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Balanced Energy Consumption Based Adaptive Routing for IoT Enabling Underwater WSNs

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ABSTRACT Applications of Internet of Things underwater wireless sensor networks, such as imaging underwater life, environmental monitoring, and supervising geological processes on the ocean floor, demand a prolonged network lifetime. However, these networks face many challenges, such as high path loss, limited available bandwidth, limited battery power, and high attenuation. For a longer network lifetime, both balanced and efficient energy consumption are equally important. In this paper, we propose a new routing protocol, called balanced energy adaptive routing (BEAR), to prolong the lifetime of UWSNs. The proposed BEAR protocol operates in three phases: 1) initialization phase; 2) tree construction phase; and 3) data transmission phase. In the initialization phase, all nodes share information related to their residual energy level and location. In the tree construction phase, our proposed BEAR exploits the location information for: a) selecting neighbour nodes and b) choosing the facilitating and successor nodes based on the value of cost function. In order to balance the energy consumption among the successor and the facilitator nodes, BEAR chooses nodes with relatively higher residual energy than the average residual energy of the network. The results of our extensive simulations show that BEAR outperforms its counterpart protocols in terms of network lifetime.

INDEX TERMS IoT, underwater wireless sensor network, energy balancing, tree construction.

I. INTRODUCTION

Advancement in sensor technology makes it possible to build low cost and small size IoT enabled wireless sensors. Technology advancement motivated the developers to build large scale UWSNs in IoT perspective for a variety of monitoring applications like environmental data collection (temperature, conductivity, pH, dissolved oxygen, etc.), imaging underwater life, supervising geological processes on the ocean floor, monitoring underwater equipments related to oil or mineral extraction, etc. UWSNs are particularly used for military and homeland security purposes. These networks consist of sensor nodes with potentially one or more sinks. The underwater sensors sense the attribute of interest and transmit the sensed data to the sink. Due to high absorption rate of electromagnetic waves in water, acoustic waves are used for underwater communication. Moreover, the UWSNs face many design challenges like high path loss, limited available bandwidth, limited battery capacity, high attenuation, high bit error rate, etc. [1], [2].

In order to prolong the lifetime of UWSNs, many energy efficient routing protocols have been proposed [3]–[5]. However, in these routing protocols, nodes near the sink dissipate their energy more quickly as compared to nodes farthest from the sink. According to Wills *et al.* [6], at a stage when the one hop away nodes from the sink exhaust their initial energy, 93% initial energy is left at the nodes farthest from the sink. Khan and Cho [7], Cao et al. [8], and Han et al. [9] have contributed in terms of balanced energy consumption, however, at the cost of reduced network lifetime.

In this paper, we solve the problem of imbalanced and inefficient energy utilization in IoTUWSNs. Like the model in [8], we logically divide the network field into sectors. We solve the unbalanced energy consumption problem in two steps: (i) intra Sector Energy Balancing ($intra-SEB$) and (ii) inter Sector Energy Balancing ($inter-SEB$). Energy efficiency of the network is improved by utilizing mixed routing and by selecting a better forwarder node based on the value of our introduced cost function. During transmission(s), energy

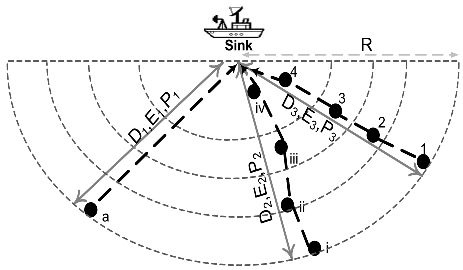


FIGURE 1. **Energy consumption on different paths.**

consumption increases with the increase in communication distance. As shown in the Fig. 1, distance D_1 and distance D_3 are same however energy consumption to transmit a data packet over path P_3 is less than the energy consumption to transmit a data packet on path P_1. D_2 is slightly greater than D_1, however, energy consumption with respect to path P_2 is less than that with respect to path P_1 (refer to Eq. (2), Eq. (3)). This difference of energy consumption, between hop by hop transmission and direct transmission increases with the increase in transmission distance. Due to more traffic load, nodes near the sink consume more energy as compared to the nodes away from the sink. This situation leads to imbalanced energy consumption among the network nodes [10]. Static routing also results imbalanced energy consumption among the network nodes [6]. So, we introduce the concept of the facilitating node (see Section 5) and use hop by hop transmission for prolonging the lifetime of the network.

In order to evenly distribute the traffic load among the network nodes, density of the deployed nodes needs to be increased towards sink [11], [12]. If uneven deployment strategy is not used then nodes near the sink need to be equipped with higher initial energy in a hierarchical manner. Once the network nodes are deployed, energy consumption pattern is defined by the routing protocol being used. Energy aware adaptive routing ensures the balanced energy consumption in the network [13]. Our main contributions in this paper (an extension of [14]) are summarized as follows.

- An energy balancing adaptive routing protocol, called BEAR, is proposed which intelligently utilizes the energy of the nodes and ensures the network connectivity for a longer period of time.
- The proposed BEAR scheme minimizes and balances energy consumption by utilizing the computed optimal number of zones.
- Extensive simulations are conducted to evaluate the performance of the proposed scheme. Results show that BEAR outperforms its counterpart protocols.

The rest of paper is organized as follows: Section II describes the related work. Network model is presented in Section III. In Section IV, feasible solution and some concepts which are important to understand the performance of the proposed model are discussed. Proposed routing protocol is described in Section V. The validation of the proposed model is done with the help of simulations, which is described in Section VI. Conclusion and future work are presented in Section VII.

II. RELATED WORK

Energy efficiency is one of the key parameters in battery constraint equipments such as sensors. Due to limited availability of energy for sensors, this unique resource considers to be the backbone for the wireless sensor networks lifespan. Therefore, in this regard, numerous routing strategies have been devoted in IoTUWSNs in order to utilize energy of sensors efficiently for optimal network lifetime. Few of them, closed to our proposed work, are discussed in this section as follows:

Hao et al. [16] increase QoS in terms of throughput without using the redundant transmission. In this regard, a Partial Network Coding (PNC) mechanism is used. Each node of the network is assigned a code which is orthogonal to each other, to minimize the chances of interference. Improved throughput of 22% is achieved at the cost of increased energy consumption.

In [17], Depth Adjustment based on Connected Tree (CTDA) protocol is proposed. It optimizes the coverage area of the network for a given number of nodes. While optimizing the coverage area, it ensures that the energy consumption is lower than the already proposed model. Nodes are deployed randomly in the network. These nodes are homogeneous in nature and are provided with motor and balloon mechanism to adjust their depth. Routing process is divided into two phases. In the phase one, nearest node to the sink is marked as root node. This root node searches for its neighbor nodes to complete its branches, in first round. In second round, branch nodes of the first round mark themselves as root nodes and search for their branch nodes. This process continues till all nodes in the network become part of the tree. In the second phase, coverage area is calculated. If the coverage area of two branches of the tree overlap, one of the branches is moved apart, while maintaining the connectivity. In this way, maximum area of the network is covered with minimum number of nodes. However, protocol efficiency is associated with the assumption of limited movement of nodes.

Yan *et al.* [4] utilize the depth information of a node for routing data packets, hence named as depth based routing protocol (DBR). The aim is to minimize the energy consumption during a transmission, which is accomplished successfully. Total energy consumption in DBR is half of its counter part protocols. However, it comes with a problem of lower network lifetime.

Diao *et al.* [18] proposed a routing protocol to increase the efficiency of DBR protocol. DBR does not consider the relative distance or depth of the next hop node from the sink, while choosing next forwarder node. Due to this reason, selected path in DBR is not optimum. To overcome this problem, the authors use Time of Arrival (ToA) technique and include three dimensional position of a node to choose the next hop node. Differential DBR (D-DBR) is proposed to reduce the end-to-end delay of DBR by 36.2%. While energy consumption is reduced by 81.5% with energy efficient DBR (EE-DBR).

Ahmed *et al.* [19] improve reliability of the network along with efficient energy utilization. To ensure efficient energy utilization, energy consumption for all possible routes (from a sending node to the sink) are calculated. Route with respect to minimum energy consumption is selected as energy efficient route. Residual energy and Signal to Noise Ratio (SNR) of the energy efficient route is observed, to incorporate reliability of the network.

Ghoreyshi *et al.* [20] identified a problem in opportunistic routing named as ''void region''. This situation occurs when a forwarding node (node that starts transmission) does not have any qualified node (relay node) in its vicinity, to send data towards the sink. To overcome this problem, Opportunistic Void Avoidance Routing (OVRA) scheme is purposed. OVAR holds the best trade-off between reliability and energy efficiency.

In protocol [21], aim is to increase reliability and reduce transmission delay in network. A set of forwarding nodes is calculated, for every node in network. In case of packet drop from one forwarding node, other forwarding node sends its copy towards destination and ensures reliability in the network. To reduce transmission delay, $T_{deadline}$ is introduced. ''Relay priority'', assigned to each node of forwarding set, ensures delivery of data packets from the source node to the destination node within $T_{deadline}$.

Wang *et al.* [3], propose energy efficient data-aggregation scheme. Aim is to use TWSNs' techniques, Compressed Sensing (CS) and Differential CS (DCS) in UWSNs. With small changes in DCS, according to the underwater environment, 95% of energy cost is reduced. However, new protocol is computationally extensive as compared to the conventional data aggregation schemes.

Khan and Cho [7] propose energy ef_cient data develop a data gathering routing protocol. Data gathering is done with the help of Autonomous Underwater Vehicles (AUVs). AVUs gather the data and balance the energy consumption in the network. Non-traditional movement of AUVs results in increased throughput and network lifetime.

Many protocols have been proposed to minimize the energy consumption of UWSNs like Depth Based Routing (DBR) [4], Energy Efficient DBR (EEDBR) [5], Cooperative energy efficient protocol for Underwater Water Sensor Networks (Co-UWSN) [22], etc.

Similarly, issue of balanced energy consumption is discussed in Balanced Transmission Mechanism (BTM) [8]. BTM protocol consists of two phases:

1) Route defining phase, and
2) Balanced transmission phase.

In route defining phase, node n_i searches for neighbors within its transmission range and selects the nodes whose relative distance from the sink is small as compared to the node n_i's relative distance from sink. The neighbor node with minimum cost function value is selected as a successor node. In balanced data transmission phase, initial energy of nodes is divided into m energy levels. Node n_i transmits data packet towards its successor if and only if, successor node is at a higher energy level than the n_i. Otherwise n_i transmits data packet directly towards the sink. Though, BTM balances the energy consumption of the network, however, trade-off has been made on the network lifetime. In [9], an energy balancing routing protocol is proposed. Node with maximum residual power among neighbor nodes is selected as a parent node. To balance the energy consumption, parent node is updated by every node, in each round. Energy balancing is achieved at the cost of network lifetime.

Zhang *et al.* [23] propose a routing algorithm to balance the energy consumption among the network nodes. It computes the weight function of the link before transmitting the data packet towards the destination. Weight of the link is symbolic representation of the distance from the sending node towards the sink. Ren *et al.* [24] work on energy efficiency as well as energy balancing. They have divided network field is divided into small coronas. Moreover, each corona is divided into sub-coronas and each sub-corona is further divided into two kind of zones: ''zone to zone'' and ''zone to sink''. The division is made, in order to minimize the communication destination between sender and receiver for balanced and efficient energy consumption. The communication over short distances resulted in 28.5% improved network lifetime. However, low network throughput is the price paid for improved network lifespan.

Abd *et al.* [25] aim to achieve an improved network lifetime by balancing the energy consumption of the node in the network. In this regard, energy balancing task is divided into two subtasks. The first one is, Node Level Energy Balancing (NLEB) and the other one is, Region LEB (RLEB). In RLEB, transmission distance of a node is divided into k subregions. Extended Game Theory (EGT) is used to select forwarding region amongst k subregions. In NLEB non-cooperative Classic Game Theory (CGT) is used to select a forwarder node. This procedure continues till packet reaches the destination. Table 1 shows comparative summary of the state-of-the-art work.

III. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we present the basic features of network model and the energy consumption model. Problem formulation is done at the end of this section.

A. NETWORK MODEL

The network model is based on the following assumptions.

- *Tn* number of sensor nodes are randomly deployed in a semicircle network field of radius *R* as shown in Fig. 2. We assume a two dimentional environment because we focus on water column monitoring for environmental sensing applications. For example, ''to determine the temperature profile of a water column several sensors

TABLE 1. Comparison of the state-of-the-art work.

Category	Protocol	Features	Draw Backs	Achievements	Remarks
Energy Balancing	OVAR [20]	Opportunistic routing is utilized.	Higher energy consumption.	High throughput is achieved. End-to-end delay is reduced. Void region is avoided.	A real problem identification and a satisfactory answer to identified problem.
	GPNC [16]	Partial Network coding technique is used. Geographical routing protocol is used.	Increased energy consumption as compared to DBR. Network lifetime comparison is not done with DBR VBF-NC.	Low end-to-end delay as compared to DBR. Low energy consumption as compared to VBF-NC.	Development of PNC. Simulation of PNC is done for different data packet size.
	CTDA [17]	A deployment technique which improves the network connectivity and results in QoS improvement.	Protocol efficiency is associated with the assumption of limited movement of nodes.	An energy efficient protocol. Provides optimal coverage area under given number of nodes.	Nontraditional approach is used to improve the QoS. of the network.
	EE-DBR [18] D-DBR	ToA routing technique is introduced to address the latency and the energy issues in the network.	EE-DBR lacks in latency. D-DBR lacks in energy efficiency.	Efficient energy consumption in EE-DBR. Low end-to-end delay in D-DBR. An increased throughput.	EE-DBR is good for energy sensitive applications. D-DBR is good for delay sensitive applications.
Data Gathering	BUTM-DCS [3] BDM-DCS	Theory of DCS is utilized to do compression in underwater sensor networks.	Computationally Extensive. No comparison is done with already existing underwater routing protocols.	Reduced communication cost. Prolong network lifetime.	Effectively utilized the TWSNs technique in UWSNs.
	AUV-CH [7] AUV-PN	Non traditional movement of AUVs. Two channels for commu- -nication of AUVs.	Computational overhead inv- -olved Do not say anything about throughput.	Balanced energy consumption. Network lifetime improvement. Efficient energy utilization.	Proposed scheme can be used for the energy sensitive applications.
Energy Efficiency	EEDBR [5]	A depth based routing protocol, ensures efficient energy utilization.	Computationally extensive algorithm. End-to-end delay is imp- -roved atx the cost of repetend transmissions.	Improved network lifetime as compared to DBR. Low end-to-end delay.	A benchmark for UWSNs routing protocols.
	Co-UWSN [22]	Diversity techniques are used to combat fading.	End-to-end delay is decreased at the cost of time lag.	High throughput. Reliable. Energy efficient.	Co-UWSN beats the EEDBR and iAMCTD in low end-to-end delay, high throughput and low transmission loss.
Energy Blancing	BTM [8]	Construction of routing tree. Direct and hop-by-hop mode of communication.	Unnecessary long distance direct communication comp- -romises on network lifetime	Energy balancing is achieved	An initiative in UWSNs to- wards balanced energy co- nsumption in the network
	GSTEB [9]	Construction of routing tree. Direct and hop-by-hop mode of communication	Computationally extensive. long distance direct commu- -nication compromises on network lifetime.	Energy balancing is achieved.	Updation of parent node in each round results into en- -ergy balancing in the network.
	FAF-EBRP [23]	Controlled communication. range Weight of edge and comm- unication link is introduced.	Low throughput. Computationally extensive.	Energy balancing is achieved in the network.	Energy balancing is achieved with the help of sponta- neous reconstruction of forwarding path.

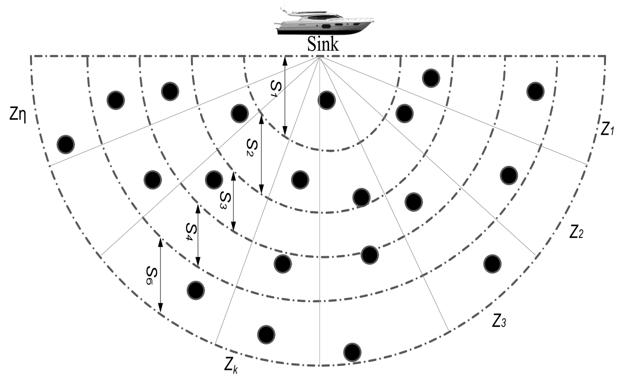


FIGURE 2. System model of BEAR.

will have to be placed at different depths on the same vertical line" [26].

- $S_1, S_2, ...S_\partial$ are the concentric semicircles each of radius r, where $r \leq$ optimum transmission range ($r_{opt\_TxRange}$).
- Sensor nodes are stationary and energy constrained. In fact, the nodes are anchored in the ocean such that only horizontal movement is significant. However, during horizontal movement the depth of sensors is unchanged. Therefore, we simulate the protocol operations with static nodes.
- Each node can adjust its transmission power level according to the mode of transmission, i.e., direct and multihop. The power levels, for direct and multihop modes, vary according to distance between sender and receiver.
- One single sink of network is placed at the centre of the semicircle.
- Lifetime of the network is calculated in terms of rounds. The round has the same meaning as mentioned among the other protocols [4], [5], [8], etc. Round is not a real time measurement unit, but it is a period in which sink receives data packets from all nodes, one from each node.

B. ENERGY MODEL

Energy consumption (E_n) by a node n, is calculated in two parts as given in Eq. (1),

$$E_n = E_{n-tx} + E_{n-rx}. \tag{1}$$

When a node transmits an 'l' bit data packet over distance 'x', it consumes E_{n-tx} given by Eq. (2) as follows,

$$E_{n-tx} = lP_0 x^k a^x. \tag{2}$$

On receiving a transmitted packet, a node consumes E_{n-rx} given by Eq. (3),

$$E_{n-rx} = lP_r. \tag{3}$$

C. PROBLEM FORMULATION

Let T be the network lifetime. In entire T, H_n and D_n denote the total number of hop by hop and the total number of direct

TABLE 2. Nomenclature.

Notation	Definition
BN	Broadcast node
BI	Broadcast initiator
P_0	Reference power level
λ	$(\frac{\pi\times\theta}{360})\times(r_{opt\_TxRange})^2$
a	Absorption coefficient [15]
RE_i	Residual energy of a node
k	Energy spreading factor [15]
$C(S_j)$	Total no of nodes in Sector j
ρ	Node density in the network
∂	Set of sectors $\{S_j\}$, $1 \le j \le \partial$
NPS	Total number of Nodes Per Sector
Th_Value	Threshold value for $inter - SEB$
η	Total number of cones in the network
Q	Total number of nodes in the network
Q_{ij}	Cost function value of node j w.r.t node i
$N_{Z_{jk}}$	Total number of nodes in zone$k$ of sector j
ξ	Total number of packets forwarded by a zone
P_r	Constant parameter depends on receiver device
A_{Z_x}	Area of the cone with distance x from sink, see Fig. 5.
A_{Z_y}	Area of the cone with distance y from sink, see Fig. 5.
N_{Z_x}	Total number of nodes in a zone, x distance apart from sink
S_n	Total number of hop by hop transmission towards successor node
F_n	Total number of hop by hop transmission towards facilitating node
E_{S_j}	Energy consumed by Sector j nodes
$E_{S_{j+1}}$	Energy consumed by Sector j+1 nodes
E_{n-rx}	Energy consumed by a node during reception
E_{n-tx}	Energy consumed by a node during transmission
E_{etx_rt}	Energy consumed by a node to receive one packet
E_{etx_dt}	Energy consumed by a node to send one packet towards sink
E_{etx_st}	Energy consumed by a node to send one packet towards its successor
E_{etx_ht}	Energy consumed by a node to send one packet at distance $r_{opt\_TxRange}$
E_{etx_ft}	Energy consumed by a node to send one packet towards its facilitating node

transmission by a given node, respectively. R_n denotes the total number of receptions by a node in T.

$$E_{n-rx} = R_n E_{etx\_rt}. \tag{4}$$

$$E_{n-tx} = D_n E_{etx\_dt} + H_n E_{etx\_ht}. \tag{5}$$

Where, $H_n = F_n + S_n$.

$$E_n = D_n E_{etx\_dt} + F_n E_{etx\_ft} + S_n E_{etx\_st} + R_n E_{etx\_rt}. \tag{6}$$

For calculation of energy please refer to Section III-B.

$$\begin{cases} min & (\sum_{S_j \in \partial} \sum_{i=1}^{C(S_j)} E_{ij}). \\ s.t. & E_{S_j} \approx E_{S_{j+1}} \\ & E_{ij} \le E_0. \end{cases} \tag{7}$$

Where, each variable is defined in Table 2.

The aim of Eq. (7) is to minimize the transmission energy consumption of the network. While constraints guarantee that during energy minimization, overall energy consumption in each sector of the network remains balanced. Based on above model, problems can be defined as:

- How to balance energy consumption between the nodes of a sector? We refer to this problem as $intra - SEB$.
- How to balance energy consumption of the sectors, adjacent to each other? We name this problem as $inter - SEB$.
- What is the optimal threshold value of $inter - SEB$?
- How to maintain network connectivity for a longer period of time subject to conditions stated above.

IV. FEASIBLE SOLUTION

In this section, we discuss the solution and checks its feasibility.

A. INTRA SECTOR ENERGY BALANCING

Nodes that belong to the same sector have the same transmission distribution ratio (P_j), as described in Section V. All nodes have the same data generation rate, regardless of their deployment sectors. So, within a sector, imbalanced energy consumption is a clear consequence of, uneven distribution of incoming traffic load. This phenomenon is more prominent in sectors near the sink. If we are able to distribute the incoming traffic evenly then we can achieve the even energy consumption between the nodes of a sector.

For $intra - SEB$, network field is divided into cones as shown in Fig. 2. A small portion of sector S_j which belongs to a cone k ($1 \le k \le \eta$) is called zone (Z_{jk}). Nodes in sector S_j, forward the data packet to the successor or facilitating node (Detailed discussion on successor and facilitating node is given in Section 5) in sector S_{j-1} belong to the same zone. This zone-to-zone (Z_{jk} to Z_{j-1k}) communication, from source sector to the destination sector, distributes the traffic load evenly in the destination sector.

B. AREA OF ZONE

According to the Section 5, node n in zone Z_{jk} chooses its successor and facilitating nodes from zone Z_{j-1k}. So, the area of the zone must not be too small, otherwise, node n can not select its successor and facilitating nodes. At the same time area must not be too large because it imbalanced the energy consumption among the network nodes.

$$N_{Z_x} \ge 2. \tag{8}$$

$$N_{Z_x} = A_{Z_x} \times \rho. \tag{9}$$

$$N_{Z_x} = \frac{\theta}{360}(\pi x^2)\rho. \tag{10}$$

Where, $A_{Z_x} = \frac{\theta}{360}(\pi x^2)$, as shown in Fig. 5. Now Eq. (8) becomes,

$$\frac{\theta}{360}(\pi x^2)\rho \ge 2. \tag{11}$$

$$\theta \ge \frac{2 \times 360}{\pi x^2 \rho}. \tag{12}$$

To balance the $intra - SEB$, total number of cones in the network are $\eta = \frac{180}{\theta}$.

C. INTER SECTOR ENERGY BALANCING

Towards the relative direction of the sink, the load on the nodes in each respective sector increases. As described in Section 5, to balance the energy consumption among nodes of adjacent sectors, an adaptive threshold value is set which is given in Eq. (13),

$$Th\_Value = \frac{1}{Tn}\sum_{i=1}^{Tn} RE_i. \tag{13}$$

Th_Value is a measure of average residual energy of the network. With each transmission, nodes' residual energy changes. So, Th_Value value is updated after each round. Every node compares the residual energy of its successor

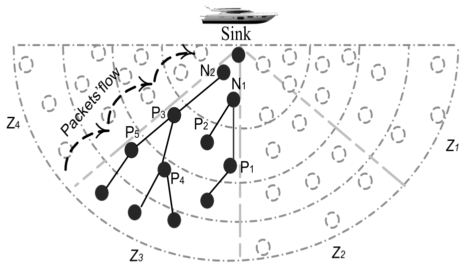


FIGURE 3. Load estimation with respect to predecessor nodes.

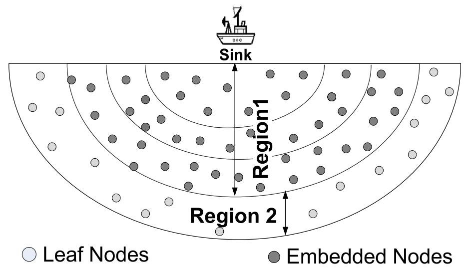


FIGURE 4. Network division on the basis of nodes.

and facilitating node with *Th_Value* and data packet is sent towards the node whose residual energy is greater than the *Th_Value*. Thus the incoming traffic is diverted from the sector where nodes' residual energy is less than the average residual energy of the network. This conditional routing leads to balanced energy consumption among sector.

D. LOAD ESTIMATION

Definition: Load on a node in the network is defined as the total number of data packets it forwards during one round. Estimation of traffic load on a node depends upon two parameters:

1) Location of the node in the network, and
2) Number of predecessors of the node

It is a perception that greater is the number of predecessors of a node, greater is the forwarding load on it. However, estimation of forwarding load, based on only the predecessors' information, is quite misleading.

In Fig. 3, node N_1 has two predecessors p_1 and p_2 and node N_2 has only one predecessor p_3. Hence, on average, node N_1 should forward more packets per round than node N_2. But actually it is not the case. Node N_2 transmits 7 packet per round while node N_1 transmits 4 packets per round as shown in the Fig. 3. For load estimation of a node, its predecessors' information is not sufficient. The information required for the estimation of traffic load on a node consists of, location of the node in the network and the total number of nodes connected in the branch the current node is leading.

On the basis of incoming and outgoing traffic on a node, network field is divided into two regions, as shown in Fig. 4.

1) REGION 1

This region of the network consists number of sectors from S_1 to $S_{\partial-1}$. Region 1 nodes perform two tasks:

- Transmit their sensed data to nearby sink nodes, and
- Relay the sensed data of high depth nodes towards the sink.

Nodes in this region are called embedded nodes.

2) REGION 2

The outermost semicircle $S_j = S_\partial$ of the network lies in this region. Nodes in this region are responsible to transmit their sensed data only. These nodes are called leaf nodes.

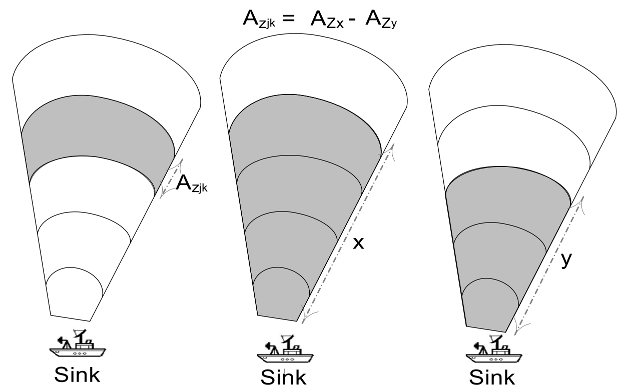


FIGURE 5. Area of a zone.

Lemma 1: If β^* is the estimated load per node in a given round, then:

$$\beta^* = \begin{cases} \frac{(j-1)^2-(\partial)^2}{j^2-(j-1)^2} & S_1 \le S_j \le S_{\partial-1} \\ 1 & S_j = S_\partial \end{cases} \tag{14}$$

Proof: In region 1, Z_{jk} is responsible for the zones, $Z_{\partial k}$, $Z_{\partial-1k}$, $Z_{\partial-2k}, \ldots, Z_{j-1k}$ and Z_{jk}, to relay their data packets towards the sink.

Let β is given by following equation.

$$\beta^* = \frac{\xi}{N_{Z_{jk}}}. \tag{15}$$

$$\xi = \sum_{i=j}^{\partial} N_{Z_{ik}}. \tag{16}$$

Using Eq. (9), we can rewrite the Eq. (16) as follow,

$$\xi = \sum_{i=j}^{\partial} A_{Z_{ik}} \rho. \tag{17}$$

$$A_{Z_{jk}} = A_{Z_x} - A_{Z_y}. \tag{18}$$

According to Section 4, Eq. (18) can be written as,

$$A_{Z_{jk}} = \frac{\theta}{360}\pi x^2 - \frac{\theta}{360}\pi y^2.$$

$$A_{Z_{jk}} = (\frac{\theta}{360})\pi(x^2 - y^2).$$

If $x = jr_{opt\_TxRange}$ and $y = (j-1)r_{opt\_TxRange}$, as depicted in Fig. 6.

$$Then\ x^2 - y^2 = (jr_{opt\_TxRange})^2 - ((j-1)r_{opt\_TxRange})^2.$$

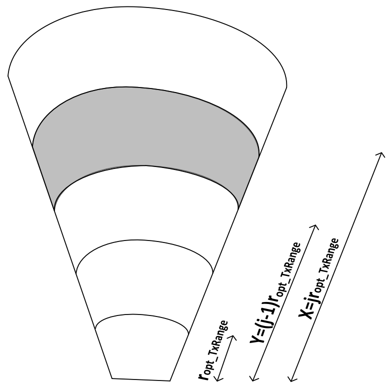


FIGURE 6. Values of x and y for the calculation of area of a zone.

$$x^2 - y^2 = (r_{opt\_TxRange})^2((j)^2 - (j-1)^2).$$
$$A_{Z_{jk}} = (\frac{\theta}{360})\pi(r_{opt\_TxRange})^2(j^2 - (j-1)^2).$$
$$A_{Z_{jk}} = \lambda \times (j^2 - (j-1)^2). \quad (19)$$
$$N_{Z_{jk}} = \lambda \times (j^2 - (j-1)^2) \times \rho. \quad (20)$$

Now Eq. (16) looks like this,

$$\xi = [(\lambda \times (j^2 - (j-1)^2) + \lambda \times ((j+1)^2 - (j)^2) + ... + \lambda \times ((\partial - 1)^2 - (\partial - 2)^2) + +\lambda \times ((\partial)^2 - (\partial - 1)^2))] \times \rho. \quad (21)$$
$$\xi = \lambda \times ((j-1)^2 - (\partial)^2) \times \rho. \quad (22)$$

Hence, it is proved that Eq. (16) can be rewritten as,

$$\beta^* = \frac{\lambda \times\ (j-1)^2 - \partial^2 \times \rho}{\lambda \times j^2 - (j-1)^2 \times \rho}.$$
$$\beta^* = \frac{(j-1)^2 - \partial^2}{j^2 - (j-1)^2}.$$

V. BEAR: THE PROPOSED TECHNIQUE

The proposed BEAR protocol operates in three phases; initialization phase, tree construction phase and data transmission phase, as shown in Fig. 9.

Details are as follows:

A. INITIALIZATION PHASE

In initialization phase, sink broadcasts a packet to all nodes in the network to inform them of total number of nodes in the network and start and end time of the phase. In this phase, all nodes calculate their:

- Relative location,
- Relative distance from the sink, and
- Identify the sector, node is located in.

B. TREE CONSTRUCTION PHASE

Tree construction phase is completed in two steps. In step one all nodes search for their neighbour nodes (ref. algorithm 1). In step two, each node chooses its successor and facilitating node from its neighbours nodes.

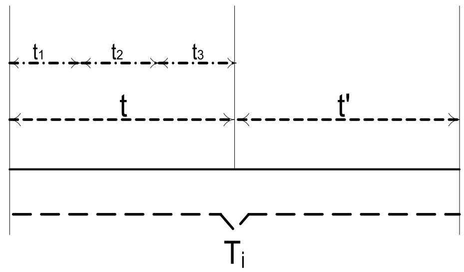


FIGURE 7. Time slot of 4-way handshake for *i*th node.

1) NEIGHBOUR FINDING

In this phase, each node searches for the lower depth nodes within sector to establish its root towards sink. Each node is allotted a time slot by the sink for communication as shown in Fig. 7. Each time slot T_i is further divided into 2 segments. One segment has a maximum length that equals 4-way handshake as shown in the Fig. 10. Since the node deployment is random, a node may not have neighbour(s). In such situations, node uses the second time slot for neighbour discovery. The complete process is shown in Fig. 10(b).

Algorithm 1 Neighbour Finding in BEAR

```
input : Q,NPS,∂
output: Successor and facilitating nodes for each node
Start1=(length(Q)-NPS)+1;
Stop1=length(Q);
for ii ← 2 to ∂-1 do
    Start2=Start1-NPS;
    Stop2=Start1-1;
    for i ← Start1 to Stop1 do
        index=0;
        for j ← Start2 to Stop2 do
            D(i,j) ← Find distance b/w node i and j
            according to euclidian distance formula;
            if D(i,j) <= r_opt_TxRange then
                Neighbour(index) ← j;
                index=index+1;
        Start2=Start1-NPS;
        Stop2=Start1-1;
```

Case 1: In 4-way handshake node i of sector S_j broadcasts its Hello packet within $r_{opt-TxRange}$. Nodes within the transmission range, respond with ACK1 packet. Node i can only select neighbors from its next hop sector S_{j-1} which is at lower depth than itself, (see Fig. 8(a)). After receiving ACK1, *ith* node broadcasts neighbour request towards nodes that have previously replied with ACK1, i.e., S_{j-1} nodes. Only intended nodes accept the incoming requests and acknowledge with ACK2 packet while recording the ID of the node i in their respective predecessor field. On reception of ACK2, node i stores the IDs of the neighbour nodes that respond

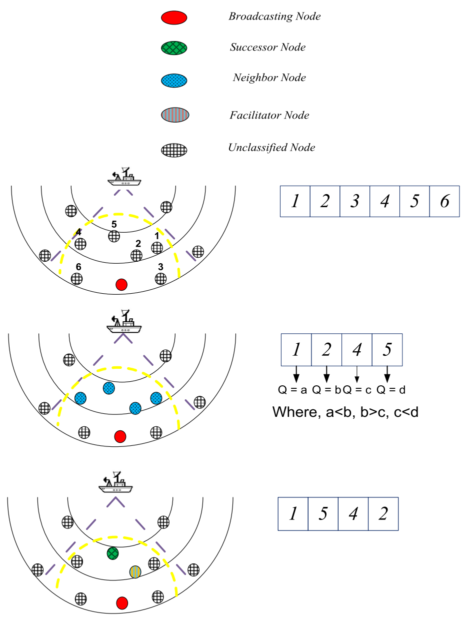


FIGURE 8. Tree construction phase.

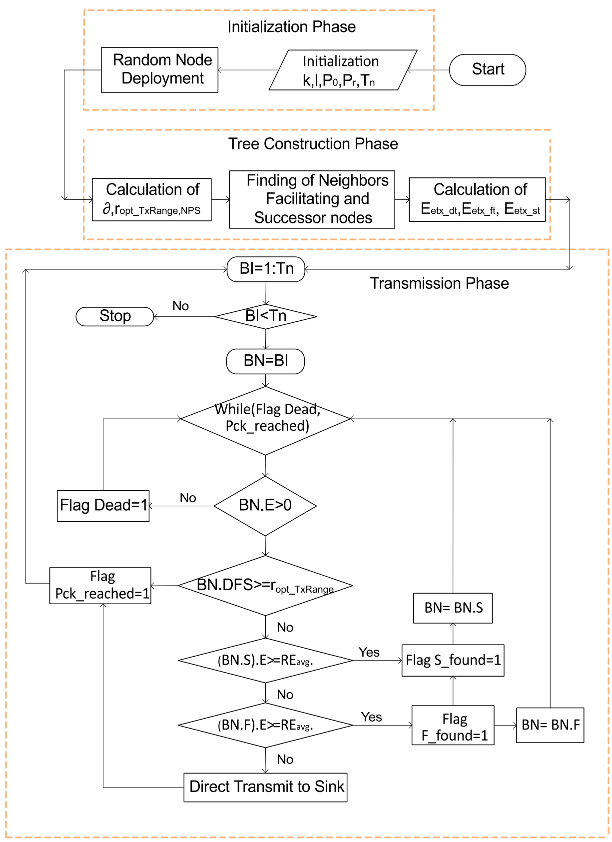


FIGURE 9. BEAR: work flow.

with ACK2 and further intimates the sink after successful handshake. Fig. 11 shows the structure of packets used in 4-way handshake. A 4-way handshake is shown in Fig. 10(a).

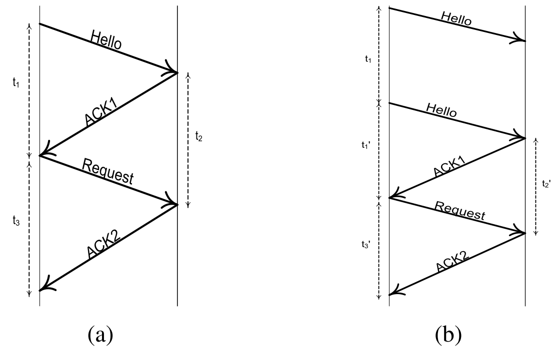


FIGURE 10. Neighbour finding phase of BEAR. (a) Packets dropped. (b) Packets received.

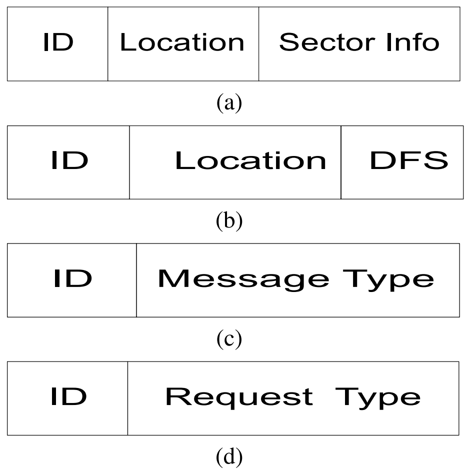


FIGURE 11. Packets formats exchanged during 4-way handshake. (a) Hello packet format. (b) ACK1 packet format. (c) ACK2 packet format. (d) Neighbour request packet.

Case 2: It is similar to the case 1 as shown in Fig. 10(b) except that after a given time t_1 if node i does not receive ACK1, it retransmits the Hello packet with increased transmission range. In the case of successful handshake, on the expiration of time T_i, tree construction phase moves to the next node.

2) SEARCH FOR ENERGY EFFICIENT PATH

In BEAR, communication is governed by the successors and facilitating nodes. So the task is to select the successor nodes and the facilitating nodes in such a way that if a source node transmits the data packet toward its successor node or the facilitating node it consumes minimum possible energy in this transmission. If Q_{ij} is the cost function when node i communicate with node j, then:

$$Q_{ij} = \alpha \times d(i,j) + (1-\alpha) \times d(j, sink) \quad (23)$$

Where $d(i,j)$ is the distance between node i and node j, and $d(j, sink)$ is the distance between node j and sink. The broadcasting node calculate the cost function value for its neighbor nodes. Once the node i is done with calculating the cost function value, these values are sorted in ascending order, such that node id corresponding to the first value is selected as successor node and node id corresponding to the second value is selected as facilitating node. This procedure is shown in Fig. 8(b) and its pseudo code is shown in algorithm 2.

Algorithm 2 Search for Successor and Facilitating Node in BEAR

---

input : Q, NPS, ∂
output: Successor and facilitating nodes for each node

for $i \leftarrow 1$ **to** T_n **do**
  for $j \leftarrow 1$ **to** $length(neighbour(i))$ **do**
    $D(i, j) \leftarrow$ Find distance b/w node i and j *according to euclidian distance formula*;
    $D(j, sink) \leftarrow$ Find distance b/w node j and *sink* *according to euclidian distance formula*;
    $Q_{i,j} \leftarrow$ Find cost function value *according to Eq. (23)*;
  cost_function(j) $\longleftarrow Q_{i,j}$;
  Sort the cost_function(j) in ascending order as shown in the Fig. 12(c);
  Successor_node(i) $\longleftarrow$ *cost_function*(1);
  Facilitaing_node(i) $\longleftarrow$ *cost_function*(2);

C. TRANSMISSION PHASE

In each round, the broadcasting node checks its distance from the sink, if it is less than the $r_{opt\_TxRange}$ it directly transmits the packet towards the sink. If above condition is not satisfied then node will check the residual energy of its successor node if its energy is greater than the average residual energy of the network then packet is transmitted towards successor. If second check fails, then broadcast node check the residual energy of its facilitating node and if the condition is met then data packet is transmitted towards the facilitating node. Otherwise, the broadcast node directly communicates with sink.

VI. SIMULATIONS AND RESULTS

In the simulations, we have compared our proposed protocol with two recent existing protocols: [20] and [21]. These two protocols are chosen due to close resemblance in terms of network topology and protocol operations. Please, note that the work in [21] is for terrestrial sensor networks. For fair comparison, we have implemented the protocol operations of [21] in underwater using acoustic technology. There are other alternatives for comparison, however, these are not as close as [20] and [21] are. Therefore, we avoid comparing our proposed protocol with other alternatives. Simulations are conducted in two scenarios: (i) 80 nodes are randomly deployed in a network of radius 0.2km-1km, and (ii) 160 nodes are randomly deployed in a network of radius 1km-5km. In scenario 1 and scenario 2, the initial energy of each node is 0.5J and 10J, respectively. We use the parameters of the Physical and MAC layers of [20] (the values used in

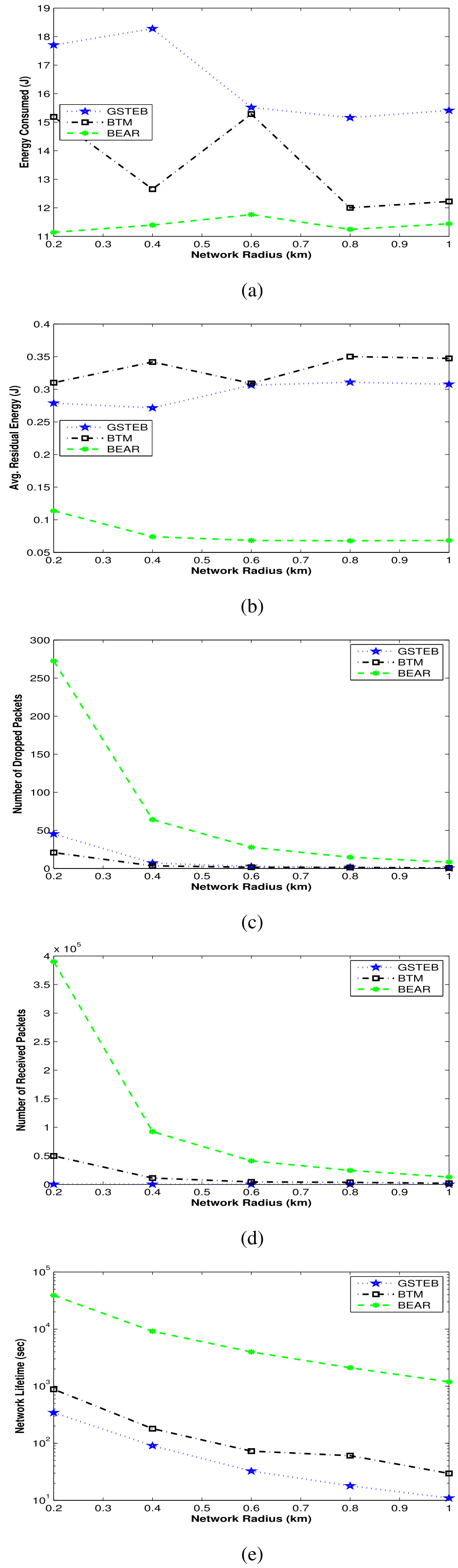


FIGURE 12. Simulation results for 0.2*Km* - 1*Km* network radius. (a) Energy consumption. (b) Average residual energy. (c) Packets dropped. (d) Packets received. (e) Network lifetime.

simulations for transmit power level, operating frequency, spreading loss coefficient, etc. are given in Table 3. For

TABLE 3. Parameters configuration.

Scenario-1	No of Nodes Initial Energy Radius of Network	80 0.5J 0.2-1 km
Scenario-2	No of Nodes Initial Energy Radius of Network	160 10J 1-5 km
Scenario-1 and Scenario-2	P_r P_0 α Frequency Spreading Factor	$0.2 \times 10^{-}4J/bit$ $1 \times 10^{-}4\ J/bit$ 0.7 10 kHz 2

throughput calculation, we use the *Random Uniform* packet drop model of [28]).

Fig. 12(a) and Fig. 12(b) show that BEAR performs better than the other protocols in term of energy consumption. The reason behind this improved performance of the BEAR is the proposed traffic balancing mechanism, for $inter - SEB$ and $intra - SEB$. Moreover, average residual energy of the network is set as threshold, which keeps track of energy consumption between sectors and diverts the traffic from the sector whose energy is less than the average residual energy of the network. BTM balances the energy consumption among the network nodes by long haul direct transmission(s). As a consequence, the network lifetime is reduced. GSTEB diverts the traffic load towards the highest power nodes for load balancing, however, it fails in term of load distribution. As a result, nodes near the sink receive higher traffic load. When the first node in the network dies, a large amount of residual energy still as evident from Fig. 12(b) and Fig. 13(b). In Fig. 14(a) and Fig. 14(b), all sectors of the network have almost same residual energy. This result validates effectiveness of our proposed scheme in term of balanced energy consumption.

Fig. 12(e) shows the average network lifetime for small radius network while Fig. 13(e) plots the average lifetime of the network vs large network radius. In both scenarios BEAR outperforms. To increase the network lifetime BEAR works on hop by hop mode for initial period, afterwards it starts transmitting on direct mode too. while its contenders use both the modes throughout the communication process.

Maximum lifetime in Fig. 12(e) and Fig. 13(e) is an evidence that we have achieved our goal of efficient energy utilization. BEAR consumes less energy per round as compared to the BTM and GSTEB. GSTEB has the most energy consumed. Consumed energy graphs are plotted in Fig. 12(a) and Fig. 13(a). To reduced the energy consumption, BEAR avoids long distance transmissions by using the concept of successor nodes and facilitating nodes. BEAR first tries to send data to the successor node. If successor nodes do not fulfill the criteria, then it checks the facilitating nodes (that are within the transmission distance of the node). BEAR transmits data over a longer distance only when it has exploited all its choices.

Fig. 12(c) and Fig. 13(c) compares the packet drop for all three protocols against different network radii. When the nodes, two or more hop away from the sink, transmit the

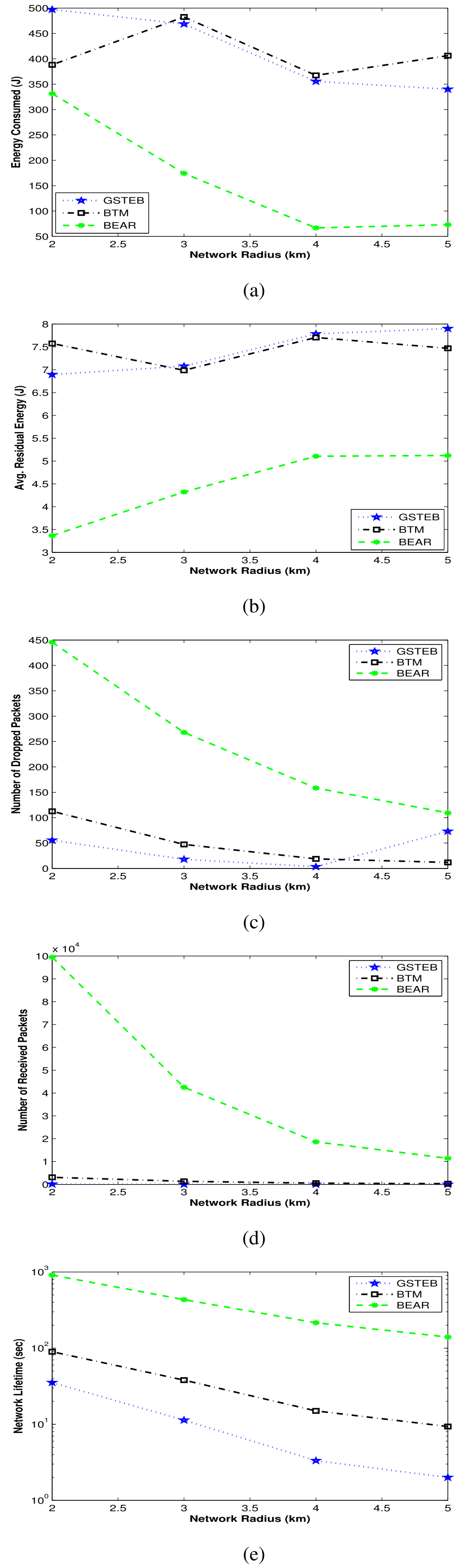
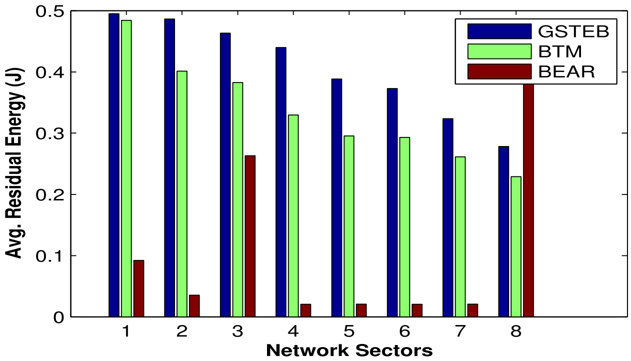
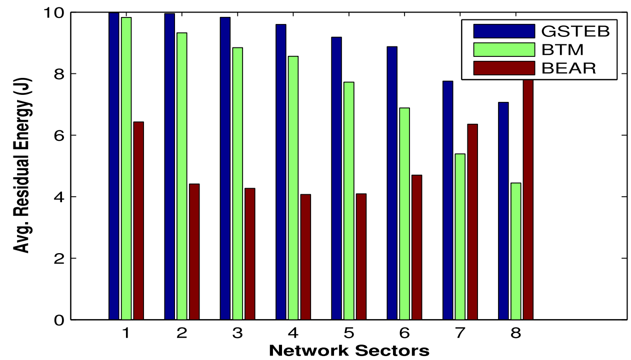


FIGURE 13. Simulation results for 2*Km* - 5*Km* network radius. (a) Energy consumption. (b) Average residual energy. (c) Packets dropped. (d) Packets received. (e) Network lifetime.

data packets directly toward the sink, the packets are not able to reach the sink. As sink is far away from the optimum



(a)



(b)

FIGURE 14. Energy consumption in different sectors of the network. (a) Energy balancing in 1*km* network radius. (b) Energy balancing in 5*km* network radius.

TABLE 4. Performance trade-offs made by the analyzed routing protocols.

Protocol	Achievements	Reference	Price to Pay	Reference
BEAR	Improved Network Lifetime	Fig.14 (e) Fig.15 (e)	Increased Energy Consumption	Fig.14 (a) Fig.15 (a)
	Balanced Energy Consumption	Fig.16 (a) Fig.16 (b)	Increased number of Packet Dropped	Fig.14 (c) Fig.15 (c)
	Efficient Energy Utilization	Fig.14 (a) Fig.15 (a)	Minimum Average Residual Energy	Fig.14 (b) Fig.15 (b)
BTM	Balanced Energy Consumption	Fig.16 (a) Fig.16 (b)	Increased number of Packet Dropped	Fig.14 (c) Fig.15 (c)
GSTEB	Balanced Energy Consumption	Fig.16 (a) Fig.16 (b)	Increased number of Packet Dropped	Fig.14 (c) Fig.15 (c)

transmission range of these nodes. So, these packets dropped somewhere in the network. In BEAR, packet drop is zero at the start of the network, due to the hop by hop communication at shorter distances. With the passage of time, residual energy of each node becomes lower than the average residual energy of the network, such that BEAR allows nodes to communicate directly with the sink leading to increase in the number of packets being dropped. This increased number of dropped packets is also due to its prolonged network lifetime. Due to low energy consumption, the nodes stay alive for longer period of time resulting in higher network throughput as shown in Fig. 12(d) and Fig. 13(d). In BTM and GSTEB, from the start of the network life the sensing nodes switch frequently from hop by hop mode to direct transmission mode. When hop by hop mode is adopted packet drop decreases and when nodes start direct transmission packet drop increases. In BEAR nodes will remain alive for longer period of the time as compared to BTM and GSTEB. Due to efficient and balanced energy consumption, death rate of the nodes of BEAR is lowest compared to BTM and GSTEB. To sum up, Table 4 shows the performance trade-offs made by the analyzed routing protocols.

VII. CONCLUSION

Efficient energy utilization and balanced energy consumption in the network prolonged the network lifetime. For a fixed transmission distance, direct mode of communication consumed more energy as compared to the multihop mode of communication. Subject to these investigations, we have proposed BEAR, an adaptive routing protocol. BEAR exploits the location information, selects the neighbours, chooses the facilitating and successor nodes based on cost function value and, finally selects the forwarder node, one having residual energy more than the average residual energy of the network. The simulation results demonstrated that BEAR improved the network lifetime by approximately 55%.

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