An Energy Efficient Gravitational Model for Tree Based Routing in Wireless Sensor Networks

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***Abstract*—** **Wireless Sensor Networks (WSNs) are commonly utilized to collect data from a variety of locations. The most important factor is to reduce energy use for WSN to maximize the network lifetime. A bottleneck free dynamic network for WSN is very effective to achieve the flexibility for data gathering to save energy, thereby enhancing network lifetime. We present a novel tree-clustering algorithm in this paper based on the natural gravitational model to save energy in WSN. We have used the concept of natural gravitational force to construct the tree cluster routing structure for wireless sensor nodes. The main goal of this strategy is to use gravitational tree-cluster and multi-hop concepts to reduce data transmission distance while maintaining a bottleneck-free routing path for sensor nodes. To develop an effective routing structure, the residual energy of sensor nodes and the distance between them are considered. By balancing the network load and using the most reliable routing channel, the sensor nodes' energy consumption is minimized and their lifetime is extended. We demonstrate that our suggested approach outperforms comparable works in terms of energy usage, network life, throughput, and transmission overheads using computer simulation. Furthermore, by employing the network, a sufficient delay time, minimum distance communication, and a minimum number of message retransmissions are achieved.**

***Index Terms*—** **Network lifetime, energy consumption, gravitational tree, distance, sensor networks.**

I. INTRODUCTION

The recent growth of Wireless Sensor Network (WSN) infrastructure has inspired the researcher's interest in analyzing and discovering new communication techniques. Sensor-based communication networks have been used as a supplement to wireless and mobile communication systems. The recent uses of a sensor network in habitat sensing, agricultural crop monitoring, battlefield surveillance, vehicle monitoring, object tracking, environmental monitoring, and many other applications have drawn enormous popularity. With the rise of WSN applications, there have been expectations from the network for collecting data from the environment within a feasible network lifetime [15]. In general, sensors are deployed randomly in a dynamic environment or hazardous area. Once it is deployed, in most cases, it is almost impossible for the user to replace its resources, such as battery power. The battery power is the most critical functionality in a sensor, thereby, making it a scope for designing new protocol and architecture for WSNs, which are the most challenging parts [11]. The sensors gather information from the environment and transfer it to sensor nodes nearby. The neighbor sensor node collects and aggregates it with its own data and route it to the next neighbor nodes. This procedure continues until the data reaches the network's base station (BS), as seen in fig. 1.

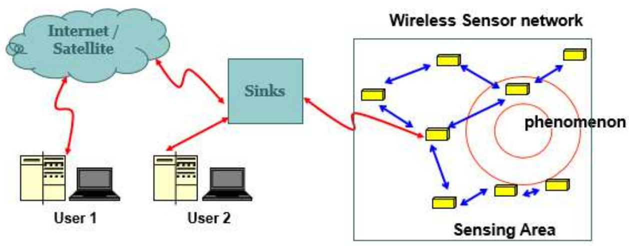

Fig. 1 Simple wireless sensor networks.

Sensing, processing, communicating, sleeping, and idle/waiting consume the energy of a sensor node. The communication phase (sending and receiving data) uses the majority of the power of the sensor nodes, shortening the network life and causing the network to fail to deliver the expected output during deployment[1]. If the network is disconnected, due to the death of some nodes during operation for the want of battery power, the network operator is required to reinstall rechargeable/replicable batteries or replace the dead sensor nodes. Both cases are complicated, time-consuming, and sometimes impossible. Such situations, therefore, demand the designing of an energy-efficient routing protocol that will reduce the data transfer distance and make a reliable routing path for radio propagation, thereby ensuring the desired lifetime of WSNs.

Existing WSN routing protocols can be categorized based on network architecture, communications type, topological, and trustworthy routing based on sensor node cooperation in data collection [11]. Cluster-based, chain-based, and tree-based protocols are three prevalent types of network structure-based protocols [8]. A circle-like area is termed a cluster in cluster-based protocols, and a special node within a cluster is chosen as a cluster-head by some preset probability, and other nodes in the cluster combine with the cluster-head to build a Voronoi-structure topology. The cluster-based protocol's major goal is to enable multi-hop data transmission between the sensor and the base station. The quantity of transmitted messages can be minimized using data aggregation, and certain nodes can sleep for a while, saving a lot of energy for sensor nodes.

The sensor nodes in chain-based protocols are grouped in such a way that they form a logical chain structure. The chain is formed by the sensor nodes or greedy algorithms that starts with a few nodes initially. A chain head is chosen from among the nodes in the chain with the most energy, and other nodes relay data to the chain head via their neighbor nodes. The chain head is directly connected to the base station.

The *contributions* of this work are

- Propose a novel energy efficient bottleneck-free tree cluster and cluster head selection algorithm for WSN that can survive longer.
- Develop a mathematical model for tree clustering
- Validate the model through extensive simulation

Our findings show that the suggested system may collect data for a longer period of time (in comparison to others) without being disrupted by path reconstruction and/or bottlenecks. The remaining part of this work is arranged as follows. We studied related works from the existing literature in Section II. In Section III, we give a mathematical definition of our suggested system model. We provide our simulation model in Section IV and compare it to existing schemes. Section V brings us to a close.

II. LITERATURE REVIEW

With their limited computational power, memory, and battery resources, the sensors utilized in WSNs can only perform a few number of computational operations. Therefore, energy is a very critical element and efficient use of energy is very crucial. The sensor node's communication(sending and receiving data) consumes the majority of its energy. Therefore, the selection of an optimal route for communication is very important while designing an energy-efficient protocol. Many studies on energy conservation and extending the network life of WSNs have been done in recent years.The routing techniques in WSNs are different from other types of wireless networks because of their application-specific data flow, stationary nature, and energy limitation. WSNs have some disparities in routing. To address these issues, a number of routing protocols have been developed. These routing protocols have been proposed based on their intended use and architectural considerations [15]. Highly efficient routing protocols can save significant amounts of node resources and can have prolonged the network lifetime. The routing protocols were divided into four primary schemes by the authors in [11]: network structure, communication model, topology-oriented, and reliable routing scheme.

Some of the most popular protocols like LEACH [4], HEED [21], and CEDA [17] are cluster-based. The cluster-based protocols gained their popularity due to their easy implementation and the resource of sensor and cluster-head are easily manageable. If some child node dies out, the overall performance of data collection and accuracy does not affect so much. The main drawbacks of the cluster-based protocol are that its distributed algorithm will not confirm about a specific number of cluster head (CH). The CH node performs most of the communicating activities (sending and receiving the message) that consumes more energy than other nodes and die-out earlier which causes network disconnection and data loss. The size of the cluster is difficult to predict or control in those schemes.

Sensor nodes in tree-based protocols are arranged in a hierarchical tree form. Leaf nodes, intermediate nodes, and root or cluster head nodes are the three types of nodes. The data is only sensed by the leaf node and send to an intermediate node. The intermediate node collects and accumulates data from the leaf nodes before transmitting to the root head node of the cluster. The root or cluster head is also in charge of collecting and aggregating data from intermediate nodes before sending it to the base station.

There are several chain-based protocols; among them, the most popular protocols are PEGASIS [9], CCS [13], GCHC [20], etc. Chain-based protocols connect with their neighbors by transmitting data to the chain head using low-power radio energy, which saves a significant amount of energy and prolong the network lifetime. In the chain-based protocols, the sensor nodes are not required to form a cluster (as in the cluster-based protocols) and it can avoid the overhead for cluster formation. However, a sensor node in the chain-based protocols is required to monitor its neighbor to identify the data routing path. The main problem of this topology is the length of the chain. If the length of the chain is higher, it takes a large delay to deliver data to the chain head.

The most popular tree-based protocols are Maximum Lifetime Data Gathering Algorithm(MLA) [19], Power Efficient Data Collection and Accumulation(PEA) [5], Tree Based Data collecton for Maximum Life(TMA) [22], Efficient Tree-Based Power Saving Scheme for Wireless Sensor Networks With Mobile Sink(TRMS) [6] and Energy efficient gravitational model for tree based routing in n Wireless Sensor Networks (GTR)[12], Optimal Locations of Mobile Sink(OLMS) [10], Tree-Cluster-oriented Data-collection Algorithms for Industrial WSNs with a Mobile BS or Sink(TIMS) [2], etc. Here, MLA, PEA, and TMA use a static sink or base station whereas TRMS, TIMS, and OLMS use the mobile sink. Tree-based schemes ensure less delay than chain-based schemes. The overhead problem of CH can be reduced than other schemes. In tree-based schemes, the leaf node and other nodes are organized in a hierarchical manner; hence, nodes can sleep periodically in the non-operational moments, thereby saving a a substantial amount of energy. The networks are also maintained by multi-hop communication which further reduces energy consumptions, enhancing network lifetime. The tree is a simple topology and it maintains minimum graph structure [20]. Due to the above-mentioned reasons, we have chosen tree structured-based protocols in our work.

The major limitations of the work discussed earlier:

- Residual energy and distance both are not considered for cluster formation.
- Low energy node may become the intermediate node of the routing path which may die within the round, and it will disconnect the network, and which will create a negative impact on data accuracy.

III. PROPOSED SYSTEM

The most difficult challenge in the sensor network is efficiently collecting data from the environmental phenomenon and transfer it to the sink or base station. The WSNs are applied in many practical and dynamic applications which attract the researchers to contribute more for its better performance. Numerous researchers are still working for constructing energy efficient tree-based routing structures. So, it is required to participate in the establishment of a standard technique with higher network quality with an expected lifetime. In this section, we discuss different schemes and identify some interesting problems which are needed to solve immediately. In LEACH [3, 16, 7, 13, 14] based protocols, the CH selection is random and the CH distribution is not uniform. So, a large number of nodes may cover by a single CH which creates an extensive load to a CH and dies out quickly.

TRMS [6] is a proposed tree structure based on a dynamic sorting algorithms. In the tree formation process, the choice of intermediate node is according to the distance only. However, a low-energy node has a greater chance to become an intermediate node of the tree which will create a bottleneck and may die out before completing a round. The major problems discussed above are taken into consideration for analysis and then provide a solution in this paper. The following are the main contributions of this paper: i) developing a tree-cluster based on the distance between sensor nodes and each node's residual energy, ii) ensuring that the low energy node has no chance of becoming an intermediate node or CH, and iii) selecting the higher energy local node with the best distance as a CH.

A. Network Model and Assumptions

A group of sensor nodes $N = \{a_1, a_2, \ldots a_n\}$ are distributed randomly in an area as the system's basis. They build a graph G(N,E,D) that is interconnected, where D is the distance between sensor nodes, while E is the bidirectional wireless link. If two nodes, α_i and $\alpha_j$are within their communication range, the link represents $e(\alpha_i, \alpha_j) \in E$, and the distance between nodes is $d_{ij} \in D$. We classify the sensor nodes into three categories: they are CH nodes, non-CH nodes or leaf nodes, and hop nodes or intermediate nodes. A global positioning system (GPS) or a radio signal strength identification (RSSI) system can be used to track the sensors' location [14, 24]. The sensor nodes can calculate the distance between them using location and RSSI. The sensor nodes always monitor their residual energy which is used to make routing decisions along with distanceThis strategy saves energy by allowing the leaf node to merely detect the environment and transmit data to the intermediate node. Data can be collected and forwarded to CH or some other intermediate node after compression by the intermediate or hop node. The CH node collects data from sensor nodes or intermediary nodes and compresses it before sending it to the base station (BS). We assume that the sensor is used to detect the phenomena in an outside setting such as an agricultural field, a hostile zone, or a dangerous place.

A. Radio Model

The data transmission and receiving phases of a WSN get most of the sensor nodes' energy. The CH node, intermediate node, and leaf node consume the network's energy while transmitting and receiving data. Moreover, some energy is used for data aggregation of all nodes. Fig. 2 shows the energy dissipation model of WSNs.For radio hardware energy, the model is a basic energy dissipation model. The transmitter consumes energy to power its electronics as well as an amplifier that amplifies the signal over a long distance in the open air.The receiver uses the energy for running electronics components and data aggregationFree space propagation and multipath fading are used depending on the distance between the transmitter and receiver. Free space propagation and multipath fading both have power loss when d is the distance between transmitter and receiver. We can use the appropriate setting of power amplifiers to invert the loss due to varied path distances.

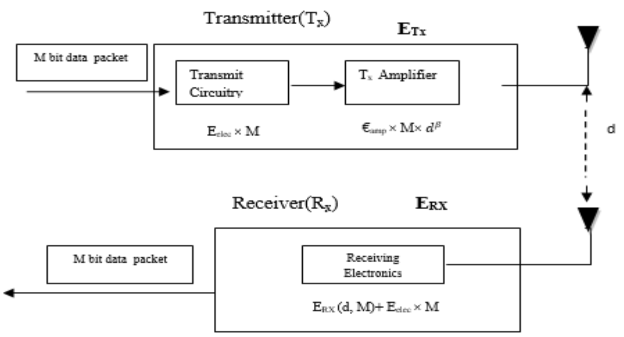

Fig. 2 Radio Model for proposed GTR.

When a M-bit message is being sent between two sensor nodes in this approach, the following Eqs. 1 and 2 would be used to calculate the energy consumption:

$$E_{TX}(M, d) = M \times E_{TX-elec} + M \times E_{TX-amp} \\ = M(E_{TX-elec} + E_{TX-amp}) \quad (1)$$

$$E_{RX}(M) = (M \times E_{TX-elec} + M \times E_{CA})E_{RX}(n) \\ = M(E_{RX-elec} + E_{CA})E_{RX}(n) \quad (2)$$

where, the amount of bits in a message to be transmitted is M, and the distance between the transmitter and receiver is d, $E_{TX}(M, d)$ is the total energy consumed by the transmitter when transmitting a M bit message across a d distance and $E_{RX}(M)$ is the total energy consumption of receiving sensor node. The $E_{TX-elec}$ and $E_{RX-elec}$ are the amount of energy used by the transmitter and receiver devices to process each bit of a message respectively, the different factors may have an effect on $E_{TX-elec}$ and $E_{RX-elec}$ like modulation, spreading and noise filtering.E_{CA} is the amount of energy consumed to compress and aggregate data. E_{TX-amp} is the energy consumption of sensors transmission amplifiers. The following Eq. 3 can be used to compute it.

$$E_{TX-amp} = \begin{cases} \varepsilon_{fs} d^2, whend < d_0 \\ \varepsilon_{mp} d^4, whend \geq d_0 \end{cases} \quad (3)$$

where,ε_{fs} and $\varepsilon_{mp}$are the free space and multipath fading communication parameter and $d_0$is the threshold distance The free space propagation strategy is able if the distance (d) between transmitter and receiver is less than the threshold value (d_0). The multipath fading channel is employed in all other cases. More energy is required for communication when the distance between the transmitter and receiver exceeds the threshold value(d_0). The threshold distance value (d_0) can be calculated by the following Eq. 14.

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (4)$$

Consider the case where a leaf node wishes to transmit a M-bit message data to the MS. The leaf node can just monitor the environment in this model, but in a multipath communication system, the leaf node can send data straight to the CH node or relay data to multiple intermediary nodes. Let E_{leaf} is the amount of energy required by the leaf node.

The following Eq. 5 can be used to calculate the energy usage of a leaf node when transmitting data to a CH or intermediate node.

$$E_{leaf} = E_{TX}(M, d_n) \quad (5)$$

where the distance between the leaf and intermediate node or cluster head node is d_n. The leaf node sends data to the intermediate node and the intermediate node collects data and forwards it to another intermediate node or CH. An intermediate node may collect data from several leaf nodes or lower-order intermediate nodes. Let E_{IN} be the intermediate node's energy usage. If an intermediate node gathers data from the n leaf node or a lower-order intermediate node and sends it to the CH or a higher-order intermediate node, the intermediate node's energy consumption can be represented as Eq. 6.

$$E_{IN} = nE_{RX}(M) + E_{TX}(M, d_{IIC}) \quad (6)$$

where, d_{IIC} is used to denote distance from the lower-level intermediate node to the higher-level intermediate node or intermediate node to CH. In this process, the data from the leaf node will reach the CH. The CH aggregates the data and sends it to the MS. When a node is selected as a CH, then it will turn on its GPS so that the MS can reposition itself into an optimal location (for convenient data gathering). The distance between the CH and the MS is denoted by d_{CM}. Let's say E_{CH} is the energy usage of the CH node. E_{CH} can be determined using Eq. 7 if the CH collects data from N sensor nodes.

$$E_{CH} = NE_{RX}(M) + E_{TX}(M, d_{CM}) + E_{GPS} \quad (7)$$

where, E_{GPS} is the energy consumption needed for receiving location information. It is clear from the preceding discussion that the sensor node expends the majority of its energy during the communication phase. Considering the energy consumption of nodes, an uninterruptable and reliable communication path must be created, and The transmission distance needs to be lowered. As a result, in WSNs, energy usage and dependable routing path design become major concerns.

B. Protocol Description

In our method, we incorporate techniques for energy-saving and prolonging network lifetime by designing a tree cluster for WSNs. We have developed a power-saving scheme by constructing an uninterruptable routing path and reducing transmission distance. Considering the sensing area, transmission distance, and residual energy, we choose a tree-based cluster with multi-hop concepts. If a sensor node uses the minimum amount of energy, a longer lifetime is achieved. In our proposed scheme, we ensure that all sensor nodes can calculate distance from their neighboring node and nodes also use its residual energy. We use the natural gravitational technique to construct a tree structure. The procedure is divided into two phases in this strategy: setup and steady-state.

1. Setup Phase

The recommended approaches for forming the gravitational tree cluster are described in this subsection. This phase also tree-select the cluster head. The basic objective is to build a tree structure, locate intermediate nodes, and determine the CH. Initially, the sensor nodes are placed in the sensing region at random which is shown in Fig. 4 it also shows that the sensor nodes broadcast beacon messages to identify their neighboring nodes. Each of the sensors can calculate the distance between its neighboring nodes by received signal strength indication (RSSI). The node itself can also monitor its own energy level. A sensor node uses its distance from the neighboring node and its residual energy to discover an outgoing data path. Fig. 3 represents a triangle that is used to formulate our concepts. Let α and β be two sensor nodes with $d_{\alpha\beta}$ distance between them. Let e_α and e_β be the remaining energy of α and β node, respectively.

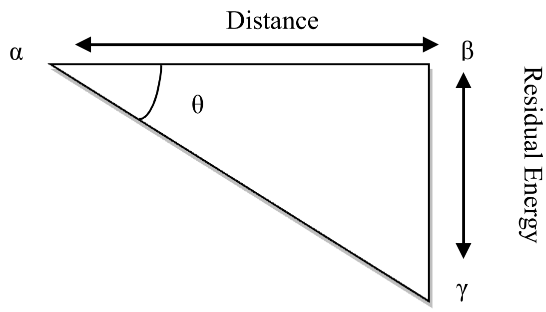

Fig. 3 Energy-distance triangle.

If we consider the distance between two sensors as the base of the triangle of Fig. 3 and the height or depth of the triangle is the residual energy of a neighboring node, we can easily find out the angle θ between the base and the hypotenuse using the following equation:

$$\theta_{\alpha\beta} = cos^{-1} \frac{d_{\alpha\beta}}{\sqrt{{d_{\alpha\beta}}^2 + {e_\beta}^2}} \quad (8)$$

If a sensor node α has several neighbor nodes, such as $\beta_1, \beta_2, \beta_3 \cdots \beta_n$, the angle between the sensor node α to all of its neighbor nodes are $\theta_{\alpha\beta_1}, \theta_{\alpha\beta_2}, \theta_{\alpha\beta_3} \cdots \theta_{\alpha\beta_n}$. The sensor node α calculate the angle with neighbor nodes and finds the maximum angle as follows:

$$\theta_{\alpha\_\max} = \max(\theta_{\alpha\beta_1}, \theta_{\alpha\beta_2}, \theta_{\alpha\beta_3} \ldots \theta_{\alpha\beta_n}) \quad (9)$$

Let us suppose that the angle $\theta_{\alpha\beta_i}$ is the maximum angle for the source node α. Then, the node α request the reverse angle to β_i node and node β_i send $\theta_{\beta_i\alpha}$ to α. The sensor node α checks the maximum angle between them. If $\theta_{\alpha\beta_i}$ is greater than $\theta_{\beta_i\alpha}$, then a link or routing path is created from α to β, where α represents the child node and β represent parent nodes. Otherwise, the α node treated itself as the maximum rich node among its neighbors and it will declare itself as a CH. The process of creating a routing path and selecting CH is like the natural gravity phenomenon described earlier. The single tree structure formation and CH selection are shown in Fig. 5.

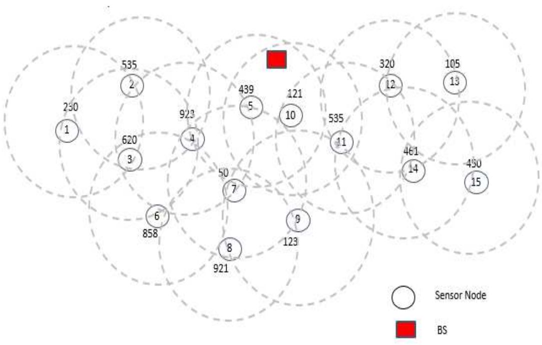

Fig. 4 The neighboring nodes identification.

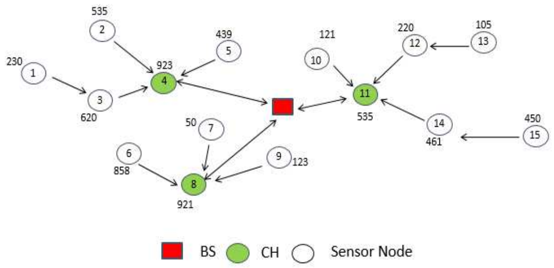

Fig. 5 The final tree-cluster structure.

The tree-cluster-based structures are shown in Fig. 5. It is evident that the transmission distance is shortened, and bottleneck free routing path is selected by this gravitational routing algorithm. The intermediate node performs a role in both the sensing and receiving data from the leaf node as well as from another intermediate node. The tree cluster is built using energy-distance optimization approaches that ensure fairness and load distribution. As a result, energy consumption is minimized, and a reliable route for the cluster network is established, ensuring that it will exist for as long as feasible.

2. Steady State

The TDMA schedule is set once the tree clusters are built (which we have adopted from [18]). Data transmission can then be started. The sensor nodes sense the environment directly and transfer data to its CH either directly or via intermediate sensor nodes. When the CH gets the data, it performs data processing and delivers it to the MS. Data compression of intermediate and CH nodes reduces the amount of data. Following this cycle, the procedure is repeated, starting with a setup phase and ending after a steady-state phase.

IV. SIMULATION AND RESULTS

We have performed our experiments in a simulation environment by considering time and costs. We have used a discrete event simulator OMNET++. We first create a simulation environment for our proposed system, then compare our findings to those of the pioneer procedure (LEACH) [4] and recent protocol (TRMS) [6]. We calculate the performance metrics with our proposed mathematical model. The tree construction, CH selection were done by our assumption. The experimental setup uses a number of performance metrics to evaluate the proposed system's performance. A wireless sensor of 50 nodes is deployed randomly over $200 \times 200\, m^2$. Within the sensing area, the base station (BS) is positioned in a convenient location. The simulation parameters of TRMS [6] and LEACH [4] are used. The network lifetime, average energy use per round is used to compare the proposed system with some existing protocols. The proposed gravity model for tree-based routing's(GTR) simulation results are discussed in this section and compares the result with the pioneer protocol LEACH and recent protocol TRMS. The different experimental result is shown here based on different performance parameter. We have run our simulation 5 times and average and finally take the average value to represent in a graph. We explain why the suggested protocol performs better than existing protocols. Below are the simulation findings and comparisons with LEACH and TRMS.

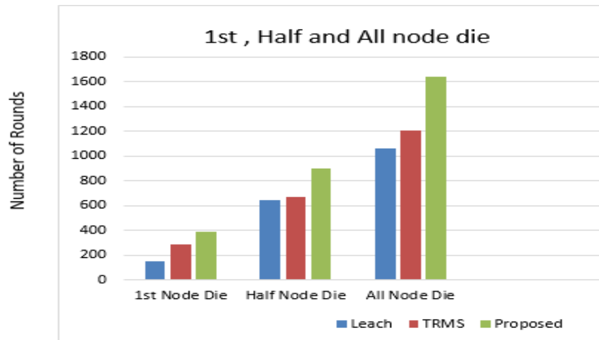

Fig. 6: FND, HND, and LND with respect to round for 50 nodes.

A. FND, HND, and LND regarding Number of Rounds

The FND, HND, and LND are used to represent network lifetime. This was initially invented by Handy et.al.[23]. Fig. 6 depicts the network lifetime in terms of LEACH's FND, HND, and LND, TRMS, and the proposed protocol. For 50 nodes in LEACH and TRMS, the first node dies within 285 rounds while in the proposed protocol, it is about 386 rounds. On the other hand, the last node survives up to 1638 rounds whereas, in LEACH and TRMS, it is not over 1250 rounds.

B. Remaining Energy of the Network Per Round

In this experiment, heterogeneous nodes are considered, and every node has different initial energy. Fig. 7 represents the remaining energy of the networks with respect to rounds. The Y-axis represents the total energy of the network, while the X-axis represents the number of rounds. The networks look very steady because of creating a bottleneck-free cluster so there is no unexpected energy consumption through the entier lifetime of the sensor networks. The proposed scheme saves more energy than TRMS and LEACH. For 50 nodes it survives about 35% more than LEACH and about 26% more than TRMS.

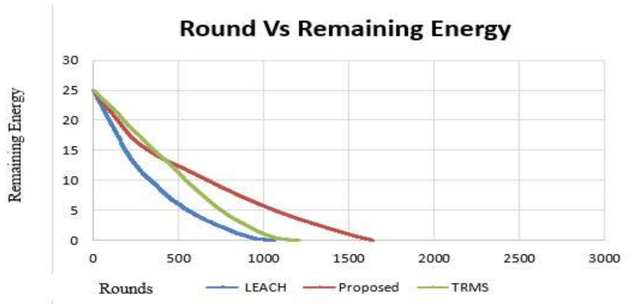

Fig. 7: Remaining energy of the network for 50 nodes.

V. CONCLUSION

The application and adjustment of Wireless Sensor Networks (WSNs) for different real-life purposes have been increasing rapidly. However, it is an energy-scarce technology where replacing or recharging battery power is nearly impossible. Sometimes, the sensor node dies out due to a lack of energy before its expected lifetime which causes a disconnection, significant data loss, and monetary loss, thereby degrading network quality. Designing energy efficient communication protocol is a very challenging task in wireless sensor networks. We present a new energy-efficient tree clustering method in this study that takes into account residual energy and node distance. We have developed a mathematical model based on the natural gravitational model to identify data route from nodes that leads to the construction of tree-topology. Our mathematical model has been validated through extensive simulations. We have found that in our proposed methodology, the lower energy node has no chance to become an intermediate node, thereby the network will not create any bottleneck during the data gathering process. This proposed approach can be useful for agent-based data collection and monitoring applications in smart agriculture, area monitoring, forest and wildlife observation, etc.

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