network operation till the first node dies (also known as stability period) or till the death of the last node depending on the application. The current work considers the network lifetime in terms of stability period i.e. before the death of the first node. This is so because p_{opt} is taken in the case of LEACH protocol works satisfactorily only till the network is operational in its initial strength.

This work modifies p_{opt} to p_{nmr} and p_{sup} which extends the stability period as it takes into consideration the extra amount of energy provided to the nodes. The death of the nodes is influenced due to the utilization of energy from the advanced nodes first then from the normal nodes. Figure 6 shows network lifetime, depicted in terms of the number of nodes dead per unit time, this can also be analyzed as the number of nodes alive per unit time (alive nodes = total strength − dead nodes). Further, this is also to be noted in Fig. 6a that the first node dies almost at the same time as in the case of previous works, this is due to the probable death of the normal node which doesn't have any advanced node associated to it. While death pattern of the advanced node and normal nodes (represented by other steeps in the curve) is more stable in case of NMR due to less amount of energy consumption

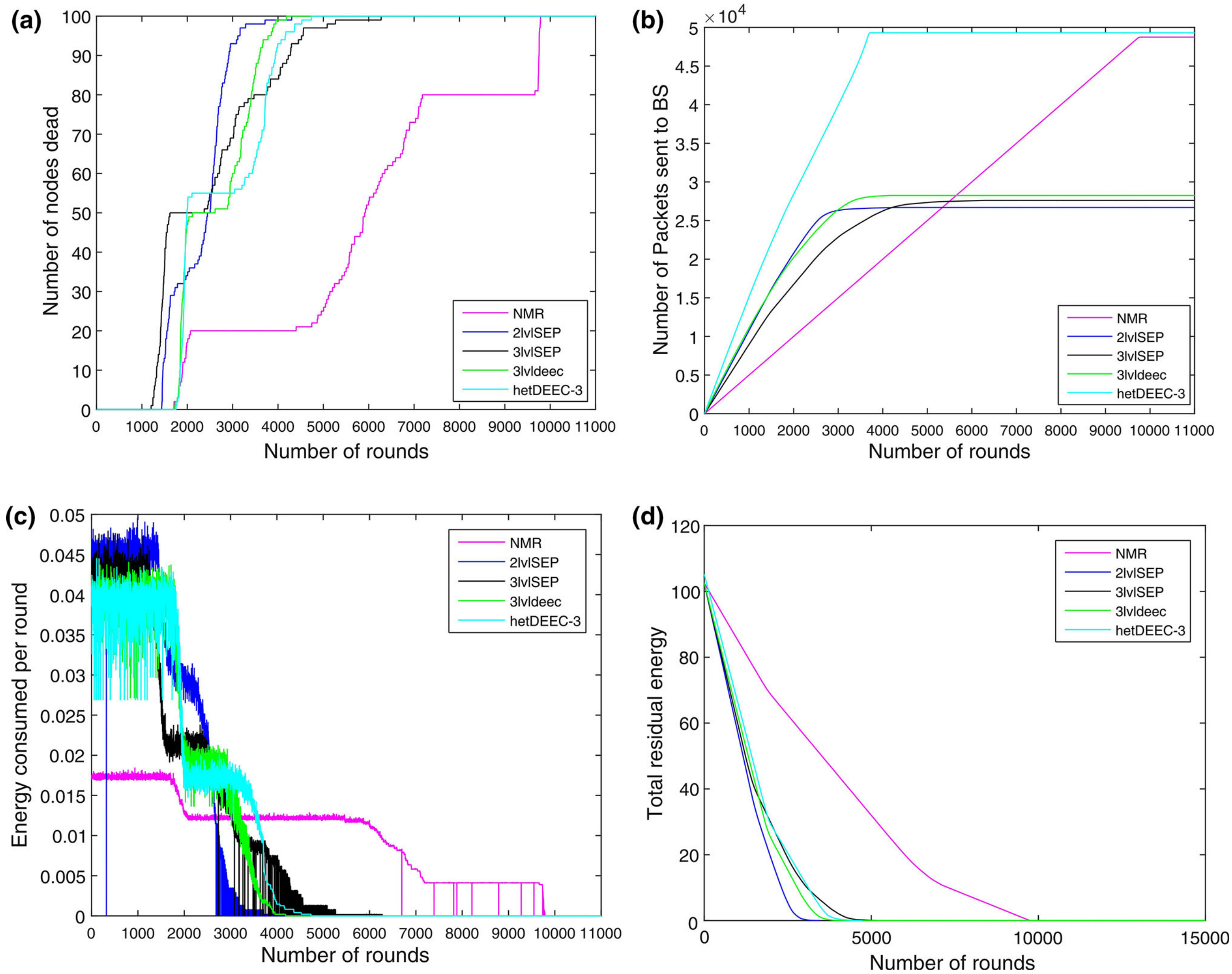


Fig. 6 Comparative analysis with existing protocols. (Top-down, left-right) **a** number of nodes dead per round, **b** number of packets sent to base station per round, **c** energy consumption per round, **d** total residual energy per round

per round. This is an illustration of time elapse till the network sends some information to the base station.

Figure 6d shows the total amount of residual energy in the network per unit time. Here the unit time implies time interval of completion of a round i.e. time elapsed from data sensing at a node till reception at the base station. The figure illustrates that NMR has the higher amount of residual energy in the network as compared to existing protocols under consideration, this is because it is taking less number of hops to deliver data to the base station. Moreover, this work compares networks which have the same amount of initial energy instead of the higher amount of initial energy.

Figure 6c shows the amount of energy consumed per round, which is very less in case of NMR due to less number of nodes from which data is to be collected. This is because of network deployment where normal nodes communicate only when it has no associated advanced node or the associated advanced node has already utilized its energy.

Figure 6b shows the number of packets send to the base station per unit time or throughput. NMR protocol shows more reliability in terms of the amount of information being sent to the base station. This is due to even load distribution in NMR which allows a higher number of nodes to be alive for a longer period of time thus providing more packets to the base station.

The even load distribution in NMR is also due to almost fixed number of cluster heads per round, further this too is to be noted that communication in NMR is mostly through CHs i.e. data originator node sends its data to cluster head among normal node or its associated advanced node, which is further forwarded to cluster head among super nodes or to the base station if closer as compared to cluster head from super node.

7 Conclusion and future scope

This work comes up with hierarchical heterogeneous energy efficient protocol which is inspired by the behavioral pattern of an African mole rat named naked mole rat. Here, the deployment of nodes has been done in a strategic manner. Further, heterogeneity doesn't add extra energy to the network as compared to the network in [10, 12], i.e. total initial energy of the network under comparison is same. Still, our network protocol provides more stable lifetime to the network in terms of stability period, packets sent to the base station, energy consumption per round and total residual energy of the network. Further, the work can be extended to the application of the above protocol to the different size of networks. Moreover, the protocol can also be validated mathematically using benchmark functions [24].

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