A PROACTIVE GREEDY ROUTING PROTOCOL PRECLUDES SINK-HOLE FORMATION IN WIRELESS SENSOR NETWORKS

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ABSTRACT

A tree topology is a commonly employed topology for wireless sensor networks (WSN) to connect sensors to one or more remote gateways. In many-to-one traffic, routing imposes a heavy burden on downstream nodes, as the same routes are repeatedly used for packet forwarding from one or more sensor chains. The challenge is traffic paths that ensure balanced energy consumption at sink-hole to protect sensors from fast death. This paper proposes an energy consumption pattern-aware greedy routing protocol that proactively protects many-to-one topology from the sink-hole formation. The proposed protocol, Energy Balance-Based Energy Hole Alleviation in Tree Topology (EBEHA-T), precludes energy hole formation rather than retrospectively responding to a hole detection. Updated status of variations in energy consumption patterns at the sink-hole along with construction feature of joint nodes in the tree topology aids EBEHA-T in routing decision. Performance evaluation of EBEHA-T against benchmark method RaSMaLai shows increased energy-saving across the entire network and a marked improvement in energy consumption balance in energy hole zones. This precludes energy hole formation and the consequent network partitioning, leading to improved network lifetime beyond that of the RasMaLai.

KEYWORDS

WSN, Lifetime, Energy Hole, Tree Topology, Greedy Routing

1. INTRODUCTION

Wireless sensor nodes are energy-constrained devices that can transfer sensed data from the field to servers in remote locations. This is generally done over multi-hop networks comprising of other similar nodes. Sensor nodes that are one-hop away from their respective gateways (referred to hereinafter as deputy nodes, (DNs) are responsible for major traffic delivery to this sink node (gateway node). The energy consumption rate is proportional to the amount of the data traffic handled by sensor node; received (R_x) or transmitted (T_x). Fast energy consumption of such a node "DN" end up in fast node death that causes energy holes in the sink zone. This hole isolates the sink node from its connected network and henceforth, a short network lifetime [1][2][3]. Thus, efficient use of energy consumption and how to prolong the lifetime of the network has become the subject of much research [4][5][6][7]. A first sensor node that runs out of energy constitutes one important metric of network life [8]. The problem of fast energy consumption is addressed from different perspectives [9][10][11][12]. The authors in [13] proposed cooperative routing to minimize energy consumption, particularly at the sink zone. In [14], an associative header is a cluster member with the highest energy that replaces the cluster head when an energy hole is detected. The study in [15] presented On-Hole Children Reconnection (OHCR) and On-Hole Alert (OHA) in a tree topology. In this study, the number of interconnected child nodes is identified as a factor influencing the energy consumption pattern in the network.

In recent years, balanced energy consumption over the network has been identified as one of the promising solutions to extend the network lifetime [16][17] [18]. The study [11] proposed is energy-aware balanced energy consumption and hole alleviating algorithm (BECHA). Its strategy is to balance load distribution among nodes of minimum and maximum energy consumption. The studies [11][19][20][21] are routing protocols targeted at fair energy consumption to alleviate hole formation. Their selection of relaying nodes was based on maximum residual energy, maximum load, least hop count, and optimum distance.

However, the certainty of the shortest distance, as well as the high residual energy of candidate next-node-based routing protocol does not necessarily guarantee balanced energy consumption at the sink zone. In addition to that, a lack of study that consider the correlation between energy balance-based traffic routing and the drawbacks of many-to-one long-distance communications.

In this paper, we propose Energy Balance-Based Energy Hole Alleviation in tree topology (EBEHA-T) routing protocol that addresses these gaps in a way that has not been previously considered. It precludes energy sink-hole formation through traffic forwarding management that balances energy consumption among hols nodes. It is a greedy routing protocol that selects its next-hop relaying nodes in such a way that ensures proactive protection against large variation in energy consumption at sink-holes. The proposed metric-based the candidates for next-node combines the updates of energy consumption pattern at sink zone and significant construction features of the tree topology; such as hop count and joint nodes, that influence energy consumption behaviour. Extensive simulations using Omnet++ have been carried out to validate the performance of EBEHA-T. The rest of this paper is organized as follows: Section 2 discusses previous works for energy hole in WSN.

A taxonomy of major remedies that tackled sink-energy hole alleviation based routing protocol in WSN are descriped in Section 2. Theoretical analysis for tree topology in WSN and Traffic Routings and inefficiency in energy consumption are discussed in Section 3. Node association manners to tree topology and its impact on energy consumption patterns in critical zones are analyzed in Section 4 Description of our proposed work and discussion of simulation results are presented in Section 5 and 6, respectively. Finally, the conclusion and future direction of the research are given in Section 7.

2. RELATED WORKS

This section discusses previous works that tackled the problem of energy hole alleviation in WSN. Figure 1 illustrates a taxonomy of major remedies proposed by several researchers; topology control, node deployment, traffic routing, and hybrid mechanisms. The topology control is classified into power control and power management [22][23]. One of the Power control studies was Dynamic re-adjustment of transmission power by sensor nodes where neighbour nodes association, and subsequently network connectivity and coverage of node are affected. The node deployment is another strategy for hole alleviation classified into; sensor node distribution, sink mobility, and multiple sinks [24][25][26]. The study in [14] proposed dividing the network into hierarchical circles where the inner ones decrease gradually in size as they get closer to the sink nodes. Each layer is divided into sectors each with a header node to accumulate data. One of the important remedies is routing protocols that address the problem of non-fair energy consumption in critical zones. These protocols are classified into heuristic routing and greedy routing as in [27][28]. The heuristic routing is based on a function estimate cost of routing paths from the source node to destination node. The heuristic value changes are infrequently occurring because most sensor nodes are statics and adjust routes, particularly when unpredictable topological changes occur. Little overhead is introduced by the transmission of heuristic value. The authors in [29] proposed a Heuristic Load Distribution algorithm (HeLD) multipath routing to achieve equal energy consumption rate among nodes of the same depth which subsequently saves the cost of transmission. A sensor node compares its parents in a pairwise manner and switch to other parents if the cost of the route of current parent is higher than the others. Traffic flow is controlled by a central agent with full knowledge of the network topology. On the other hand, the greedy routing; which is the focus of this study, is based on the selection of a candidate neighbor node in the path to the destination. Common key criteria based on the next node election are node position, hop count and node energy [28][30][31]. The authors in [32] proposed Adaptive Greedy-Compass Energy-Aware Multipath (AGEM) which gives a score to each one-hop neighbor and selects a set with smallest angular offset from a virtual line toward the destination. This set of neighbors ensures multiple paths from a source node. The routing decisions are performed based on limited and localized knowledge of the network. A packet with the smallest number of hops is forwarded through the neighbor nodes with higher energy consumption and vice versa where a packet with the highest number of hops is forwarded through neighbor nodes with the lowest energy consumption. Multipath capabilities ensure uniform energy consumption and meets the delay and packet loss constraint. The algorithm confirms the occurrence of an energy a hole when it fails to find a set of neighbors, it accordingly forwards the responsibility to the neighbors nearer to the source node. The paper in [33]proposed a supervisory routing control for dynamic load balancing. This greedy algorithm avoids the early death of relatively overloaded nodes that cause network partition. The traffic load of nodes is monitored and overloaded nodes are identified. Monitoring is done by means of in-network path tagging which is deterministic and light-weight. The ch of the overloaded node is then instructed to switch from its parent node. The instruction is sent via the Sink to the child node while acknowledge for successful switching is sent back from child to sink. The research in [34] proposed Hole Avoiding In advance Routing protocol (HAIR) where local information about one-hop neighbors is maintained. If a hole is detected by a node, then neighbors are informed by the “a hole detection” message via “push” action. Accordingly, neighbors reroute their data traffic to another parent node according to traditional geographic routing protocols where distance is considered for the selection of the next hop is the shortest distance to the destination. The paper in [35] proposed a supervisory routing control for dynamic load balancing algorithm to avoid early death of relatively overloaded nodes. The child nodes of the overloaded node are instructed to switch from their parent nodes to another downstream route. The instruction is sent via the Sink to the child node while acknowledgement for successful switching is sent back from child to sink. The study [36] proposed optimum candidate nodes selection criteria; distance to the target, link quality, density of nodes, and the priority for data transmission. Due to the mobility of the vehicular the link is prone to be lost and accordingly the node will be discarded as one of the candidate nodes. A hybrid remedies integrates a number of previously discussed mechanisms to alleviate energy holes are also introduced [38].

As a result of extensive study, reducing the variation in energy consumption pattern in hole zone to prolongs the lifetime of the network is a hot research area. In particular, proactive protection precludes energy hole formation-based greedy routing mechanism instead of energy hole detection. However, this requires analysis of tree topology to identify most significant construction features of the tree topology that affects energy behaviour pattern.

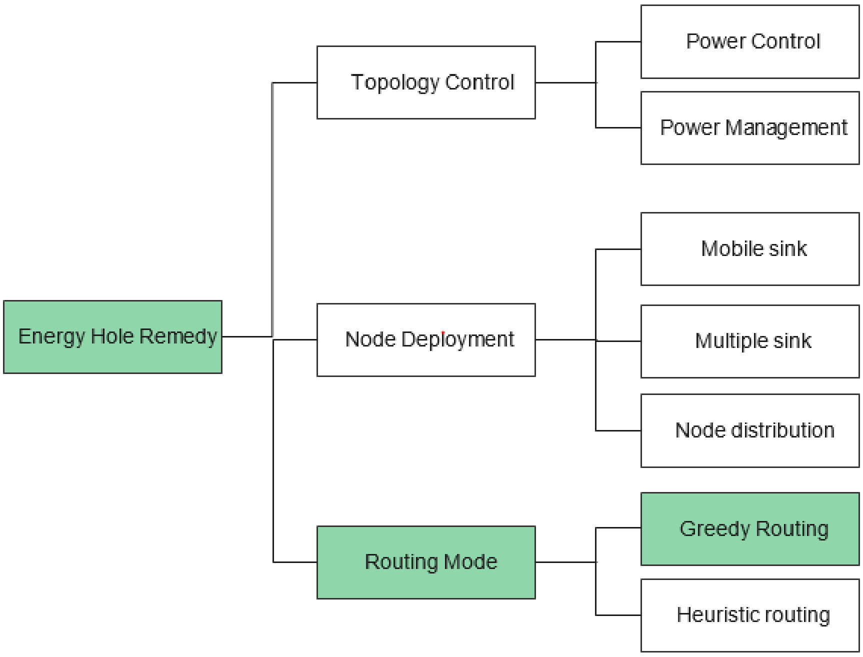


Figure 1. Sink energy hole remedies and the framework

3. THEORETICAL ANALYSIS FOR TREE TOPOLOGY

Generally, the main WSN topology studied is of type hierarchical, flat and location-based. However, the most well-known tree topology is either of type cluster or flat-based network [39]. A flat topology is when all nodes play equal roles in network formation while in hierarchical network nodes are different in their roles. Different topologies lay on the exact radio propagation model of WSN most likely consumes different amounts of energy [40]. Moreover, a previous study [41] verifies that performance in terms of average energy consumption, delay, lifetime, and coverage is topology dependent.

The tree topology is considered a promising underlying topology in WSN. Three phases are essential in a tree setting; topology construction, routing phase, and transmission phase, following the many-to-one traffic pattern in Figure 2.

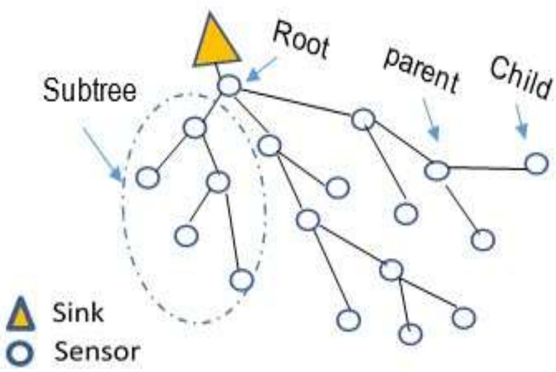


Figure 2. Tree Topology in WSN.

The sensor nodes closer to the sink consumed more energy and got their energy depleted sooner as compared with the other distant sensor nodes. Researchers have verified that 90% to 80% of nodes' energy at a higher level of a tree topology is still available by the time the sensor nodes that surround the sink node have consumed their entire energy budget [42][43]. Figure 3 illustrates that the amount of energy consumption of the sensor node is inversely proportional to its distance from the sink- node. The early death of nodes at a lower level in tree topology creates energy sink-holes and isolates descendent nodes from their sink node and prevents data from reaching their destination. Consequently, the functioning time of the network is cut short, rendering the lifetime span insufficient for accomplishing targeted tasks.

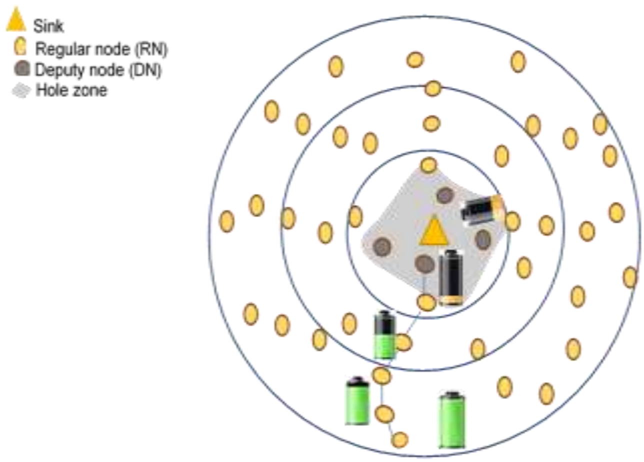


Figure 3. Energy consumption with respect to distance from the sink.

3.1. Traffic Routings and Inefficiency in Energy Consumption

As explained in Section 1, tree-based sensor networks that follow a many-to-one traffic flow pattern, are prone to energy-hole formation around the sink node, which will disconnect the network from the gateway or cause it to partition. Thus, the challenge is how to delay this phenomenon so as not to end the network prematurely. Sensor nodes with similar residual energy levels do not necessarily share the same lifespan, as the nodes may be randomly distributed in the network and the traffic intensity across the entire network may vary.

During data transmission phase, nodes that receive data packets from a number of descendent nodes is considered a node with the largest forwarding loads in its subtree. Thus, the parent nodes in tree topology are selected by considering several parameters such as remaining energy, position, hop count [27][32]. It consumes more energies than the other nodes in the subtree, raising the energy unbalance problem [44]. Several researches stated that energy consumption at a sensor node is less as long as the topology with fewer neighbour nodes is deployed, even if a longer hop-count is encountered to deliver traffic to a sink node. The heaviest energy consumption occurs at the lower level of the tree where the root nodes that deliver the entire data traffic to the sink are likely to deplete their energy soon and die relatively earlier than other nodes.

An energy-efficient routing protocol decreases the consumption of the nodes by routing data through a path with the least amount of energy consumption[45]. Auto-routing in conventional tree topology inherently causes sensor nodes in the primary path to consume high energy from repeatedly using the same path. The inefficiency in energy consumption is made worst when the data traffic traverses the same path repeatedly.

Keeping WSN alive for as long as possible is dependent upon the energy balancing among nodes in the network coupled with reducing energy consumption during network communications [46]. Reliable and energy-efficient data routing mechanisms in tree topology requires improvement in route discovery and decision making as well as end-to-end transmissions. The basic information that is required by each source node to send its packet includes destination ID, hop count, parent ID and link quality; however, the information needed varies according to the aim of the routing mechanism and should be updated synchronously with the dynamic nature of the sensor topology. Therefore, the early energy exhaustion around the sink area is a problem that needs to be addressed. Recent research in this area focuses on determining the most significant parameters that influence energy behaviour in a tree topology. However, most of the proposals are based on reactive strategies that react to energy hole detection [15][47]. In contrast, proactive-based strategies approach the problem by managing the energy-consumption pattern across the network, particularly of those in the hole zones [14][48][49].

Figure 4 illustrates the framework of our study showing topology construction, identification of critical gaps in energy consumption, and exploration of key factors contributing to energy performance enhancement in WSN.

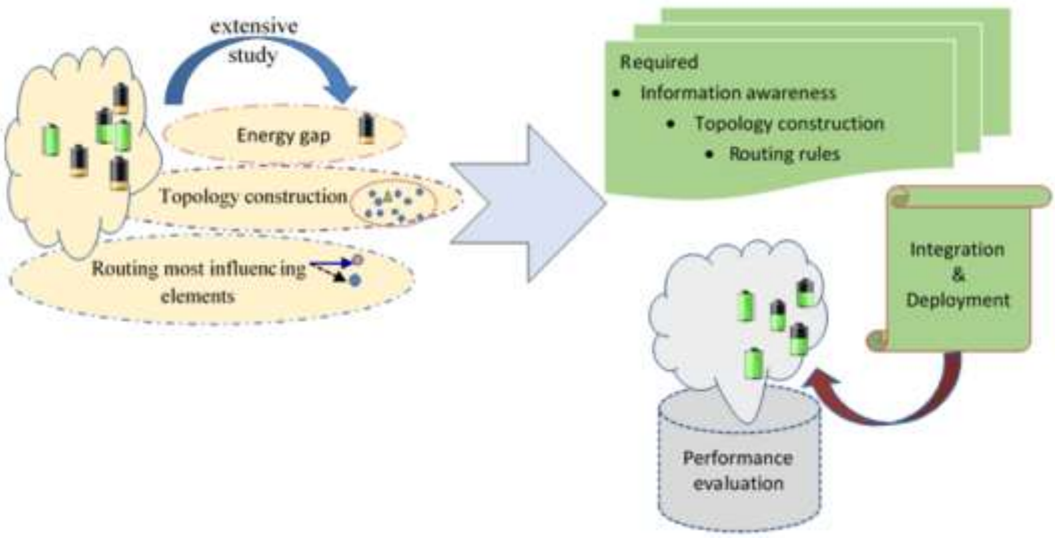


Figure 4. Model of Research Flow.

4. Energy Hole Adaptability to Tree Topology Feature

This section analyses energy consumption in energy hole zones closest to the sink nodes and the impact of different tree topology constructions. Energy consumption based on radio energy model in Figure 5 is discussed in [50].

In this paper, relaying sensor node (RN) is defined as the nodes having at least one child node or one sensor chain. As shown in Figure 6, nodes at the lower levels of a tree (closer to the sink node) which merge several upper-level branches, tend to be more prone to energy exhaustion compared with nodes at the upper levels.

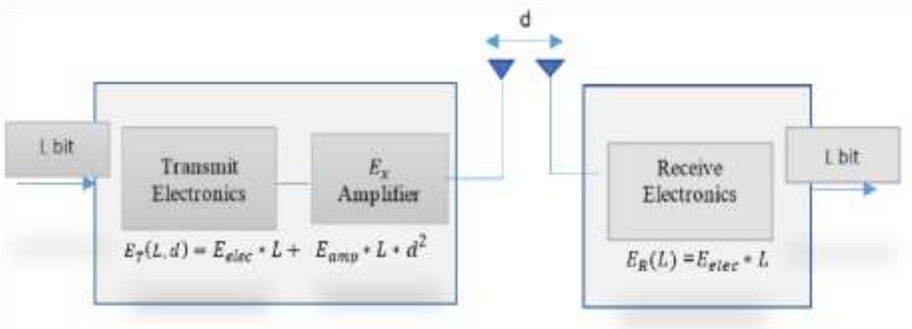


Figure 5. Basic sensor node energy dissipation model.

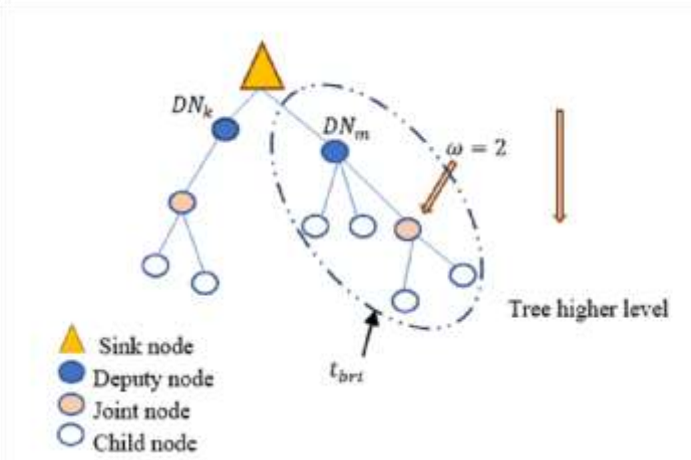


Figure 6. Tree topology of joint nodes.

An analysis is made on such joint nodes, denoted by zeta (ζ) and how the distribution of ζ impacts the diversity of variations in energy dissipation amongst all subtrees in a tree topology. A joint node is characterized by more than one child node or more than one chain of descendant nodes. The energy consumption behavior is strictly correlated to the node association manners in tree topology alongside the traffic route that satisfies the performance requirement. Energy consumption in RN associated to a subtree can be given as a function of transmission and reception of packets [51], given as follows:

$$E_{Tt_{bri}}(L,d) = \sum_{l=1}^{RN}[\, E_l^a + E_l^b] \quad (1)$$

where RN is the entire number of sensor nodes in tree topology

$$E^a = E_{consu\boldsymbol{Tx}}(\mathrm{L, d}) = E_{elec} * L + E_{amp} * L * d^2 \quad (2)$$

$$E^b = E_{consu\boldsymbol{Rx}}(\mathrm{L}) = E_{elec} * \mathrm{L} \quad (3)$$

E_{consu} is the energy consumed by a sensor node to transmit and receive data.
R_x and T_x denote the function of reception and transmission of packets, respectively.
L is the number of bits in a packet.
D is the distance between two communicating sensor nodes,
E_{amp} is the sensor node amplification energy for transmitting.

E_{elec} is the sensor node circuit energy consumption.

ζ is not the same as with relaying node (RN) in its rate of energy consumption pattern but is similar in that the amount of energy consumption is inversely proportional to its distance from the sink node. From Equation (3), the increase in energy consumption $E^{(b*)}$ to receive packets in a joint node ζ is based on the number of downstream traffic,

$$E^{b*} = \sum_{j=2}^{\omega} E_j^b \tag{4}$$

Where ω is the number of child nodes or chains of leaf nodes interconnected to joint node ζ. Hence, while the total number of nodes is fixed in a tree topology, the diversity and variations in energy consumption $E_{ConsuRx}$ due to packet receive is influenced by the number of joint nodes in each subtree out of its total number of nodes. The total energy consumed by the number of nodes, n during packet reception in a subtree t_{bri} can be expressed as follows:

$$E_{tot_{Rxt_{bri}}}(L) = \sum_{i=1}^{n} E^b{}_i \tag{5}$$

If h is the number of relay nodes in a subtree not including joint nodes, then the total energy consumed by a sensor node to receive a packet can be given as:

$$E_{tot_{Rxt_{bri}}}(L) = \sum_{k=1}^{h} E_k^b + \sum_{m=1}^{\zeta} E_m^{b*} \tag{6}$$

Accordingly,

$$E_{tot_{Rxt_{bri}}}(L) = \sum_{k=1}^{\boldsymbol{h}} E_k^b + \sum_{m=1}^{\zeta} \sum_{j=2}^{\omega} E_{mj}^b \tag{7}$$

The smallest number of interconnected children or chains of leaf nodes is ω = 2. From the second part of Equation (7), the total energy consumption will be influenced by the number of child nodes or chains of leaf nodes (ω) interconnected to the joint nodes (ζ).

The variation in energy consumption pattern between the primary route and that of alternative routes, particularly when more than one subtree $t_{(bri)}$ are interconnected to a sink node is very important to be compared. The rate of energy consumption by relay nodes (h) is different from the consumption rate by the cumulative number of joint nodes (ζ); each traversed by a number of packets proportional to the value ω; $\sum_{m=1}^{\zeta} \sum_{j=2}^{\omega} E^b{}_{mj}$. Accordingly, the second part of Equation (7) aids in determining the level of energy consumption balance among multiple subtrees. Standard deviation (STD) of energy consumption is an important energy balance indicator used to explore fairness and even performance among a number of $t_{(bri)}$. In such a network, a small STD indicates that energy consumption of all the nodes is close to each other[52]. The average energy consumption in a subtree is given by $\overline{E_{tot_{Rx,Tx\,(t_{bri})}}}$, where the sum of joint nodes ζ and the remaining regular nodes h equals to the total number of node n:

$$\overline{E_{tot_{Rx,Tx\,(t_{bri})}}}(r) \begin{cases} multihop\ disjoint\ node \left[\frac{1}{n} \sum_{i=1}^{n} [E^{a}{}_{i} + E^{b}{}_{i}] \right], \\ \quad if\ number\ of\ \zeta = 0 \\ multihopSubtree \left[\frac{1}{h} \sum_{k=1}^{h} [E^{a}{}_{k} + E^{b}_{k}] \right] + \\ \left[\frac{1}{\zeta} [\sum_{m=1}^{\zeta} E^{a}_{m} + \sum_{m=1}^{\zeta} \sum_{j=2}^{\omega} E^{b}_{mj}] \right] \end{cases} \quad (8)$$

In this section, the correlation of energy performance in tree topology to the node association manners are analysed using MATLAB, particularly the influence of the joint nodes in energy hole zones. The performance is explored under diverse configurations in terms of the distribution of the subtree's joint nodes (ζ), number of source nodes in a subtree (n), and different packet generation rate (R). Table 1 illustrates the important parameters and their corresponding values that are considered in this assessment.

Table 1. Parameter setting for tree topology analysis

Parameter	Value	Units
Analysis tools	MATLAB	
Number of nodes	90	nodes
Number of sinks	1	nodes
Packet size	56	byte
Packet rate R1, R2, and R3	1,2, and 3	Packet/sec
Number of DNs	3	nodes
Subtree1, subtree2, subtree3	30, 37, 23	nodes
1st Tree (ζ) and 2^{nd}Tree(ζ)	4,6,4 and 6,6, 6	Nodes
Case1(sub1, sub2, sub3 Case2(sub1, sub2, sub3 Case3(sub1, sub2, sub3	R1, R1, R1 R2, R2, R3 R1, R3, R3	Packet rate

Figure 7 illustrates the first constructed tree topology; 1^{st} tree, that associates 90 sensors and interconnects 3 subtrees, with each subtree exhibiting unique features. Subtrees 1 and 3 are characterised by a maximum of four joint nodes each (4ζ), whereas Subtree 2 contains six joint nodes (6ζ). Subtrees 1, 3 and 2 are associated with 30, 23 and 37 sensor nodes respectively.

The effect of diverse construction of interconnected subtrees on deviation in energy consumption, particularly hole-zone in tree topology, is addressed in this section. For extensive exploration two different features are considered; namely, the first topology (1^{st} tree) which has been described previously and the second topology (2^{nd} tree), which is characterized by equal distribution of joint nodes, that is, six for each subtree. Each tree is examined under several cases of traffic generation. In Case 1, the entire source nodes of all subtrees are equal in their traffic rates (R1). In Case 2, the source nodes of Subtrees 2 and 3 are twice and three times, R2, R3, that of Subtree 1 (R1), respectively. In Case 3, Subtrees 2 and 3 contain 3 times (R3) the source nodes of Subtree 1 (R1). Figure 8 shows that for both 1^{st} tree and 2^{nd} tree, the energy balance at sink holes is relatively smaller under Case 1, compared to Cases 2 and 3. For the 2^{nd} tree having equal distribution of joint nodes ζ over the entire subtrees, the energy consumption is more balanced compared with the 1^{st} tree, depicted by the smaller STD values.

The results indicate that the energy consumption pattern among sensor nodes in critical zones is influenced by the number of source nodes, traffic rate and joint node distribution. Therefore, the recognition of such a vital variation aid in adapting a desirable energy performance at the intended zone to achieve extended lifetime for the network.

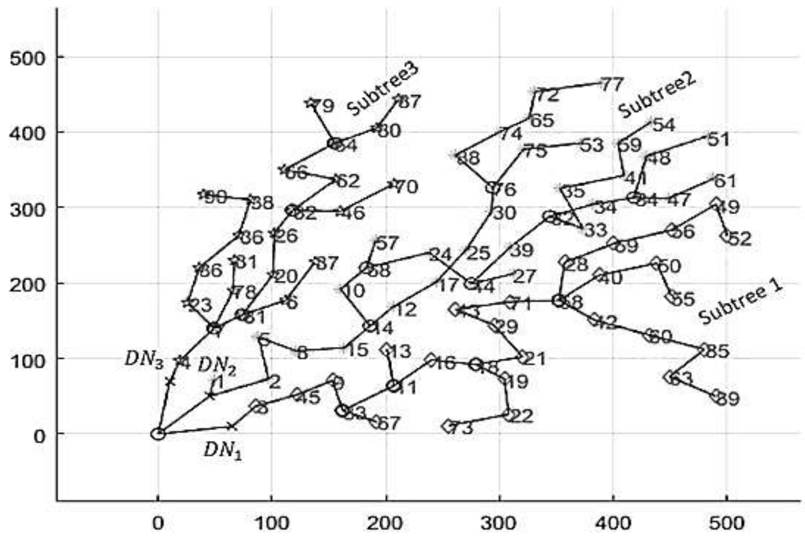
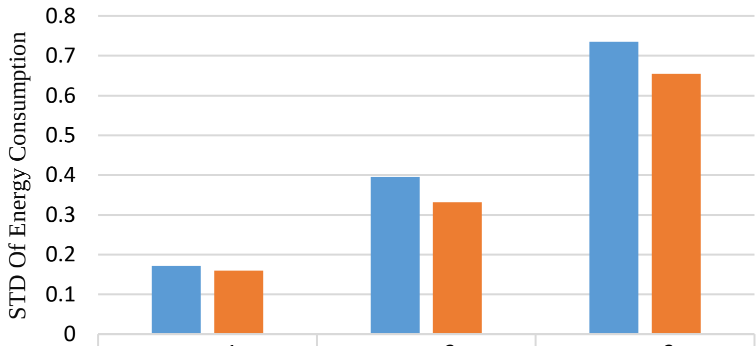


Figure 7. Sink-rooted multiple subtrees.



	case 1	case 2	case 3
1'st tree	0.171561643	0.395852028	0.735395746
2'nd tree	0.159860584	0.331385785	0.654655365

Figure 8. Energy balance of different topology constructions at sink hole.

5. HOLE STATUS AWARENESS AND ROUTING DECISION

This section describes the method to protect the deputy nodes (DN) against energy hole formation. A robust energy-aware routing algorithm plays an important role in obtaining a balanced energy consumption amongst DNs throughout the communication period. The proposed routing metric Q upon which the traffic routing decision is made, correlates energy status in critical zones, denoted by $\hat{Q}_{k,m}$, with the vital topology construction features, the joint nodes, ζ. The decision needed to be made for the next transmission round "r" is; whether to keep data traffic forwarding through the primary tree or switch to an alternative route.

Figure 9 illustrates a tree with two interconnected subtrees rooted on the deputy node (DN) labelled as k and m respectively with their respective energy pattern $Q_{bk,m}$.

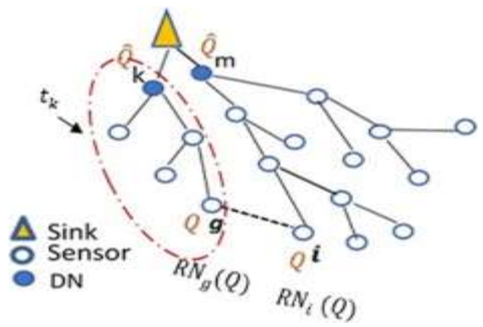


Figure 9. Tree topology of joint nodes.

The dotted line in the Figure 9 indicates that the source node can switch its traffic route to the parent node that is interconnected to a different path. Energy routing metric Q of parent node candidates are first compared to each other by the source node for taking the responsibility of traffic delivery to the sink node.

The core assumptions of this proactive energy routing metric in tree topology with a single sink are as follows:

- Any change in either tree depth or the rule of sensor nodes association will change the estimated number of joint nodes,
- A joint node encounters more data traffic as it gets closer to the sink (in hop counts).

The source node is aware of its local information in terms of short hop count and cumulative number of ζ. $SHC_{T,i}^{k,m}$ is the short hop count of the source node to the sink node through a corresponding deputy node, $\boldsymbol{DN_{k,m}}$, and $\boldsymbol{\zeta_{T_i}^{k,m}}$ refers to the number of joint nodes that are traversed by data packets in a tree $\boldsymbol{T_i}$ to the deputy nodes k or m in the sink node. The number of joint nodes ζ is accumulated from the lowest level of the tree $\boldsymbol{t_{br(k,m)}}$ (nearer to the sink) to its highest level where the source node is located. $\boldsymbol{\zeta_{T_i}^{k,m}}$ aids the routing algorithm to estimate the node chains interconnected to a possible path within a sub tree. Also, $\boldsymbol{SHC_{T_i}^{k,m}}$ is a short hop count to deliver traffic to the sink node and it is one of the parameters which influence energy consumption in tree topology, particularly, the number of packets received in each deputy node, DN. Accordingly, the product of these parameters denoted as N_{T_i}represent the route feature in tree topology that is considered in routing decisions. $N_{T_i}$is simply given as:

$$N_{T_i} = \boldsymbol{\zeta_{T_i}^{k,m}} * \boldsymbol{SHC_{T_i}^{k,m}} \tag{9}$$

In our proposed EBEHA-T, the routing metric for making routing decision for the next round is expressed as;

$$Q = \frac{\hat{Q}(k,m)}{N_{t_i}} \tag{10}$$

This is essentially the ratio between the energy level in the considered deputy nodes (k or m) to the product of number of joint nodes and hop count.

The decision to determine whether the selected DN is going to be k or m as shown in Figure 8 is expressed as:

$$\hat{Q}(k,m) = \frac{d}{r}\left(E_{sink} - E_{res(km)}\right) \tag{11}$$

Where $E_{res(k,m)}$ is the residual energy of an intended DN, referenced to sink node to enable this sink to evaluate DNs at every transmission round r; denoted by $\frac{d}{r}$. The energy status at critical zones, $\hat{Q}(k,m)$ corresponding to $DN_{k,m}$, is announced through the sink's beacon.

EBEHA-T is designed to be an energy status Q metric-based routing decision as illustrated in Figure 10. At each transmission round, the source node recognizes all the potential parent nodes by way of some "hello" messages. These parent nodes are interconnected to different deputy nodes in the hole zone. The respective source nodes then perform a comparison of their respective energy statuses to identify an energy-efficient route. Parents with the best energy status Q will be selected to be the traffic forwarding node since it belongs to the most appropriate subtree in terms of root node's energy consumption variation against the route communication costs towards the sink node. It is important to use routing metric Q to determine the quality of the different routes. Thus, referring to Figure 9 and Figure 10, when the routing metric $Q(t_m)$ of a parent node in subtree t_m is lower than a routing metric $Q_g\,(t_k)$ of the primary parent node RN_g in the subtree t_k, then the source node RN_i switches its traffic route to RN_g instead of primary parent node. This would have been the case if the decision is left to auto-routing operation. With EBEHA-T, the relay node RN_g will end up in a DN having a higher residual energy compared to that of its primary route. However, if the energy metric $Q(t_m)$) of the primary parent is higher than or equal to $Q_g(t_k)$ in subtree t_k the source node uses the primary traffic route since its DN has a higher residual energy or does not have a serious variation in energy consumption pattern among DNs in critical zones. Accordingly, it is crucial that at each transmission period, the sink nodes update the energy status amongst its deputy nodes and that the source nodes are aware of the tree typologies construction features such as hop count and joint nodes.

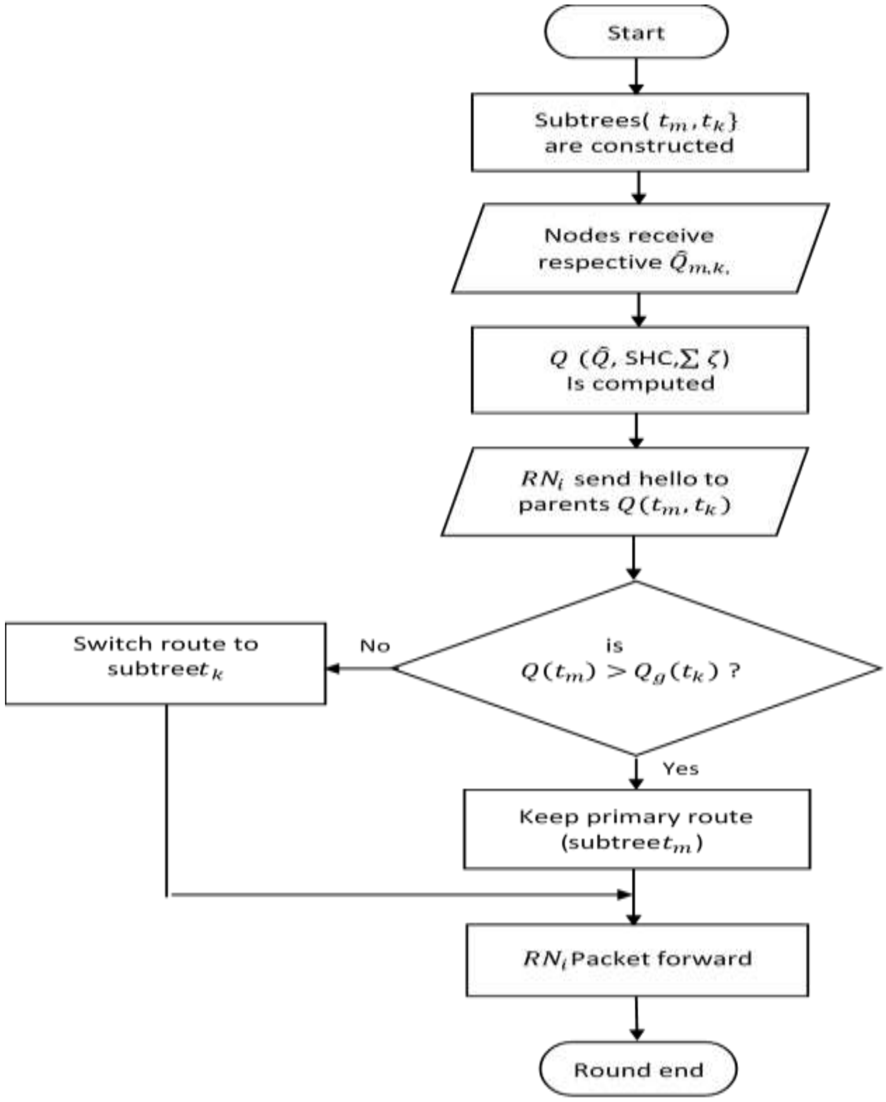


Figure 10. Flowchart of proactive energy routing metric-based traffic routing.

6. SIMULATION RESULTS AND DISCUSSIONS

This section presents the performance of our proposed EBEHA-T routing algorithm compared to Randomized Switching for Maximizing Lifetime (RaSMaLai) [53]. RaSMaLai has been selected as the benchmark method as it is one of the latest works in the literature that addresses the energy hole problem in a tree topology-based traffic routing. It aims to maximize the lifetime of a sensor network by using a routing decision considering load balance parameters to switch from original paths to other paths with lower load.

Several simulations of these schemes have been carried out using OmNet++ which is a popular open-source network simulation package. Standard radio parameters and energy dissipation model has been implemented. Table 2 presents the simulation parameters used to assess the performance of the tree topology.

Different network situations which we refer to as case studies (CS) have been modelled to study the performance of EBEHA-T and RaSMaLai under different tree topologies. The cases are basically referred to a single sink tree topology varying in sink energy hole size from four deputy nodes (4DN) to eight deputy nodes (8DN), and total number of sensor nodes from 30 to 75 for CS1 and CS2, respectively.

Table 2. Simulation parameters used in OmNet++ v4.6

Parameter	**Value**	**Units**
Number of static nodes	30 -75	nodes
Number of static sinks	1	nodes
CS1 and CS2	3 and 4	DN
Initial Energy	0.5	joule
Circuit energy to transmit /receive (Tx /Rx)	50	nJoule/bit
Energy of amplification	10	pJoule/bit/m2
Packet rates		
R1	1	packet/sec
R2	0.5	
MAC		CSMA/CA

6.1. Average Energy Consumption

Figure 11 and Figure 12 show the average consumed energy for the two cases – CS1 and CS2, and under different traffic generation rates of R1 and R2, respectively. The multiple subtree structure that our proposed EBEHA-T is based upon enables source nodes to explore available short routes which subsequently contributes to a reduction in communication costs. From the simulation run shown in Figure 10, it can be seen that EBEHA-T shows a lower energy consumption behaviour compared to that of RaSMaLai, by approximately 50%. This observation indicates that the awareness of energy pattern Q_b as well as joint nodes ζ together play a dominant role in managing the energy consumption of the network. In Figure 12, for case study CS2, it is shown that the energy consumption by EBEHA-T is 54% to that of RaSMaLai. Thus, regardless of underlying topology, EBEHA-T has shown to be an effective mechanism for energy savings in tree based wireless sensor networks.

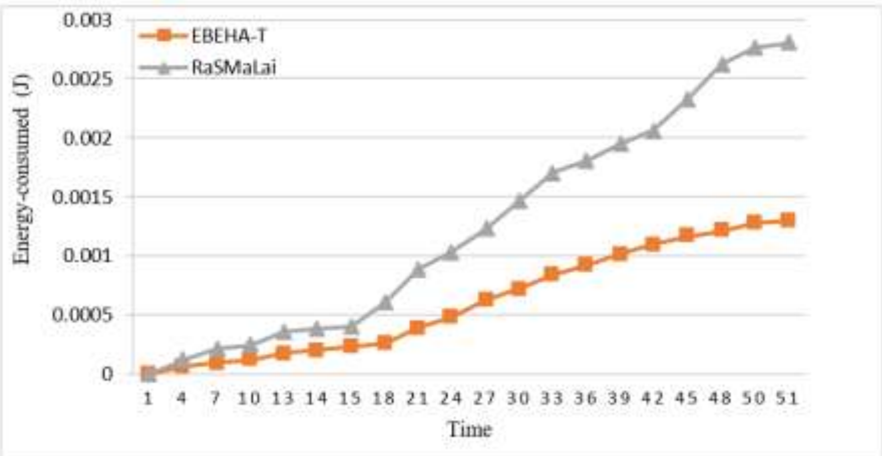


Figure 11. The average consumed energy of EBEHA-T compared to RaSMaLai with small energy hole (4DN), CS1

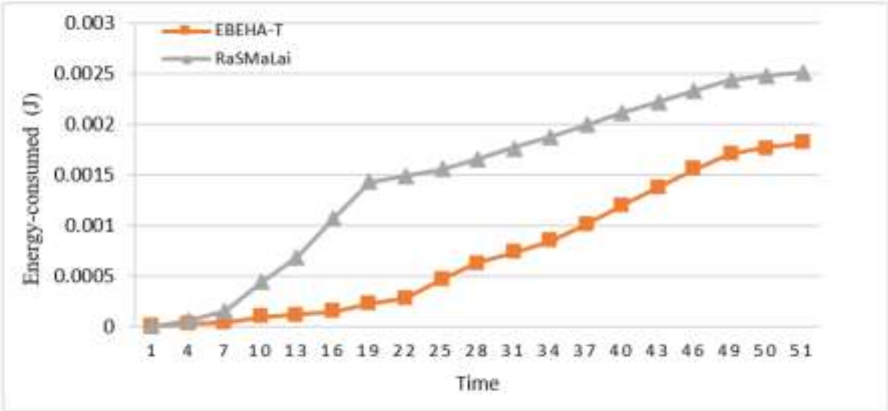


Figure 12. The average consumed energy of EBEHA-T compared to RaSMaLa with a large energy hole (8DN), CS2

6.2. Balanced Energy Consumption

The energy performance in EBEHA-T has been further examined through fair energy exhaustion across the entire network. The small standard deviation (STD) of the energy consumed by the nodes across the entire network indicates a decrease in the deviation of energy consumption among sensor nodes. This implies that there is an enhancement in fair energy usage amongst sensor nodes in the network. Figure 13 and Figure 14 show that EBEHA-T achieves enhancement in energy balance of approximately 78% and 62%, respectively compared to RaSMaLai under case study CS1; and 81% and 85%, respectively under case study CS2, with packet generation rates R1 and R2. Updated image of energy consumption pattern amongst DNs is considered as an important parameter for energy-awareness by distant source nodes in order to make their routing decisions.

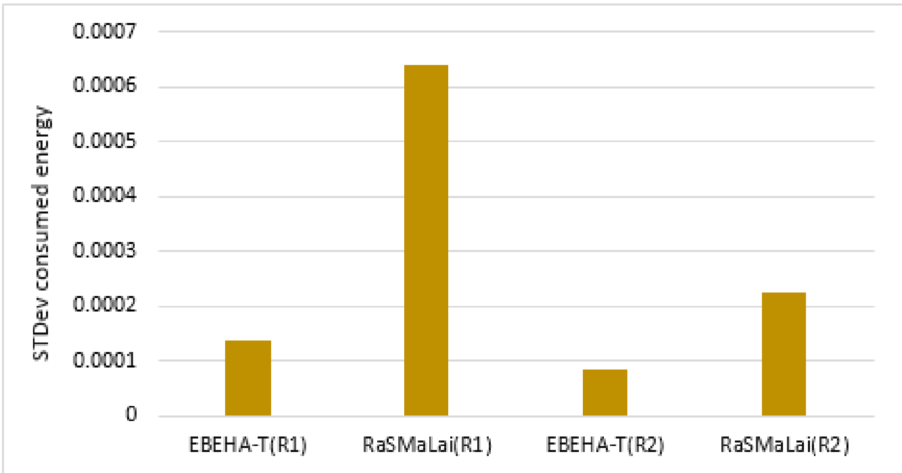


Figure 13. STD of energy consumption at sink hole zone for EBEHA-T and RaSMaLai in CS1 (4DN) under R1 and R2.

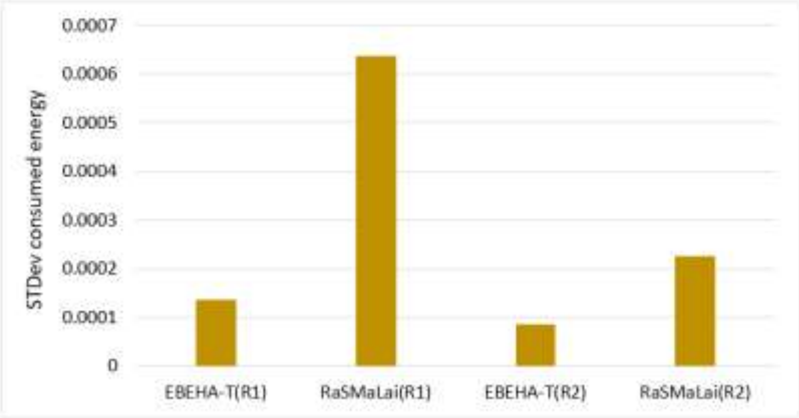


Figure 14. STD of energy consumption at sink hole zone for EBEHA-T and RaSMaLai in CS2 (8DN), under R1 and R2.

6.3. Network Lifetime

The outcome of this energy balance and savings across the entire sensor network and the reduction in the deviation in energy consumption at hole zones, is that the network lifetime is extended significantly. This is a desirable property of sensor networks as the network is expected to be left operating over a long period of time without human interventions. Network lifetime is defined as the length of time the network lasts until the first node dies. Figure 15 and Figure 16 show the operation of EBEHA-T and RaSMaLai for a tree topology over the length of simulation time. From these figures, it is clear that RaSMaLai experiences a relatively faster node death at 30 and 34 simulation time, respectively whereas EBEHA-T shows an extended lifetime beyond the furthest range of simulation time performed in this simulation exercise.

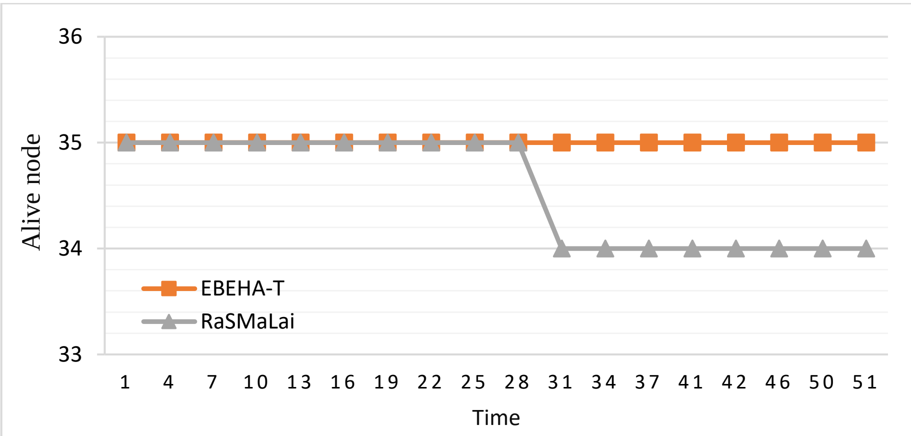


Figure 15. Sensor Network lifetime of EBEHA-T and RaSMalai under R1, CS1.

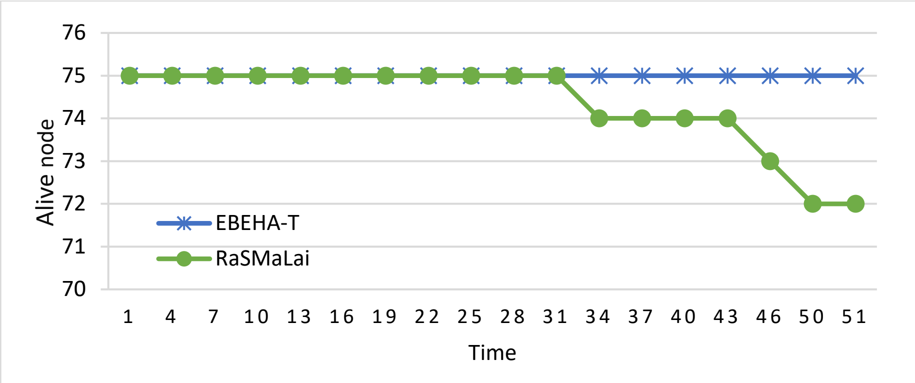


Figure 16. Sensor Network lifetime of EBEHA-T and RaSMaLai under R2, CS2.

6.4. Packet Delivery Ratio (PDR)

Another important performance assessment of a tree-based wireless sensor networks is its packet delivery ratio (PDR). This is defined as the ratio between the number of packets that are successfully delivered to the sink node, against the total packet generated by the source nodes. Figure 17 shows PDR for EBEHA-T and RaSMaLai under different traffic-generating rates in the case study CS1. Again, EBEHA-T shows a superior performance in terms of PDR of approximately 0.82 against 0.57 for RaSMaLai; while under packet rate R2, the PDRs are 0.97 and 0.64 for EBEHA-T and RaSMaLai.

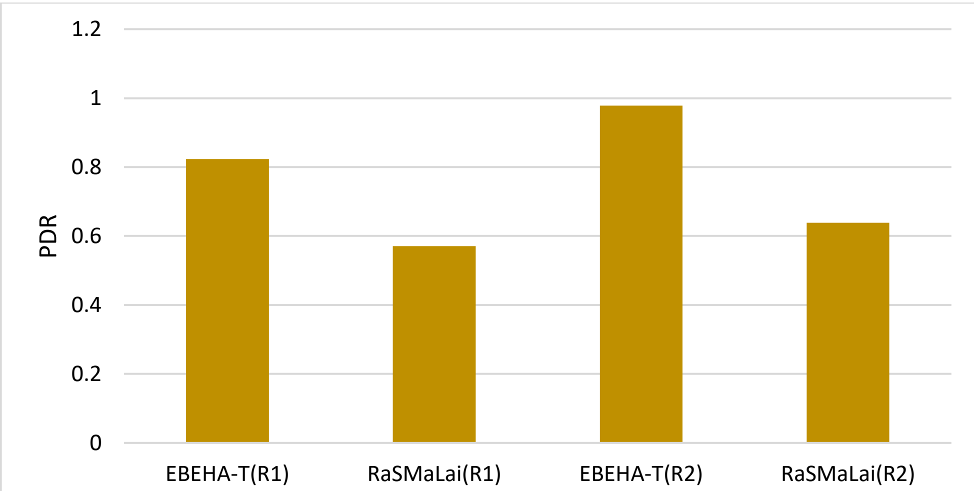


Figure 17. PDR of EBEHA-T and RaSMaLai under R1 and R2, CS1.

7. Conclusion and Future Works

This study addresses the problem of energy hole formation at sink zone and shed light on some gaps that has not yet been explored. Previous studies did not consider updated status of energy consumption pattern at the sink hole zones, which otherwise could aid in making routing decisions. Thus, correlation between energy balance-based traffic routing and the drawbacks of many-to-one long-distance communications has been well-investigated. This paper proposed greedy routing protocol named EBEHA-T that performs proactive protection precludes energy hole formation instead of hole detection. The next-hop selection based routing of EBEHA-T depends on the new metric that combines updates energy consumption pattern amongst deputy nodes (DNs) together with estimated cumulative joint nodes in tree topology is based. The superior performance of Energy Balance-Based Energy Hole Alleviation in tree topology (EBEHA-T) compared to the state-of-the-art RaSMaLai method verifies that its energy-aware routing decisions results in significant improvement in a sensor network's energy consumption balance, particularly amongst deputy nodes (DN) in hole zones. It also affords a higher reliability in terms of packet delivery to the sink node which eventually results in a prolonged network lifetime. Future studies should include protection against relatively overwhelmed traffic at some sinks in a tree topology with multiple sinks to achieve a longer network lifetime.

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