Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 11, No. 2, June 2023, pp. 586~609
ISSN: 2089-3272, DOI: 10.52549/ijeei.v11i2.4566

An Enhanced Cluster-Based Routing Model for Energy-Efficient Wireless Sensor Networks

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Article Info

Article history:

Received Mar 2, 2023
Revised Jun 8, 2023
Accepted Jun 24, 2023

Keywords:

Sensor nodes
Wireless Sensor Networks
Energy-efficiency
Cluster-based
Genetic Algorithm

ABSTRACT

Energy efficiency is a crucial consideration in wireless sensor networks since the sensor nodes are resource-constrained, and this limited resource, if not optimally utilized, may disrupt the entire network's operations. The network must ensure that the limited energy resources are used as effectively as possible to allow for longer-term operation. The study designed and simulated an improved Genetic Algorithm-Based Energy-Efficient Routing (GABEER) algorithm to combat the issue of energy depletion in wireless sensor networks. The GABEER algorithm was designed using the Free Space Path Loss Model to determine each node's location in the sensor field according to its proximity to the base station (sink) and the First-Order Radio Energy Model to measure the energy depletion of each node to obtain the residual energy. The GABEER algorithm was coded in the C++ programming language, and the wireless sensor network was simulated using Network Simulator 3 (NS-3). The outcomes of the simulation revealed that the GABEER algorithm has the capability of increasing the performance of sensor network operations with respect to lifetime and stability period.

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1. INTRODUCTION

Technological innovations in Micro-Electro-Mechanical Systems (MEMS) technology and electronic devices have paved the way for the development of compact, inexpensive, low-power, and diversified Sensor Nodes (SNs) that can be connected via wireless networks [1]. Wireless Sensor Networks (WSN) are made up of SNs that track and send data packets through a wireless medium. The network allows the channeling of monitored data from multiple SNs (sources) to a specific base station (BS) (i.e., sink). Deployment of SNs can be random, such as in disaster management applications, or planned, such as in sensors implanted for precision agriculture. Moreover, establishing a group of these sensors as a network can help lifesaving workers locate unsafe locations and gain a better understanding of the general condition in a disaster zone. The application area also includes surveillance, telemedicine, tracking, and machine failure diagnosis [2].

SNs in WSNs usually have restricted resources, such as limited battery energy, processing, and memory capabilities. The SNs' limited battery energy has a massive influence on the lifetime of WSNs. Due to their deployment in an unattended environment, SNs seldom have their battery energy resources replenished. Consequently, the efficient utilization of the battery's energy resources can guarantee the continued functioning of a WSN [2]. SNs in a WSN are grouped together into units called clusters. There is a coordinator known as a "Cluster Head" (CH) for each cluster. The cluster's remaining nodes serve as source nodes (SNs). All source nodes transmit the monitored data to the corresponding CH, which in turn aggregates and routes the data to a specialized node called the sink node [3]. Furthermore, clustering can produce node groups with uniform or asymmetric node distribution [4]. A uniform node distribution clustered system will comprise nodes situated in different locations within the sub-cluster, while a non-uniform clustered system will comprise high and low density sub-clusters with nodes situated in different locations within the sub-cluster. The location of each node in the sensor field, its distance from the BS, and its cluster density greatly influenced its energy depletion.

In reality, WSNs use batteries to power the SNs, which represent limited energy sources. SNs require energy resources for data monitoring, processing, and communication functions. However, most of the energy resources are expended during data communication for the establishment of routing paths and the forwarding of data packets [5]. This high energy consumption overhead leads to a reduction in sensor lifetime. The non-rechargeable and irreplaceable energy sources of SNs have created constraints for monitoring and tracking purposes. An energy-efficient routing model involves the determination of optimal utilization of energy resources by the SNs during the process of establishing a routing path and the transmission of data packets. Cluster-based routing, also known as hierarchical routing, is a prominent energy-efficient approach to promote sensor lifetime [6]. However, most of the existing energy-efficient cluster-based routing algorithms are characterized by imbalanced energy depletion. This imbalance leads to network partitioning and packet loss. This necessitated the development of a new energy-efficient routing model and algorithm that can address the imbalance in energy depletion. Therefore, in an attempt to enhance the lifetime of the WSNs, this study aims to address node imbalance and energy depletion. A routing algorithm will be established with the potential to extend the lifetime of WSN, increase the period of stability, reduce packet loss, and reduce switching times between routing nodes. Static clustering will be employed to make the most of the limited energy resources available to the deployed nodes. The CH and Relay Nodes (RN) will be chosen based on the node residual energy, node-to-base station distance, and cluster node density surrounding each node. As CH and RN selection will be dependent on these crucial characteristics, this will balance the energy depletion of each node in the sensor network. Additionally, this study would use a method in which each node sends its remaining energy to the base station along with the data packets. With this method, the quantity of control messages and the time it takes to choose a new CH or RN in the sensor network will be reduced. In order to increase network longevity, the method generally considers the conservation of each node's energy resource. The effective routing of data packets to the base station will also be ensured by this study.

The remaining parts of the paper are structured into the following sections: The scientific literature and the latest cluster-based routing schemes in WSN are presented in Section 2. Section 3 describes the evolutionary metaheuristics techniques required to meet the objectives. The simulation's findings and discussions are highlighted in Section 4, while Section 5 contains the study's conclusion and recommendations.

2. RELATED WORKS

In WSN, energy-efficient routing has been carried out using the cluster-based routing idea. In the literature, numerous cluster-based routing methods for WSNs have been proposed; thus, in this study, the protocols of some of the approaches were studied from the standpoint of the routing algorithm, taking into account its methodology and attributes. In a WSN, the main objective of hierarchical-based routing is to effectively manage the energy consumed by the SNs within a cluster by performing data fusion to prevent redundant packet transmission to the sink. Additionally, a cluster-based architecture allows for the utilization of high-energy nodes for data processing and packet transmission and low-energy nodes for data monitoring close to the target area. This indicates that the overall system scalability, longevity, and energy efficiency can be considerably enhanced by cluster formation and the delegation of specific tasks to CHs. However, most of the existing energy-efficient routing techniques are characterized by imbalanced energy depletion.

One of the earliest and most widely used energy-efficient communication protocols designed for WSN was Low Energy Adaptive Clustering Hierarchical (LEACH) [7]. It is a well-known cluster-based routing scheme for WSNs that supports dispersed cluster arrangements and elects CHs with a set probability at predetermined intervals. It addresses the imbalanced energy depletion of nodes in the WSN by employing an iterative random model technique to elect a CH node at every round of data routing to make certain that all nodes in the network receive an equal amount of energy demand. LEACH was demonstrated to outperform conventional communication techniques such as directed transmission routing and minimum-transmission energy routing eight times over with respect to reducing uneven energy dissipation, easy configuration, and improving the system lifetime of the network. However, it only mitigates imbalanced energy dissipation in WSN based on transmission distance and does not take into account the link weight factor as determined by the residual energy of each sensor node. Also, the LEACH cluster formation algorithm cannot guarantee how many CH nodes will be present.

Several studies were conducted in order to improve LEACH performance. Some of the approaches are: forming clusters through a centralized control mechanism [8], employing distributed clustering [9], using the notion of a vice-cluster head (VH) node to complement the CH nodes [10], using residual energy to build a directed virtual backbone (DVB) of CHs firmly grounded at the sink [11]. Other approaches to adaptive energy-efficient and clustering routing techniques for WSNs that have been proposed also include a Hybrid Energy-Efficient Distributed (HEED) clustering technique for ad-hoc sensor networks, which uses a distributed method to choose CH nodes so that the CH nodes are evenly distributed throughout the network [12], a Centralized Energy-Efficient Routing Protocol (CEERP) for WSNs, which uses an iterative random algorithm and chooses a clustering strategy with uniform node density where each CH is responsible for the equivalent number of member nodes in order to prevent CH overload [13], and an iterative topology reconstruction mechanism in selecting CH nodes as determined by the residual energy of each node [14]. These approaches addressed the imbalanced energy consumption of nodes in WSN and provided pertinent information on energy-efficient routing to prolong the lifespan of sensor networks. However, in some cases, the sensor node density within each sensor network cluster, the link weight factor of the routing path, or the residual energy of the sensor node were not adequately considered.

Also, various routing schemes were proposed in order to provide robust network stability, increase sensor network lifetime, and reduce the energy hole problem in WSN. For instance, an energy-aware routing scheme that employs a centralized single-hop evolutionary routing protocol to improve the selection of CH for cluster formation [11] [15], iterative random selection of the optimal route based on node residual energy and node distribution density in each cluster [16], a virtual hybrid potential field that forwards data packs using the normalized field strength with respect to the residual energy of each node Iterative topology reconstruction mechanisms primarily based on residual energy of the nodes and transmission distance during CH election [17], iterative random selection technique to choose a CH node using residual energy and node transmission distance [2], a decentralized iterative topology reconstruction mechanism to choose the CH node using residual energy and node transmission distance [18], a technique called the Stable Election Protocol Energy Consider (SEP-EC) dependent on node residual energy [19], Q-learning-based data-aggregation-aware energy-efficient routing technique that leveraged on reinforcement learning to optimize rewards [20], and an Energy-Efficient Layered Routing Protocol (EELRP) that segregates the network into some concentric circles of different radii [21]. These routing- based methods offered important knowledge about energy-balanced data collection protocols for the WSN. However, most of these routing-based methods did not consider the sensor network's cluster node density, the location of the node in relation to the BS, the formation of clusters with uniform node densities, the location of the CH node, the transmission of equal data packets to the BS by the CH nodes, the cluster node density, and the CH node's remaining energy. Additionally, because each node estimates its distance from the BS and the CH node election is based on a competition among cluster member nodes, the decentralized routing technique consumes energy resources more quickly.

The algorithmic paradigm is one other technique that has been proven to improve the network lifetime. Genetic Algorithm (GA) iterative reconstruction mechanism using the residual energy [22], spanning tree search technique in selecting the CH node using the residual energy [23], elitist Genetic Algorithm [24], optimization algorithms [25–26], greedy strategy [27–28], K-Means routing scheme [29], and a host of others. These algorithmic approaches provided relevant information on energy-balanced data gathering and routing protocols for the WSN. However, research attention is still required at this point for factors such as node distribution density in each cluster, the link weight factor of the CH node attributed to the cluster node density, and the algorithm's experience in switching from one CH node to another since residual energy information does not reside in the BS. Table 1 compares several techniques in terms of the network structure that has been established, the network features, the routing algorithm that has been employed, the proposed search strategy, the reported metrics, and the results achieved.

It was therefore noted that the development of routing algorithms for optimal use of limited battery energy resources involves consideration of routing methods based on either decentralized or centralized routing approaches. During the route setup phase of the decentralized routing approach, SNs contest for the post of CH node, and each node computes its distance from the BS. During this process, a significant amount of energy is depleted that could have been saved for data forwarding. In the data transmission phase of the centralized routing approach, additional energy resources are depleted due to the delay usually experienced while switching from one CH node to another.

Node deployment strategy in WSNs is a fundamental problem affecting sensor network operations. This strategy greatly influences the cluster-based routing approach usually considered during route setup and data forwarding. The choice of an approach (centralized or decentralized) in the selection of CH or relay nodes during route setup in WSNs determines the rate of energy depletion and residual energy available for data forwarding. Thus, there is a need to develop a deployment algorithm that is energy efficient. Additionally, the pattern of energy depletion in WSNs is known to be a drawback that disrupts network performance. SNs situated near the BS will dissipate their battery energy resources more rapidly than other nodes because of the reception and re-transmission of signals to and from other nodes. This results in the entire network being distressed by the energy imbalance problem. Therefore, it is absolutely desirable to develop an efficient routing algorithm to transmit packets using residual energy and transmission distance.

Therefore, this study develops a genetic algorithm-based approach to ensure energy efficiency in cluster-based routing. This work is set out to address excessive energy depletion during route path establishment in a decentralized routing approach and the delay usually experienced in switching from one CH or relay node to another in centralized routing techniques.

Table 1. Comparison Analysis of Some Selected Studies

Ref.	Problem Addressed	Methodology	shortcoming
[30]	unavailability of limited energy resources	Low energy adaptive clustering hierarchy (LEACH) in conjunction with optimization algorithm genetic algorithm (GA) was used	technique consumes more energy resources that could have been saved for data forwarding
[31]	network lifetime issues	a clustering and routing-based energy-efficient WSN strategy built on the basis of trust.	Provided a relative improvement of the network lifetime
[32]	node redundancy in WSNs	Presented a novel clustering model that is based on the duty cycle approach, to decrease the number of working nodes and conserve energy	The model is not suitable for heterogeneous wireless sensor networks
[33]	Energy imbalance dissipation issues in WSN	Propose an Artificial Neural Network (ANN)-based model in selection of the cluster head	The technique may experience delay in switching from one CH node to another because verification of the routing metrics information of each node takes a longer time.
[34]	network overhead issues	Using an energy-efficient cross-layer-based expedient routing protocol (E-CERP) to find the shortest path,	The work did not consider the CH node link weight based on cluster density.
[35]	Cluster head selection	Proposed a model that used some factors like the average intra-cluster distance, residual energy, sink distance, and cluster head balancing factor to choose the cluster head	The model is not suitable for heterogeneous wireless sensor networks
[36]	securely construct routing paths and maximize network lifetime.	presented a WSN energy-efficient secure multipath routing protocol	The algorithm experiences delay in switching from one CH node to another due to handover technique adopted i.e. residual energy does not reside in the BS

3. METHODOLOGY

The developed framework for the energy-efficient cluster-based routing model is shown in Figure 1. In the network model, nodes are randomly deployed, and relay nodes are introduced to reduce intra-cluster distance in the network. The procedure followed in the system design and modelling are as follows:

3.1. Network Modelling and Assumptions

Considering a WSN made up of M SNs and a BS distributed randomly and uniformly across a sensor field A by A m^2. Each cluster, which makes up the complete sensor field, is divided into a specific geographic area. Nodes with various roles, including relay and cluster header, are present in every cluster. Data packets are forwarded from the source node to the CH node while it keeps an eye on the surroundings. Data packets from cluster source nodes must be gathered by the CH node before being forwarded to the relay node. The relay node is responsible for forwarding data packets to the BS. The relay node reduces intra-cluster distance in order to extend the network life.

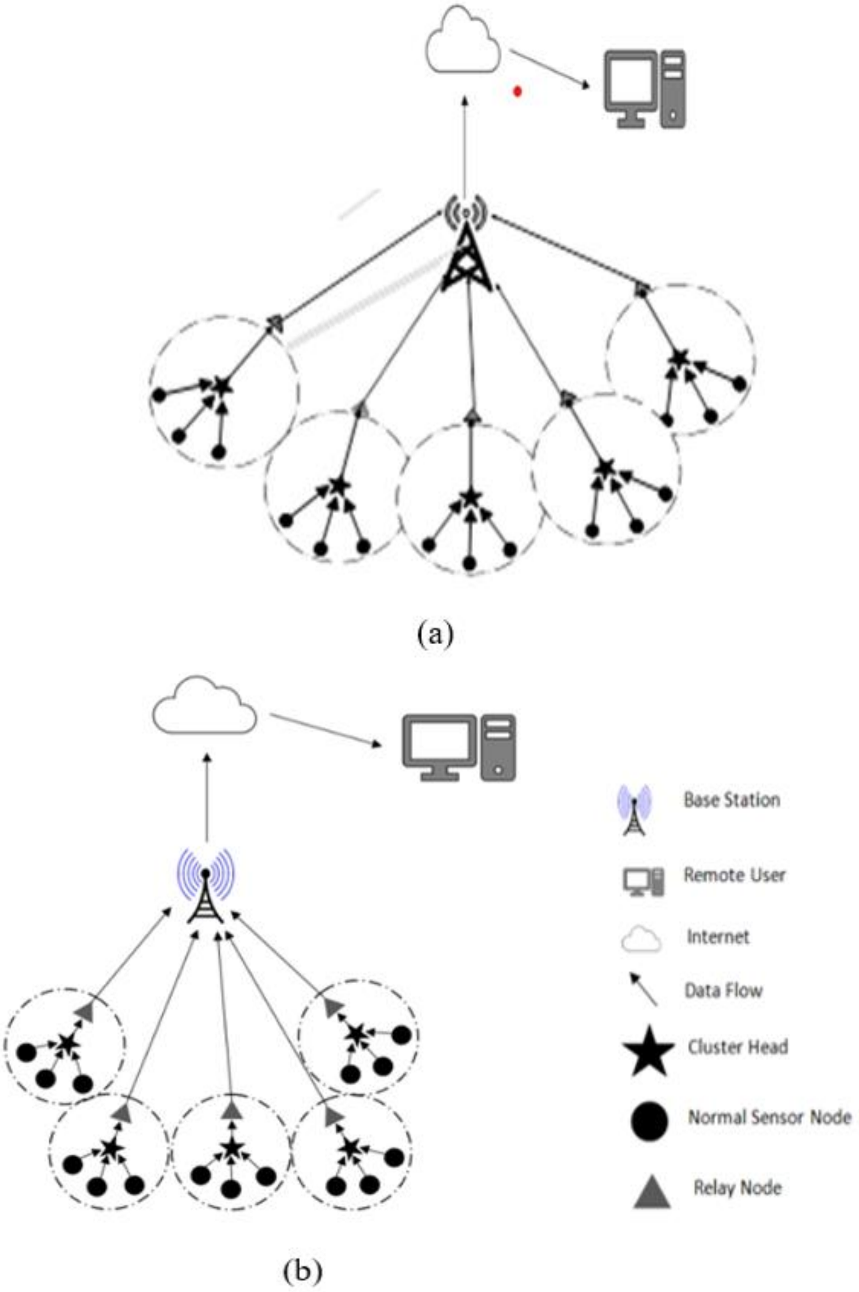


Figure 1. Proposed energy-efficient cluster-based routing framework with the relay node (a) outside the transmission radius and (b) within the transmission radius

This study assumed all SNs in the network, including the BS, were static. The BS has unlimited energy provisions and coordinates network operations such as route setup and data transmission operations. Also, the SNs have homogeneous initial energy and the capability of including location information and residual energy in the data packet. Additionally, each node has a unique identification number in a cluster. Furthermore, data aggregation employs the concept of infinite compressibility. A CH is expected to compile local information obtained from its participants into a single, fixed-length packet. When a source node is not transmitting, its radio enters a sleep state. A CH node should switch on its receiver in order to receive all local data from the connected member nodes. Then, the aggregated data is forwarded to the relay node.

3.2. Formulation of the Energy model

The energy model was formulated as an optimization problem using the Free Space Path Loss (FSPL) model and a first-order radio energy model. The FSPL model was employed to determine the location of each node in the sensor field (based on its distance) in an attempt to choose the optimal route to the BS. The first-order radio energy model was used to determine the energy depletion of each node in order to achieve an energy depletion balance between nodes. The square of the distance between each node and the BS is determined by the FSPL model. Thus, the greater the distance between each node and the BS, the lesser the received signal power [37]. The FSPL model is expressed in Equation 1.

$$\frac{P_r(d)}{P_t(d_0)} = \frac{G.\lambda^2}{(4\pi d)^2} \tag{1}$$

Where
$P_t(d_o)$ is the transmitted signal power from the reference distance (d_0) measured in milliwatts,
$P_r(d)$ is the received signal power by the node in the distance (d) measured in milliwatts,
λ is the signal wavelength measured in meters;
d is the distance from the BS measured in meters (m);
G is a dimensionless constant which is the product of the field radiation patterns of the transmitter and receiver antenna.

The ratio of the received signal power in distance (d) to the transmitted signal power from the reference distance (d_0) is inversely proportional to the square of the distance (d^2) as expressed in Equation 2. Each node computes the received signal power at a distance (d) i.e. P_r (d) as expressed in Equation 3 [37].

$$\frac{P_r\ (d)}{P_t\ (d_0)} \propto \frac{1}{d^2} \tag{2}$$

$$Pr\ (d)\ = 10\ log(P\ )/0.01 \tag{3}$$

Where P is the difference between the signal power stated in the packet sent by the BS to the node and the received signal power reported by the antenna of the node Considering Equation 1, the transmitter-receiver distance (d) is expressed as in Equation 4.

$$d_i = Q.\sqrt{\frac{P_t(d_o)}{P_r(d)}} \tag{4}$$

Where, Q is a constant defined in Equation 5 as follows:

$$\sqrt{\frac{G.\lambda^2}{(4\pi)^2}} \tag{5}$$

The transmitter-receiver distance of each node d_i (i = 1, 2, 3... P) can be obtained using the transmission power of the BS. The location of each node in the sensor field is known based on its distance from the BS. Consequently, a role is assigned to each node in the sensor field.

The energy depletion of each node during data packet forwarding is based on a first-order radio energy model [3]. This model was utilized to compute the energy depletion of each node in order to achieve an energy depletion balance between nodes. The transmitter depletes energy (E_{TX}) to operate the radio electronics and transmission amplifier circuitry, while the receiver dissipates energy (E_{RX}) in the radio electronics. Hence, since energy depletion is proportional to the transmission distance and data packets transmitted, the energy depletion in transmission and reception of one-bit data over the distance (d) is expressed in Equations 6 and 7, respectively, according to the first-order radio energy model [3].

$$E_{TX}\ (l,d)\ = \begin{cases} l * E_{elec}\ +\ l * \varepsilon_{fs} * d^2 & if d < d_0 \\ l * E_{elec} +\ l * \varepsilon_{mp} * d^4 & if\ d\ \geq d_0 \end{cases} \tag{6}$$

$$E_{RX}\ (l,d)\ =\ l\ *\ E_{elec} \tag{7}$$

whereas E_{TX} is the energy required for data packet (l) transmission over distance (d), E_{elec} is the electronic energy dissipated for transmitting and receiving bits of data packets, which depends on filtering, digital coding, modulation, and signal spread, whereas ε_{fs} and ε_{mp} are energy amplifier costs that depend on distance (d), l is message length in bits, and E_{RX} is the energy required for data packet reception. The reference distance d_0 is expressed in Equation 8 [15]. During routing path establishment, the residual energy of each node is computed by the BS using Equation 9.

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{8}$$

$$E_{res} = E_I - E_U \text{ (in nanoJoules)} \tag{9}$$

Where
E_{res} = residual energy level of each node,
E_i = initial battery energy of each node,
E_u = Energy dissipated by each node during data packet transmission. The energy dissipation by a node is dependent on the transmission distance and bits of data packet disseminated.

A relay node, a CH node, and source nodes are present in each cluster in the study's network model. If a node is a source node during data packet transmission, only the CH node receives the data packet during rounds of data transmission. Given that energy depletion is greater over longer transmission distances, this is done to ensure that the source node's remaining energy is used as efficiently as possible. If the source node and CH node are within the transmission radius, then energy depletion during data transmission is stated as in Equation 10.

$$E_{TX}\,(SN) = l * E_{elec} + l * \varepsilon_{fs} * d^2; \qquad if\ d < d_0 \tag{10}$$

If the node is a CH node, data packets are instead collected, gathered, and sent to the relay node during rounds of data transmission. Equation 11 gives the energy depletion by the CH node under the assumption that the transmission distance between the CH node and the relay node is within the transmission radius.

$$E_{CH} = [l * E_{elec}] + \left[l * E_{DA} * \sum\left(\frac{E_i}{d_i}\right)\right] + \left[l * E_{elec} + l * \varepsilon_{fs} * d^2\right]; \quad if\ d < d_0 \tag{11}$$

Where, E_{DA} is the data aggregation energy of the cluster head node, Σ(E_i/d_i) is the total number of bits in data packets from source nodes. Additionally, while receiving data packets from the CH node and transferring data packets to the BS, the relay node uses up battery power. Equations 12 and 13 expresses the energy loss by the relay node, assuming a lengthy distance between the relay node and BS. Therefore, energy dissipated in a cluster during a round of data transmission is expressed in Equation 14. The radio energy dissipation model is depicted in Figure 2.

$$E_{TX}(RN) = l * E_{elec} + l * \varepsilon_{fs} * d^2; \qquad if\quad d_{RN} < d \tag{12}$$

$$E_{TX}(RN) = l * E_{elec} + l * \varepsilon_{mp} * d^4; \quad if\ \ d \geq d_0 \tag{13}$$

$$E_{Cluster} = E_{TX}(SN) + E_{CH} + E_{TX}(RN) \tag{14}$$

3.3. Theoretical basis for cluster density metrics

Assuming M numbers of nodes are dispersed uniformly in an *A x A* m^2 and clusters of uniform node density have formed. There are typically m/*q* nodes per cluster if there are *q* clusters. The energy depletion rate and network lifetime increase with the number of nodes in a cluster. The network lifetime and energy depletion are longer in clusters with fewer nodes. In Equation 15, the cluster node density $L(x_i)$ is given.

$$L(x_i) = \frac{\text{Total number of nodes in the network (M)}}{\text{Total number of cluster (q)}} \tag{15}$$

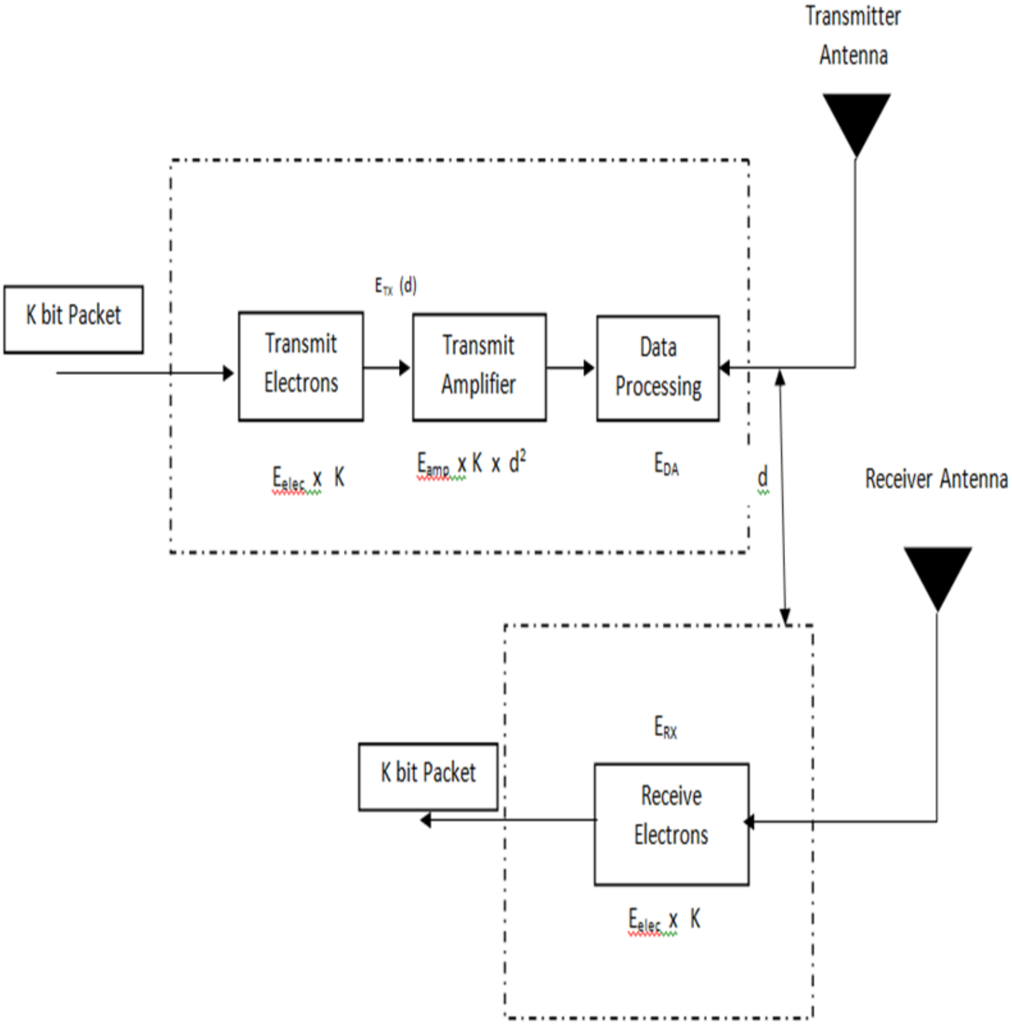


Figure 2. The radio energy dissipation model

3.4. Derivation of the energy-efficient routing model

The objective function of this study is expressed in Equations 16 and 17 as follows:

$$Max\ E_{res} = E_i - l * E_{elec} + l * \varepsilon_{fs} * d^2 \ ; \qquad d < d_0 \ (in\ nanoJoules) \tag{16}$$

$$Max\ E_{res} = E_i - l * E_{elec} + l * \varepsilon_{mp} * d^4 \ ; \qquad d \geq d_0 \ (in\ nanoJoules) \tag{17}$$

Subject to the following constraints in Equations 18 to 21:

$$\textstyle\sum_{a_j \in A_i} q_{ij} = 1, \qquad \forall q_i \in \text{Ai} \tag{18}$$

$$\textstyle\sum_{b_k \in A_i} a_{jk} = 1, \qquad \forall a_j \in Ai \tag{19}$$

$$\textstyle\sum_{q_i \in Q} d_i\, q_{ij} < d_0 \quad \forall q_i \in U \tag{20}$$

$$\textstyle\sum_{q_i \in Q} d_i\, a_{jk} \geq d_0 \quad \forall a_j \in U \tag{21}$$

Equation 16 is the objective function to maximize residual battery energy of individual node (x_i), q_{ij} *and* a_{jk} in Equations 18 and 19 are binary variables, and one (1) if the source node (q_i) transmits data packets to only one CH (a_j) and the CH (a_j) transmits data packets to only one relay node (b_k) respectively otherwise 0.

Equation 18 is a constraint that each source node (q_i)should be assigned to only one CH,a_j in every cluster A_i. Equation 19 is a constraint that each CH, a_j should be assigned to only one relay node $b_{k.}$ in every cluster A_i. Equation 20 is a constraint that the summation of the product of transmission radius (d_i) and hop count of each node should not exceed the reference distance (d_o) in a sensor field. Equation 21 is a constraint that the summation of the product of transmission radius (d_i) and hop count of each node could exceed or equal to the reference distance (d_o).

3.5. Proposed Algorithm

The design of the genetic algorithm-based energy-efficient routing (GABEER) algorithm was established following the presumption that the BS coordinates all the network operations. This entails establishing a routing path and forwarding data packets via the established route. The first phase of network operation starts with the network route setup phase and is followed by the data transmission phase (steady-state phase). During the routing path setup phase, the position of each node was determined using a free-space path loss model. In this case, the BS broadcasts its location information to all the nodes at a specified power level. The specified signal power is computed by each node based on the received signal power. Each node computes the received signal power at a given distance (*d*) that is *Pr (d)* as expressed in Equation 3 [37]. Then, each node forwards the received signal power to the BS accordingly. The BS determines the location of each of the nodes based on the received signal power. The location of each node is a measure of its distance from the BS. Also, the BS computes each node's current battery energy by subtracting the energy dissipated by each node while sending the received signal power from the initial energy assigned to each node as expressed in Equation 9.

Furthermore, the fitness of each node is a function of the residual energy, given that the constraints on transmission distance and cluster density are satisfied. It is assumed that each cluster has a uniform node density. This was followed by assigning roles to cluster member nodes. A genetic algorithm was used in choosing the CH and the relay nodes for each cluster according to the node's current energy level given the constraint of transmission distance to the BS. Selection is an important operator in genetic algorithms, where the best individuals from the population are selected to form the mating pool. The remaining member nodes in the cluster are the source nodes that perform data monitoring tasks.

In addition, since this study optimizes battery energy, the algorithm employed a Time Division Multiple Access (TDMA) scheduling technique to avoid interference of data packets between source nodes and the CH node. Time Division Multiple Access allows each source node to transmit monitored data packets to its respective CH node only within the specified time slot. After the routing path has been established, the BS assigns identities to each of the nodes (node id) in the cluster and to the cluster itself (cluster id). These identities are broadcast to each member node in a cluster. The BS also computes and broadcasts to each member node in the cluster the threshold energy and reference distance. The BS, based on the initial battery energy, computes threshold energy as an average value of the total energy dissipated by each of the nodes during routing path establishment, as expressed in Equation 22 [15]

$$E_{th=} \sum_{u=1}^{M} \frac{E_U}{m} \tag{22}$$

Where:
E_{th} is the energy consumed or utilized by each node E_U during transmission of the received signal power to the BS, M is the total number of nodes, E_{th} the threshold energy value. The reference distance (d_0) is determined as expressed in Equation 8 [13]. Each member node in a cluster updates its routing table. The number of clusters in the proposed model is expressed in Equation 23 [18].

$$\text{Number of Clusters} = \frac{\sqrt{N}}{\sqrt{2\pi}} \frac{\sqrt{\varepsilon_{fs}}}{\sqrt{\varepsilon_{mp}}} \frac{A}{d^2} \tag{23}$$

Where *A* is the length of the sensor field, *d* is the square distance between the nodes and *N* is the number of nodes.

During the data communication phase, the source nodes gather captured data packets. These are transmitted to the CH node using the TDMA schedule, transmitter amplifier circuitry, transmit amplifier cost, and transmission distance (d). The SNs are geographically aggregated into clusters, where each cluster includes a CH node and a relay node. The data packet transmission from source nodes to the CH node covers a short distance, and this is achieved by the introduction of a relay node in the cluster. Once data packets from all source nodes are received, the CH node performs data aggregation using data aggregation energy (E_{DA}) thereby discarding redundant data packets and transmitting the needed data packets to the relay node. Also, the data packet transmission from CH nodes to the relay node covers a short distance since the CH node is situated between the relay node and the source node.

After aggregation, the data is compressed. The compressed data packets, together with the residual energy value and node identity of the source node, are transmitted to the BS by the relay node. The relay node properly informs the BS of the status of each node in terms of residual energy. Besides, it was also assumed that the aggregated data packets from a specific CH node do not experience further fusion as the packets hop through the relay node to the BS. Then, each source node forwards monitored packets, its residual energy value, and node identity to the CH node based on the TDMA. The residual energy values of the CH and relay nodes at this time and subsequent rounds of data transmission are compared with the threshold energy values. This comparison is carried out to ensure that the CH and relay nodes perform optimally in order to reduce packet loss.

However, if the residual energy value of the CH or the relay nodes is less than the threshold energy value, then the BS, through the current CH or relay nodes, performs the selection of new CH or relay nodes from the source nodes. In this study, the selection of the new CH or relay node is based on the node's fitness, which is determined by its residual energy value, transmission distance to the BS, and the number of source nodes in a cluster. New individual CH or relay nodes are produced by crossover and mutation. In the process of crossover, pairs of parent source nodes are selected to exchange genetic traits to produce offspring. Selection of new offspring is based on residual energy and transmission distance. Mutation restores lost genetic material by taking the position of the former CH or relay node. The routing table of each of the source nodes in a cluster is updated thereafter, and this entire cycle is repeated until the last CH or relay node depletes its battery energy below the threshold energy value [38]. Figure 3 depicts the flow chart of the energy-efficient cluster-based routing algorithm. The route setup is specified in Algorithm 1, while the data transmission is specified in Algorithm 2.

Algorithm 1: *Route Setup Algorithm in GABEER*

1. *START (information collection).*
2. *BS broadcast location information using specific signal power (SSP)*
3. *Each node computes RSP using 10 log* $\frac{p}{10}$ *and forward the RS to the BS*
4. *BS determines the location of each node using* $d_i = Q.\sqrt{\frac{P_t(d_o)}{P_r(d)}}$
5. *BS computes the fitness of each node based on the residual battery energy, transmission distance and cluster density.*
6. *BS assigns role to each node based on the fitness*
7. *Relay and CH nodes are selected based on fitness*
8. *Each node in the cluster is assigned identity and the identity is broadcast to every node in the group.*
9. *Each node is allotted time schedule (TDMA) for data transmission.*
10. *BS computes threshold energy and reference distance and broadcasts to every cluster member.*
11. *Update each node routing Table.*
12. *END*

Algorithm 2: *Data Transmission Algorithm in GABEER*

1. *When round = 1, each source node gathers captured data packets.*
2. *Cluster head (CH) node residual energy ≥ Threshold Energy*
3. *Each source node using TDMA, transmitter amplifier circuitry, transmit amplifier cost and transmission distance (d) send captured data to CH node*
4. *CH nodes receives bits of message length, perform data aggregation and forward dada packets to relay node*
5. *Check relay node (RN) residual energy ≥ threshold energy, if Yes then*
6. *CH node forwards aggregated data packet to the RN using transmitter amplifier circuitry, transmit amplifier cost and transmission distance (d).*
7. *Relay node forwards data packets to the BS using transmit amplifier circuitry, transmit amplifier cost and maximum transmission range (*R_{max}*)*
8. *Round > 1 each source node monitors and gathers data packets*
9. *Check CH or RN residual energy ≥ threshold energy, if Yes then go to step 10,11,12*
10. *Source nodes using TDMA, transmitter amplifier circuitry, transmit amplifier cost and transmission distance (d) send captured data to CH node*
11. *CH node using transmitter amplifier circuitry, transmit amplifier cost and transmission distance (d) transmit aggregated data to Relay node (RN)*
12. *Relay node forwards data packets to the BS using transmit amplifier circuitry, transmit amplifier cost and maximum transmission range (*R_{max}*)*

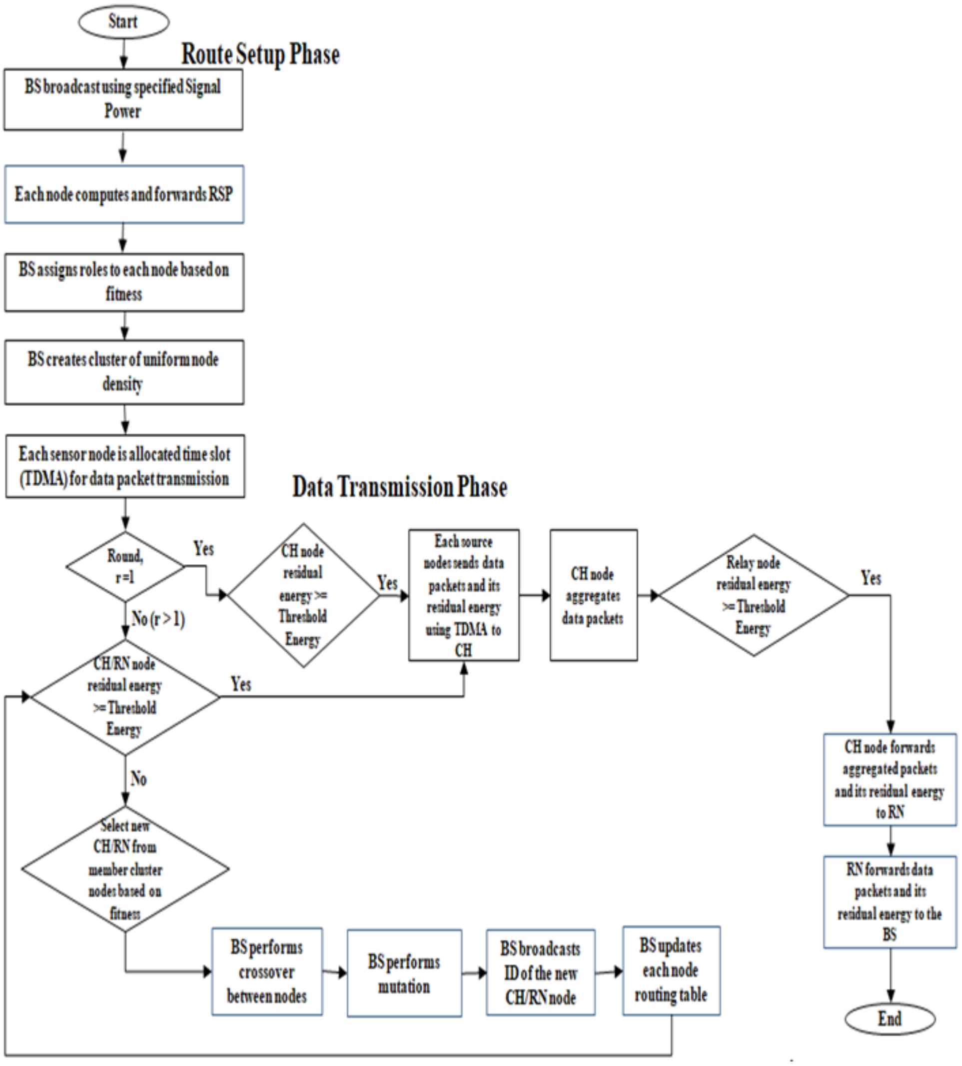


Figure 3. Flow chart of the GABEER Algorithm

Algorithm 2: *Data Transmission Algorithm in GABEER (contd)*

```
13. ELSE BS selects new CH or relay node from cluster member nodes based on the node fitness i.e. residual energy and node transmission distance.
14. Perform Crossover to produce offspring.
15. Perform mutations.
16. Computes fitness of each individual node.
17. Broadcast the identity of the new CH node or the relay node.
18. Update each node routing table
19. Go to step 8
20. Go to step 9
21. Then do steps 10, 11,12
22. END
```

4. RESULTS AND DISCUSSION

The implementation of the GABEER algorithm was carried out using the C++ programming language. The developed algorithm allowed transmission of data packets from a source node to the CH, fusion of data packets at the CH, and discarding of uncorrelated data. Additionally, the developed algorithm allowed aggregated data packets to be transmitted to the relay node and from the relay node to the BS. The WSN was simulated using the Network Simulator (NS-3). This study considered NS-3.29 on the Ubuntu 18.04 Linux version. In this study, the number of source nodes around a CH node and transmission distance are key parameters for efficient use of battery energy resources in wireless sensor networks. The number of source nodes around a CH node and transmission distance determine the energy depletion of the CH node. The longer the transmission distance, the faster the energy depletion and the lower the residual energy of the node. This results in a less stable period and shorter network lifetime. The data packets from each node are constant in this study, but the transmission distance varies.

The simulation environment for the sensor network is composed of 100 SNs deployed randomly and uniformly over a *200×200*m^2 sensor field. The nodes are homogenous and offered with an initial battery energy of *1.5J*. The location of the BS is set to 100 and 250, corresponding to the x and y coordinates of the sensor field. The parameters used in the simulation scenario are given in Table 2.

Table 2. Simulation Parameters

Parameter	**Value**
Location of the BS	(100,250)
Number of nodes(N)	100
Initial battery Energy	1.5J
Data packet size, *l*	500 bytes
Transmitted or receiver circuitry (E_{elec})	50 nJ/bit
Computational cost of fitness (E_{fitnes})	5 nJ/bit/signal
Data aggregation cost (E_{DA})	5 nJ/bit/signal
Transmit amplifier cost (ε_{mp})If d ≥d_o	0.0013PJ/bit/m^4
Transmit amplifier cost (ε_{fs})If d <do	10PJ/bit/m^2
Transmission distance (d)	94.28m
Maximum Transmission range (R_{max})	2 × d = 188.56m
Threshold energy values	0.1, 0.3, 0.5

4.1 Performance metrics and parameters

The metrics used in the simulation of the proposed model are described as follows:

4.1.1. Stability Period

This is described to as the quantity of data packet transmission rounds from the source nodes to the BS through the CH and the relay nodes until the first node dies. The smaller the residual energy value, the shorter the stability period, and the higher the residual energy value, the longer the stability period. The higher the stability period, the better the network performance; the lower the stability period, the worse the network performance. This is expressed in Equation 24.

$$Stability\ period\ = \frac{Residual\ energy\ of\ each\ node}{Energy\ depletion\ per\ round} \tag{24}$$

4.1.2. Network lifetime

This is expressed as the number of rounds of data transmission from the source node to the BS until the last CH or relay node depletes its energy. The network lifetime is proportional to the average residual energy value of the nodes. The smaller the average residual energy value, the shorter the network lifetime; the higher the average residual energy value, the longer the network lifetime. Also, the higher the network lifetime, the better the network performance; the shorter the network lifetime, the worse the network performance. This is expressed in Equation 25.

$$Network\ lifetime\ = \frac{Average\ residual\ energy\ of\ the\ nodes}{Average\ energy\ depletion\ per\ round} \tag{25}$$

4.1.3. Packet loss

This is defined as the difference between the packet sent (PS) and the throughput (PR) at the BS. The higher the throughput, the better the performance of the network; the lower the throughput, the worse the network performance. This is expressed in Equation 26.

$$Ploss\ = \sum_{i=1}^{N} P_{S-}\ P_R \tag{26}$$

4.1.4. Number of rounds

This represents the number of times data packets are effectively and efficiently transmitted from the source node to the BS through the CH and relay nodes. It also shows that the stability period of a CH node is proportional to the threshold energy value. The stability period is longer with smaller values of threshold energy and shorter with higher values of threshold energy.

4.1.5. Number of dead nodes

This depicts the total number of dead nodes throughout the network lifetime. That is the total number of rounds that the nodes are able to transmit data packets for the network lifetime. The network lifetime is proportional to the average residual energy value of the nodes. The smaller the threshold energy value, the greater the network lifetime, and the higher the threshold energy value, the smaller the network lifetime.

4.2. Simulation of the proposed algorithm on WSN

The wireless sensor network was simulated using Network simulator (NS) specifically Network simulator 3 (NS-3). In the implementation of the routing algorithm in wireless sensor network, this study considered NS-3.29 on Ubuntu 18.04 Linux version. The command *./build (./build.py)* was used to run the setup ns-allinone-3.29. The C++ code for the energy-efficient cluster-based routing algorithm was deployed in NS-3 simulator's scratch folder. The command *./waf* -- run was used to run the C++ code for the energy-efficient cluster-based routing algorithm. The command *struct* explains an array of any data type such as integer, real or float data type. While the command *printf* was used to display result.

An energy-efficient cluster-based routing algorithm simulation was leveraged on the existing modules of the Low-Energy Adaptive Clustering Hierarchical (LEACH) protocol. This research adapted existing modules in the LEACH protocol. The modules and sub-modules are described in Table 3.

Table 3. Description of modules used in simulation

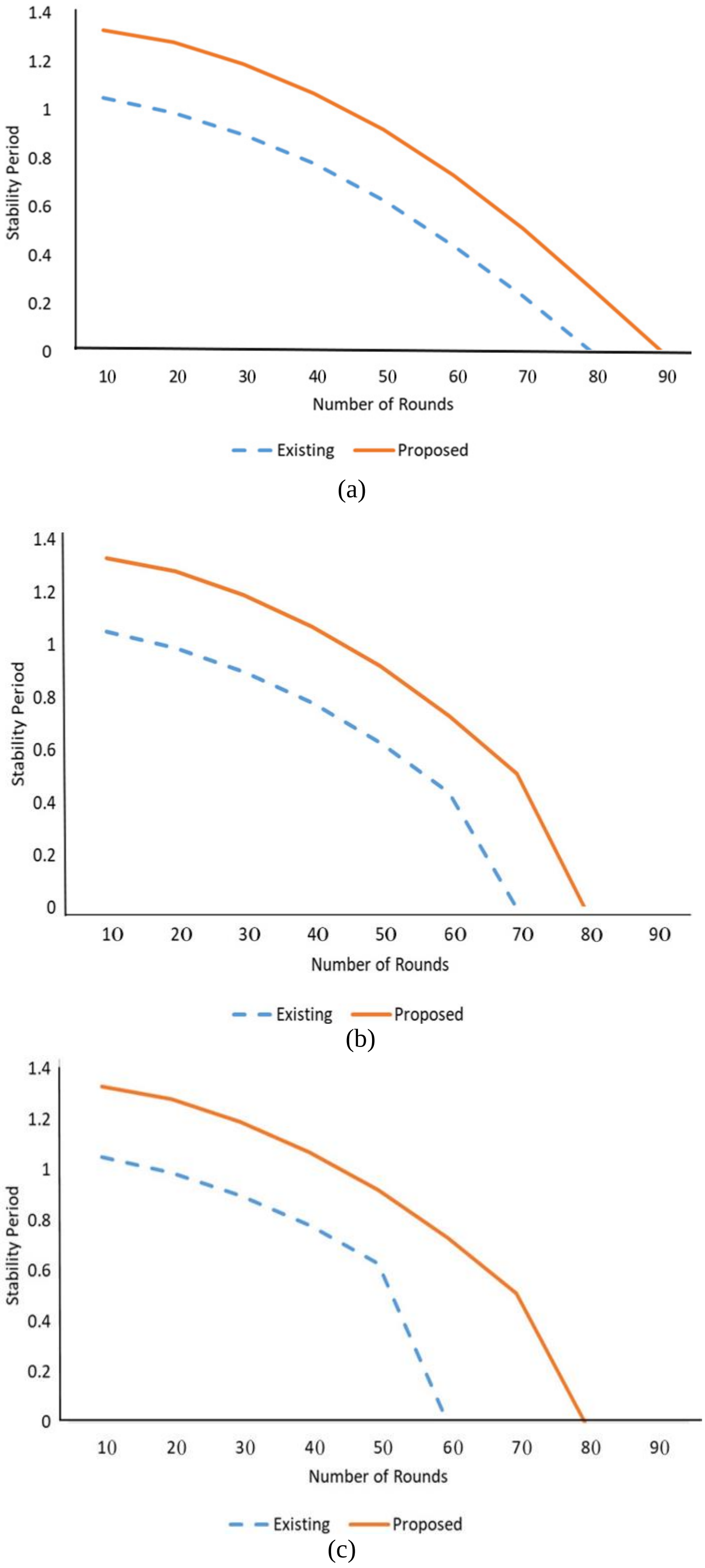
Modules	Description
Energy dissipation	This main module computes energy depletion for data transmission, reception and aggregation.
Transmission energy	This sub module computes energy depletion for data forwarding as the summation of product of message length in bits, electronic energy in nanoJoules/bits and energy amplifier which is a function of distance (d)
Reception energy	This sub module generates energy dissipation as a product of message length in bits and electronic energy in nanoJoules/bits
Aggregation energy	This sub module computes energy consumption during data fusion without losing actual information.
Selection	This module chooses new CH or Relay node.
Crossover	This module generates a new CH or Relay node as offspring from population of nodes A_i as A_1, A_2, A_3, A_4,A_5 etc based on nodes residual energy and transmission distance.
Mutation	This module creates a new CH or relay node by swapping existing CH or relay node with new offspring.

4.3. Evaluation of the Proposed model

The performance of the proposed model was compared to that of an existing algorithm, Energy Centric Cluster-Based Routing Protocol (ECCBRP), using network lifetime, stability period, and packet loss as metrics. The results were verified by a simulation experiment on a 100-node network where the number of clusters and the threshold energy values were varied to determine the maximum number of clusters where the node's limited energy resources could be optimally utilized. In the simulation, number of clusters varied between five (5), ten (10), and twenty (20), whereas the threshold energy values were 0.1, 0.3, and 0.5.

For five (5) clusters, the existing ECCBRP has a stability period of 76 rounds, 67 rounds, and 58 rounds for threshold energy values of 0.1, 0.3, and 0.5, respectively, whereas GABEER has a stability period of 86 rounds, 79 rounds, and 71 rounds for the same threshold energy values of 0.1, 0.3, and 0.5, respectively, as represented in Figure 4 (a), (b), and (c). Moreover, the existing ECCBRP has a network lifetime of 923 rounds, 819 rounds, and 710 rounds for threshold energy values of 0.1, 0.3, and 0.5, respectively, whereas the proposed GABEER has a network lifetime of 1045 rounds, 958 rounds, and 866 rounds for the same threshold energy values of 0.1, 0.3, and 0.5, respectively, as represented in Figure 5 (a), (b), and (c).

The result of the simulation for packet sent, throughput, and packet loss when the threshold energy value was 0.1 for five clusters was: for the GABEER algorithm, the packet sent was 5543000, the throughput was 5448769, 5448769 while the packet loss was 94231; for the ECCBRP algorithm, the packet sent was 94231 while ECCBRP packet sent was 4873500, the throughput was 4629825 and the packet loss was 243675. When threshold energy value was 0.3 for five clusters; GABEER algorithm packet sent was 5084500, throughput was 4998065 and packet loss was 86437 while ECCBRP packet sent was 4354000, throughput was 4136300 and packet loss was 217700. When treshold energy value was 0.5 for five clusters; for GABER the packet sent was 4601000, the throughput was 4522783 while the packet loss was 78217 while for ECCBRP the packet sent was 3786500 , the throughput was 3597175 while the packet loss was 189325.

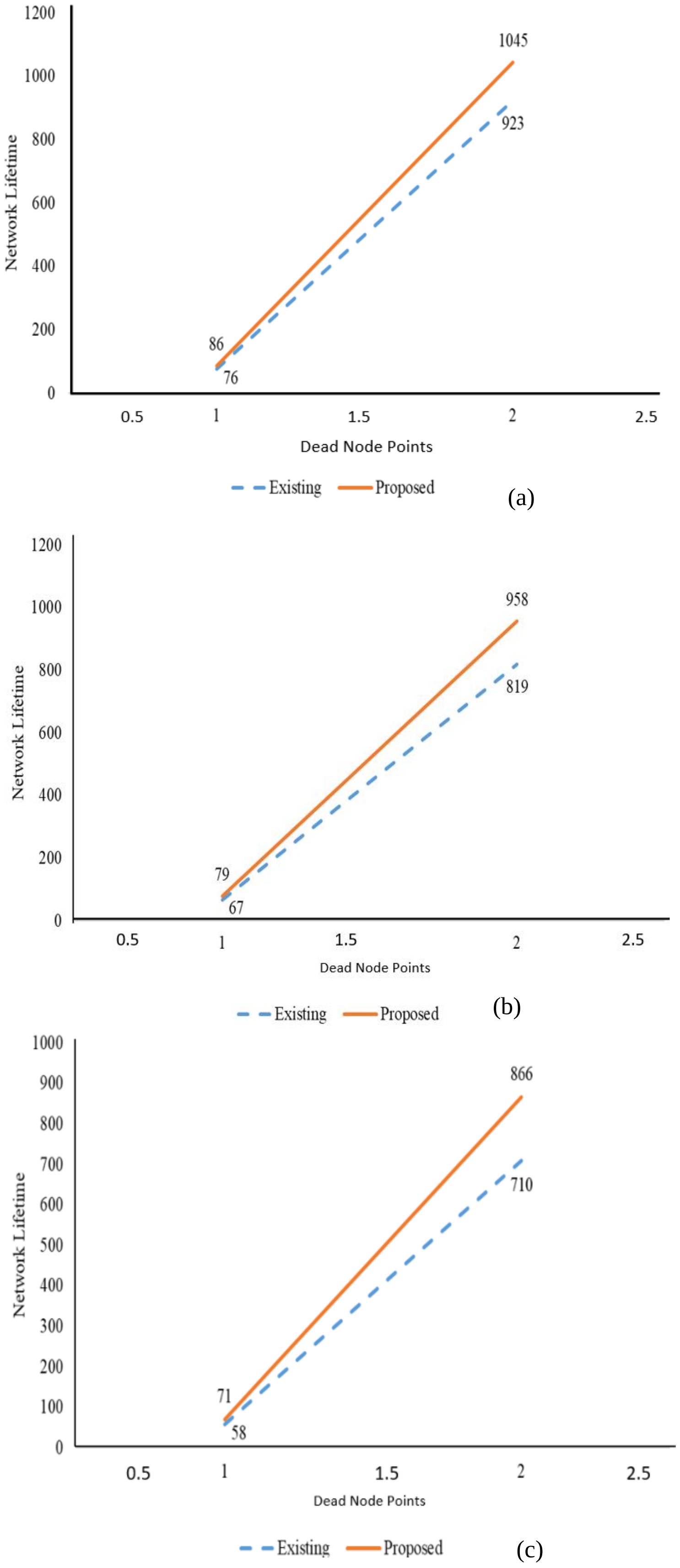


(a)

(b)

(c)

Figure 4. Stability period against number of rounds at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 for five clusters



(a)

(b)

(c)

Figure 5. Network lifetime against dead node points at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 respectively for five clusters

For ten clusters (10), the existing ECCBRP has stability period of 114 rounds, 101 rounds and 87 round for threshold energy values 0.1, 0.3 and 0.5 respectively whereas GABEER has stability period of 129 rounds, 119 rounds and 106 rounds for the same threshold energy values 0.1, 0.3 and 0.5 respectively as represented in Figure 6 (a), (b) and (c). Furthermore, the existing ECCBRP has network lifetime of 1291 rounds, 1150 rounds and 995 rounds for threshold energy values 0.1, 0.3 and 0.5 respectively whereas the proposed GABEER has network lifetime of 1464 rounds, 1346 rounds and 1214 rounds for the same threshold energy values 0.1, 0.3 and 0.5 respectively as represented in Figure 7 (a), (b) and (c).

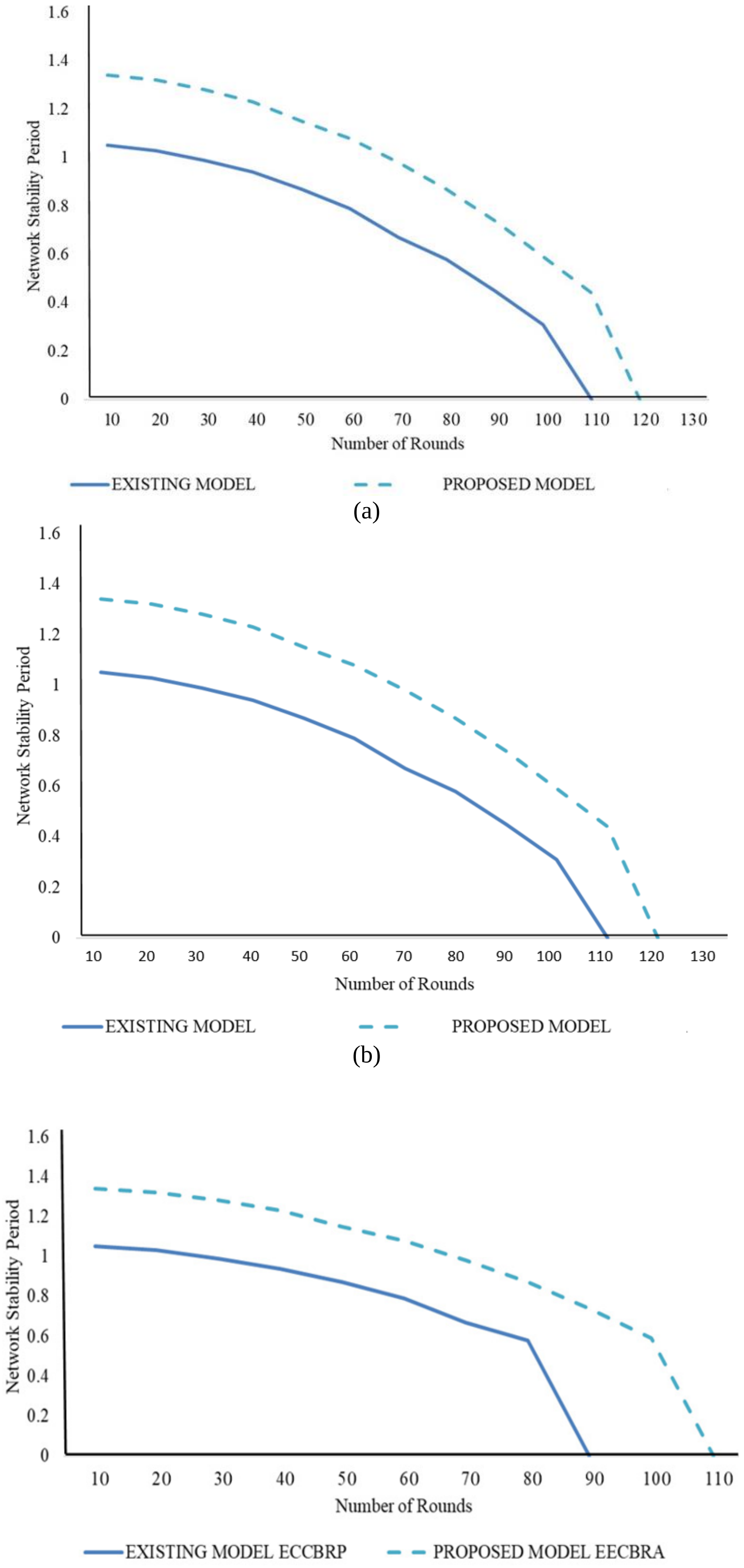
The result of the simulation for packet sent, throughput and packet loss when threshold energy value was 0.1 for ten clusters; for GABEER algorithm the packet sent was 3563000, the throughput was 3502429 while the packet loss was 60571 while ECCBRP packet sent was 3132000, the throughput was 3078756 and the packet loss was 53244. When threshold energy value was 0.3 for ten clusters; GABEER algorithm packet sent was 3269000, throughput was 3213427 and packet loss was 55573 while ECCBRP packet sent was 2796000 , throughput was 2748468 and packet loss was 47532 . When threshold energy value was 0.5 for ten clusters; for GABEER algorithm the packet sent was 2951500, the throughput was 2901324 while the packet loss was 50176 while for ECCBRP the packet sent was 2414000, the throughput was 2372962 while the packet loss was 41038.

For twenty clusters (20), the existing ECCBRP has stability period of 186 rounds, 165 rounds and 142 round for threshold energy values 0.1, 0.3 and 0.5 respectively whereas GABEER has stability period of 214 rounds, 194 rounds and 175 rounds for the same threshold energy values 0.1, 0.3 and 0.5 respectively as represented in Figure 8 (a), (b) and (c). Furthermore, the existing ECCBRP has network lifetime of 1722 rounds, 1536 rounds and 1798 rounds for threshold energy values 0.1, 0.3 and 0.5 respectively whereas the proposed GABEER has network lifetime of 1958 rounds, 1798 rounds and 1798 rounds for the same threshold energy values 0.1, 0.3 and 0.5 respectively as represented in Figure 9 (a), (b) and (c).

The result of the simulation for packet sent, throughput and packet loss when threshold energy value was 0.1 for twenty clusters; for GABEER algorithm the packet sent was 2044000, the throughput was 2009252 while the packet loss was 34748 while ECCBRP packet sent was 1796500, the throughput was 1706675 and the packet loss was 1019825. When threshold energy value was 0.3 for twenty clusters; GABEER algorithm packet sent was 1875500, throughput was 1843616 and packet loss was 41884 while ECCBRP packet sent was 1602500, throughput was 1522375 and packet loss was 80125 . When treshold energy value was 0.5 for twenty clusters; for GABER the packet sent was 1688500, the throughput was 1659795 while the packet loss was 28705 while for ECCBRP the packet sent was 138100, the throughput was 1311950 while the packet loss was 69050. Based on the residual energy, transmission distance, and number of data packets per cluster, the simulation results showed that the stability period, network lifetime, and packet loss of the energy-efficient cluster-based routing algorithm (GABEER) for different number of clusters outperforms the ECCBRP.

4.3.1. Number of clusters in the sensor field

The simulation results of the proposed GABEER algorithm shown in Tables 4, 5, and 6 present the performance in terms of the number of clusters in the sensor field for varied threshold energy levels. Table 4 displays the network stability period against the number of rounds at different threshold energy values for 5 clusters, while Tables 5 and 6 depict 10 and 20 clusters, respectively. Simulation for five (5) clusters shows that the residual energy of each node decreases with an increasing number of rounds. It also shows that the stability period of a CH node is proportional to the threshold energy value. The stability period is longer with higher values of threshold energy. Figures 4–9 show that the stability period and network lifetime of the GABEER algorithm vary based on different values of the energy threshold. The outputs of the graphs demonstrated that the stability period and network lifetime are both longer when the energy threshold value is smaller.

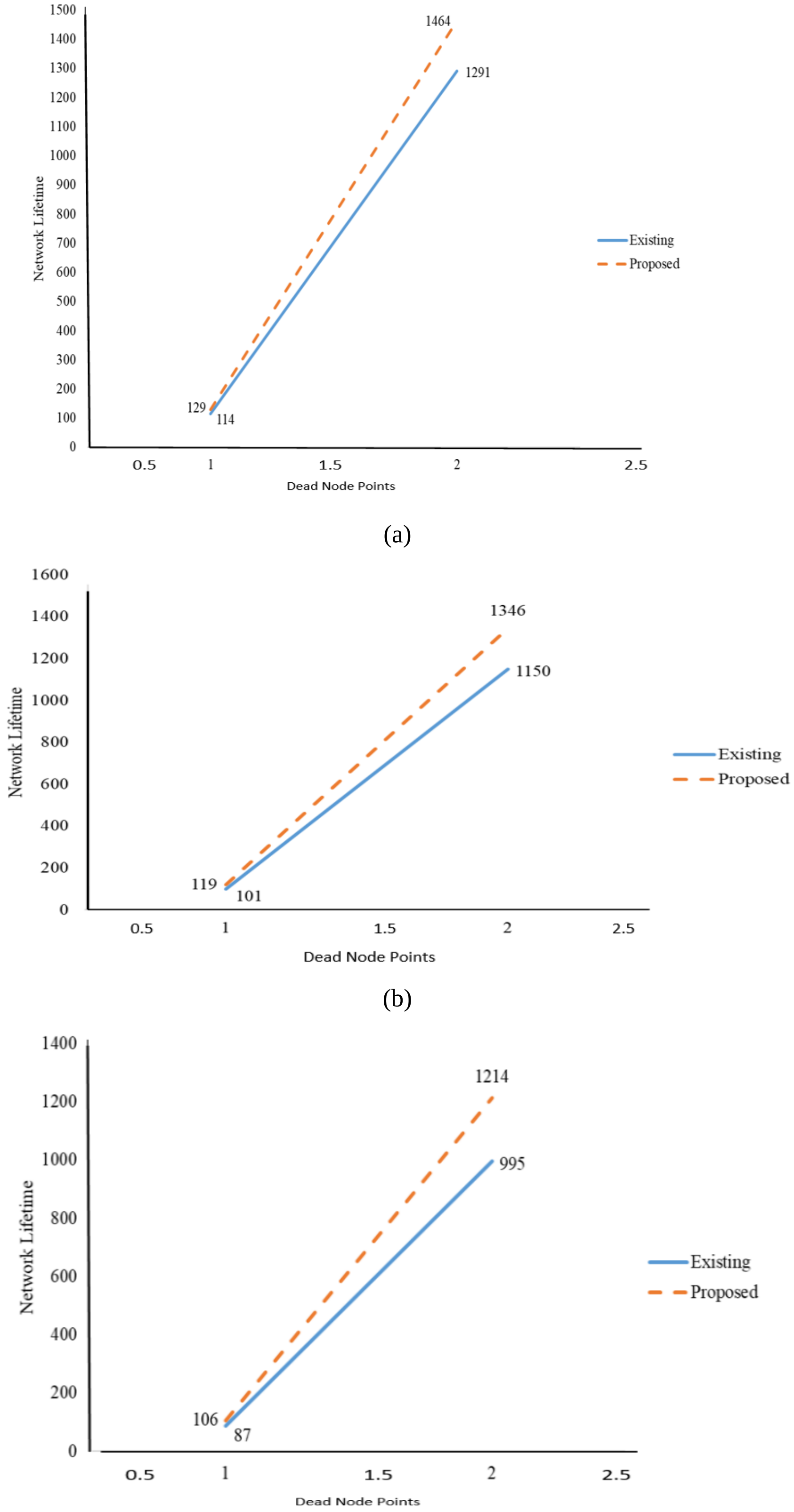


(a)

(b)

(c)

Figure 6. Stability period against number of rounds at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 for ten clusters.

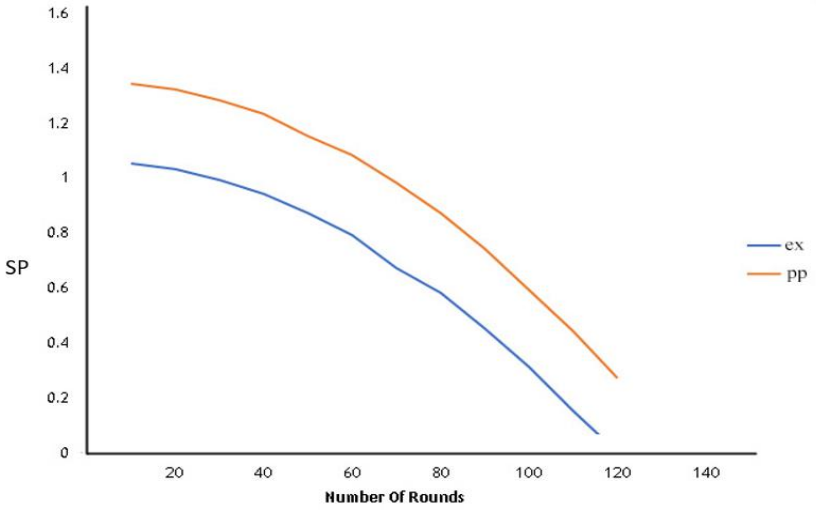


(a)

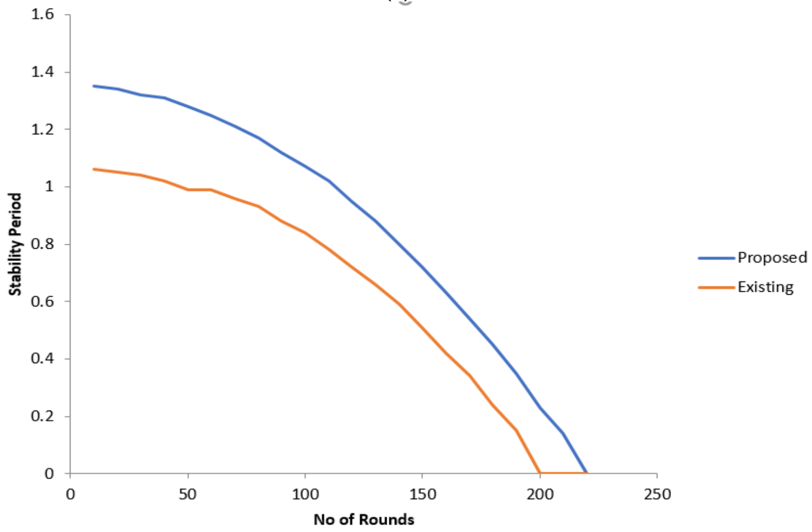
(b)

(c)

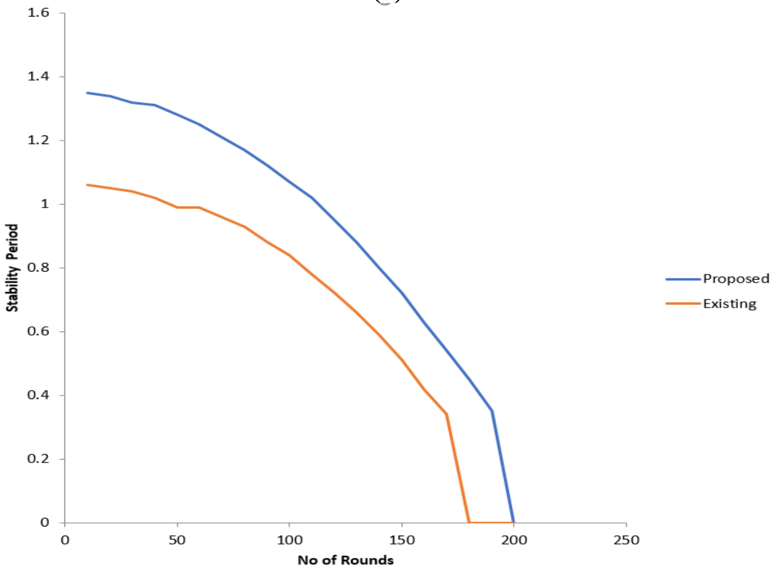
Figure 7. Network lifetime against dead node points at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 respectively for ten clusters



(a)

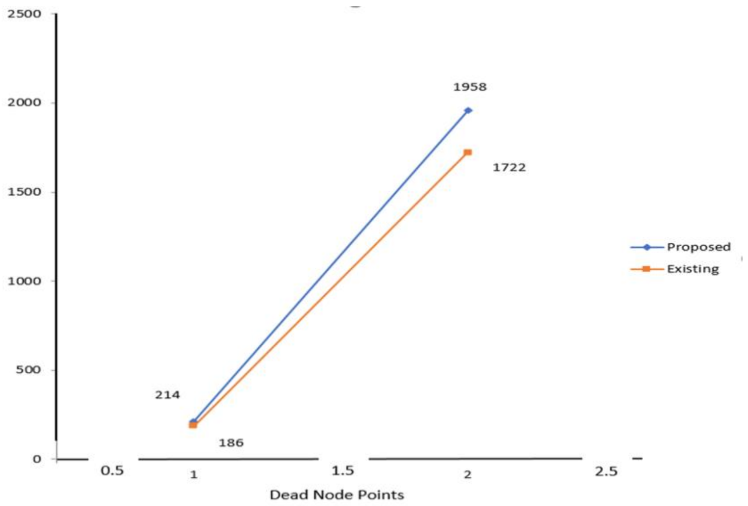


(b)

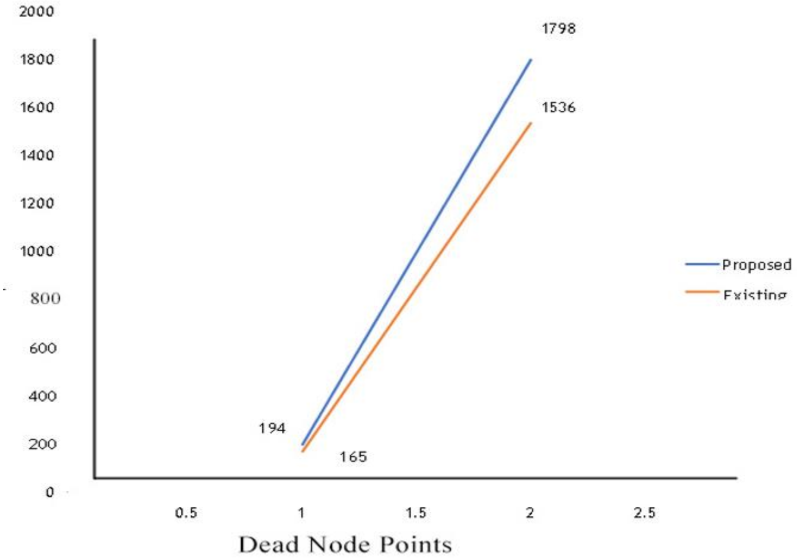


(c)

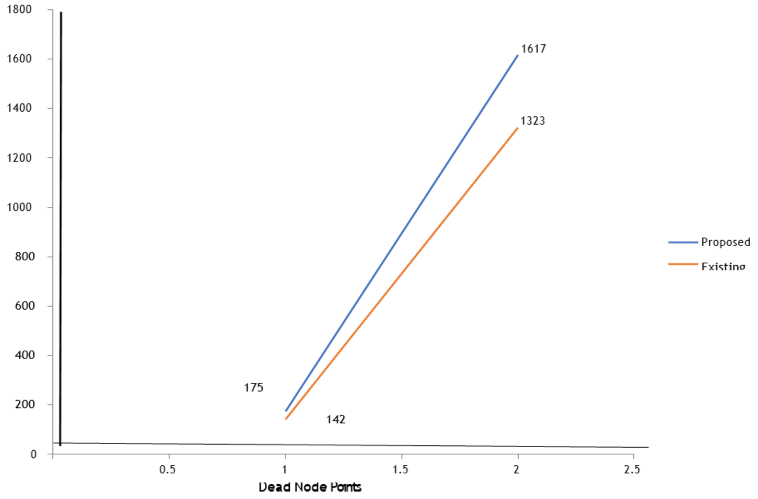
Figure 8. Stability period against number of rounds at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 for twenty clusters



(a)



(b)



(c)

Figure 9. Network lifetime against dead node points at threshold energy values of (a) 0.1 (b) 0.3 (c) 0.5 respectively for twenty clusters

Table 4. Network stability period against number of rounds at different energy threshold for 5 clusters

Number of round	Stability period (ECCBRP) for threshold energy values			Stability period (GABEER) for threshold energy values		
	0.1	0.3	0.5	0.1	0.3	0.5
10	1.05	1.05	1.05	1.33	1.33	1.33
20	0.99	0.99	0.99	1.28	1.28	1.28
30	0.9	0.9	0.9	1.19	1.19	1.19
40	0.78	0.78	0.78	1.07	1.07	1.07
50	0.63	0.63	0.63	0.92	0.92	0.92
60	0.44	0.44	0.00 (58 round)	0.73	0.73	0.73
70	0.23	0.00 (67 round)	-	0.51	0.51	0.51
80	0.00 (76 round)	-	-	0.26	0.00 (79 round)	0.00 (71 round)
90	-	-	-	0.00 (86 round)	-	-
100	-	-	-	-	-	-

Table 5. Network stability period against number of rounds at different energy threshold for 10 clusters

Number of round	Stability period (ECCBRP) for threshold energy values			Stability period (GABEER) for threshold energy values		
	0.1	0.3	0.5	0.1	0.3	0.5
10	1.05	1.05	1.05	1.34	1.34	1.34
20	0.03	0.03	0.03	1.32	1.32	1.32
30	0.99	0.99	0.99	1.28	1.28	1.28
40	0.94	0.94	0.94	1.23	1.23	1.23
50	0.87	0.87	0.87	1.15	1.15	1.15
60	0.79	0.79	0.79	1.08	1.08	1.08
70	0.69	0.69	0.69	0.98	0.98	0.98
80	0.58	0.58	0.58	0.87	0.87	0.87
90	0.45	0.45	0.00 (87 round)	0.74	0.74	0.74
100	0.31	0.31	-	0.59	0.59	0.59
110	0.15	0.00 (101 round)	-	0.44	0.44	0.00 (106 round)
120	0.00 (114 round)	-	-	0.27	0.00 (119 round)	-
130	-	-	-	0.00 (129 round)	-	-

Table 6. Network stability period against number of rounds at different energy threshold for 20 clusters

Number of round	Stability period (ECCBRP) for threshold energy values			Stability period (GABEER) for threshold energy values		
	0.1	0.3	0.5	0.1	0.3	0.5
10	1.06	1.06	1.06	1.35	1.35	1.35
20	1.05	1.05	1.05	1.34	1.34	1.34
30	1.04	1.04	1.04	1.32	1.32	1.32
40	1.02	1.02	1.02	1.31	1.31	1.31
50	0.99	0.99	0.99	1.28	1.28	1.28
60	0.96	0.96	0.96	1.25	1.25	1.25
70	0.93	0.93	0.93	1.21	1.21	1.21
80	0.88	0.88	0.88	1.17	1.17	1.17
90	0.84	0.84	0.84	1.12	1.12	1.12
100	0.78	0.78	0.78	1.07	1.07	1.07
110	0.72	0.72	0.72	1.02	1.02	1.02
120	0.66	0.66	0.66	0.95	0.95	0.95
130	0.59	0.59	0.59	0.88	0.88	0.88

Number of round	Stability period (ECCBRP) for threshold energy values			Stability period (GABEER) for threshold energy values		
	0.1	0.3	0.5	0.1	0.3	0.5
140	0.51	0.51	0.00 (142 round)	0.8	0.8	0.8
150	0.42	0.42	-	0.92	0.92	0.92
160	0.34	0.34	-	0.63	0.63	0.63
170	0.24	0.00 (165 round)	-	0.54	0.54	0.00 (175 round)
180	0.15		-	0.45	0.45	-
190	0.00 (186 round)	-	-	0.38	0.38	-
200	-	-	-	0.23	0.00 (194 round)	-
210	-	-	-	0.14	-	-
220	-	-	-	0.00 (214 round)	-	-

5. CONCLUSION

This study proposed a model and routing algorithm designed to address imbalance energy depletion for situations where SNs are static. In this case, the BS is assumed to be a node with a reference distance. The energy-efficient cluster-based routing model for WSNs was developed to promote sensor network lifetime and improve stability period of sensor nodes. In order for the deployed nodes to utilize the restricted energy resources as efficiently as possible, static clustering is used and relay node was introduced to assist in reducing the intra-cluster distance between the CH and the BS. This brought about the difference in the performance of GABEER algorithm and the existing model. Selection of the CH and relay nodes is dependent on the consideration of node residual energy, the distance between the node and the BS, and the cluster node density around each node. This balances the energy depletion of each node in the sensor network as CH and relay node selection were based on these key parameters. In addition, this study adopted a technique where each node transmits its residual energy alongside the data packets to the BS. This approach reduces the number of control messages and the delay usually experienced in selecting a new CH or relay node in the sensor network. This study ensures an efficient route of data packets to the BS. Generally, the proposed model considers the conservation of each node's energy resource in a bid to enhance the network lifetime.

ACKNOWLEDGMENTS

This Research was funded by the TETFund Research Fund and Africa Centre of Excellence OAK-Park

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