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Analysis of Radio Model Performance for Clustering Sensor Networks

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Abstract: Contemporary advancements in the field of wireless technology and sensor instrumentation have led to the proliferation of novel protocols which are specially designed for low-power networks such as wireless sensor networks. In the field of wireless sensor networks, researchers are currently interested in tackling the challenge of designing an optimum routing protocol that will satisfy the application and network requirements with minimum consumption of energy. Cluster-based routing protocols have been found to be more advantageous to other types of routing techniques when there is a relatively huge number of a sensor node to be deployed. This paper is an investigation of the performance of selected cluster-based routing protocols with special emphasis on the effectiveness of their radio propagation models. *Copyright © 2011 IFSA.*

Keywords: Clustering routing techniques, Radio models, Sensor networks, Propagation methods.

1. Introduction

Recent advances in signal processing, digital and microelectronics technology and wireless communications have tremendously led to the development of smart and miniaturized sensor devices. As a result of this technological advancement, the design and implementation of wireless sensor networks was made possible by creating opportunities for using sensor nodes for monitoring remote scenarios or events [1-4]. Applications of sensor networks include wildlife migration tracking, wild fire monitoring, reconnaissance and tactical surveillance, weather monitoring and ubiquitous computing [1-3, 5]. In a wireless sensor network, a number of nodes collaboratively work together in order to achieved a global task by forwarding the desired information to the sink. The nature of data transmission to the sink depends on cogent factors such as the amount of residual energy, time-criticality of data and other constraints due to the inherent limited processing and communication capabilities of the sensor nodes [1, 3, 4].

Customarily, sensor nodes are designed to be deployed in places where it can be very difficult to replace dead nodes or even recharge their in-built batteries. Therefore, the major objective of designing wireless sensor networks is to maximize the network lifetime by minimizing energy consumption during the transmission and reception of data. Low duty cycling which is the strategic turning on and off of sensor radio based on sensing demands is one of the solutions proffered for minimizing energy consumption. Other energy conservation techniques are data filtering, data compression, data aggregation and data fusion [2-4].

A number of routing algorithms have been proposed for wireless sensor networks [5, 6]. However, the task of developing energy-efficient routing protocols is a challenge due to the inherent limitations of the sensor nodes. Researchers in this field are currently exploring the concept of cluster-based routing which promises a better solution to the problem of energy consumption when compared to other types of routing [3, 7-12]. Furthermore, it has been claimed in the literature that despite the fact that clustering introduces overheads due to network management operations, they possess better energy conservation ability when compared to flat-based routing protocols [3, 4].

This paper is an investigation of the performance of selected cluster-based routing protocols with special emphasis on the effectiveness of their radio propagation models. The aim of this research work is to foster better understanding of clustering sensor networks and highlight possible areas of improvement for further investigation. The remainder of the paper is organized as follows: Section 2 presents a survey of selected clustering routing protocols. Section 3 summarizes the key findings of the investigated protocols and Section 4 concludes this paper.

2. Clustering Routing Techniques

In this section, a survey of selected clustering routing protocols and their radio model for wireless sensor networks are reviewed.

2.1. Low-Energy Adaptive Clustering Hierarchy

The Energy consumption in wireless sensor network [2, 7] is reduced by an adaptive and self-organizing protocol called the Low-Energy Adaptive Clustering Hierarchy (LEACH), the use of randomized rotation of cluster heads so that energy dissipation is shared evenly among all participating sensor nodes is the underlying idea behind LEACH.[2-4, 6].

Mechanism of Operation: the set up phase and the steady phase are the two phase’s category of operation of LEACH. A random number in the range of 0 and 1 is selected by a sensor node in the set-up phase, if the number is greater than a specified threshold, the sensor node will be elected as a cluster head.

The newly-elected cluster head will advertise to other nodes after selecting it as the cluster heads, each node will determine the cluster to belong to based on the signal strength of the advertisements received, minimum communication energy is required for node nearer to the cluster head due to the presence of strong signal strength. Afterwards, the nearest cluster heads to the nodes is notified of their interest in becoming a cluster member. The Time Division Multiple Access (TDMA) is the principle used by the cluster heads to allocate the time for sending data after cluster formation. Subsequently, the nodes start sensing and sending data to cluster heads. Prior to sending data finally to the sink, data aggregation is performed by the cluster heads. After successfully communicating the data to the sink, a new cluster heads is selected because the network reconfigures itself. Lastly, a single-hop communication is used by LEACH [3, 5-7].

Analysis of Performance: the data aggregation performs help enhanced the network lifetime and transmission of redundant data is reduced, the randomized rotation of the cluster head minimized the energy consumption. The intra-cluster and inter-cluster collisions are reduced by the use of TDMA MAC scheme and negotiation.

However, the use of single-hop communication which is ineffective and energy consuming for long distance communications cause the scalability problem facing the use of LEACH in a dense network scenario. The conserved energy is diminished by the extra overhead introduce such as cluster head advertisements by the use of dynamic clustering. The periodic data transmissions can rapidly drain the limited amount of energy since Data collection is centralized and periodic. There is the possibility of cluster heads being unfairly concentrated in a network segment due to non-uniform distribution of cluster heads. Hence, some nodes will suffer by not having cluster heads in their locality.

Radio model: In LEACH radio propagation model assumes that the device is placed one meter above the ground. This can degrades performance and scalability of wireless simulators. More so, a misleading result may be gotten due to an inappropriate configuration of model parameters.

2.2. Threshold-Sensitive Energy-Efficient Sensor Network Protocol

For time-critical applications, TEEN (Threshold-Sensitive Energy-Efficient Sensor Network) and APTEEN (Adaptive Periodic Threshold-Sensitive Energy-Efficient Sensor Network) were proposed in [8] and [9] respectively. A protocol developed to respond to abrupt changes in the sensed attributes is called TEEN [3-5].

Mechanism of Operation: The cluster formation is done by grouping nodes that are nearer to each other as clusters at the start. Higher priority is assigned to cluster heads of clusters nearer to the sink while lower priority is assigned to cluster heads of clusters farther from the sink [1, 3, 5-6, 8].

Hard and soft threshold are the two threshold disseminated by cluster heads to cluster members after cluster formation. The minimum possible value of the sensed attribute that will trigger nodes to turn on their radio for transmitting data to their cluster heads is the hard threshold. The transmission of the data by the node will begin if the following conditions are true: (1) The present value of the sensed attribute's is greater than the hard threshold (2) The present value sensed attribute's differs from the previous sensed value by an amount equal to or greater than the soft threshold specified. Consequently, soft threshold helps in reducing transmissions when there are no considerable changes in the sensed attributes [1, 3-6, 8].

An extension of TEEN called APTEEN, aims at reacting to time-critical events and capturing periodic data collections. The user demands and application type serve as the base use by APTEEN in changing the threshold values used in TEEN. Cluster formation is made by the base station and elected cluster heads distribute these parameters, (1) Thresholds, (2) Attributes, (3) Schedule and (4) Count Time. In APTEEN, the conditions for data transmission are just like TEEN. Data aggregation is performed by cluster heads to save energy [1, 3-6, 9].

Analysis of Performance: Redundant data transmission is prevented by reducing the number of transmission by the soft and hard threshold which leads to energy conservation. APTEEN provide a wide range of flexibility by enabling users to set the count time interval and minimize energy consumption.

However, the inability to communicate if the thresholds are lost is a drawback of TEEN. The inapplicability for networks where periodic readings need to be delivered to the sink is one of the scalability problems of TEEN. In such a situation, there is the possibility that useful data will not be transmitted because the attributes' values might not reach the threshold at all. Also, another limitation is that message can get lost if cluster heads are not in each other's transmission radius.

The complexity and overhead related to (1) cluster formation and (2) threshold management and query handling are the common weakness of both TEEN and APTEEN.

Radio model: In TEEN and APTEEN, the radio model assumes that the distance between the sensors is very short hence there is limited radio range. This is in accordance with the first order radio model proposed for LEACH. This can degrades scalability and performance of wireless simulators. More so, a misleading result may be gotten due to an unsuitable configuration of model parameters.

2.3. Geographic Adaptive Fidelity Protocol

Geographic Adaptive Fidelity (GAF) is a protocol initially developed for mobile ad hoc networks (MANETs) but realized to be useful for sensor networks [3, 5, 10]. In each grid area, a node serves as a leader to convey data to other nodes which is the basic idea behind GAF, unlike other cluster routing protocols, these leader nodes do not perform data aggregation [4, 6, 10].

Mechanism of Operation: A Global Positioning System (GPS) is use by nodes to associate themselves with a location in the virtual grid after the protocol has commences by forming a virtual grid over the deployed area. Clusters are form by nodes associated with the same location known as equivalent nodes [3-5, 10].

The discovery, active and sleeping states are the three states GAF is made up of. In the discovery state, other neighboring nodes in the same grid are discovered by nodes, by exchanging messages for specified time duration. Afterwards, routing is performed during the allotted active time and radios of active nodes are turned off for a specified sleeping period. Allowing nodes to change from sleeping to active state will ensure Load balancing. Ensuring that each node in the grid calculates it's leaving time and send it to its neighbors support mobility. Before the leaving time of the active node expires, one of the sleeping nodes wakes and becomes active. GAF is designed both for non-mobility (GAF-basic) and mobility (GAF-mobility adaptation) [3-6, 10].

Analysis of Performance: This protocol conserves energy by discovering corresponding nodes and turning off idle nodes. As a result, GAF can considerably increase network life span as the number of sensor nodes increases.

However, the use of GPS technology which is too energy-demanding and costly for a huge and dynamic network is one of the scalability problems of this algorithm. Aside this, this algorithm determines travel time in order to support mobility. This might be difficult or nearly impossible to estimate in larger networks with unfavorable environmental conditions when nodes are deployed in such area.

Radio model: In GAF a two ray ground model is used which accounts for the effect of multipathing and fading. Compared to other LEACH-type radio schemes, this provides better performance and it is more suitable for large scale sensor networks. However, there is a need for a more accurate radio model that will yield practical results that describe the real behavior of the network.

2.4. Periodic, Event-driven and Query-based Routing Protocol

Periodic, event-driven and query-based (PEQ) protocol is intended for networks which are used as surveillance systems operating under critical conditions. The use of hop level of nodes to minimize redundant data transmission is the basic idea behind PEQ [3, 4, 11].

Mechanism of Operation: The shortest distance from each sensor node to the sink is find which is the base for configuring the entire network by the protocol. Initiation of this configuration process is done by the sink via broadcasting the hop value, time-stamp, and source address to nearest neighbors. Afterwards, nodes will store, increment and send the hop level to the next neighboring nodes. The hop value for each node is compares with the one in the packet. Update is carried out and retransmission is done if the hop value is greater. This process continues until the whole network is configured [3, 4, 11].

Just as in the configuration process, the sink broadcasts subscription message over the network. If an event matching the sink's interest is detected by the node, the event packet will be send to its neighboring node by the node. When data reaches the sink, the event notification and data delivery process ends. An ACK-based repair mechanism is also implemented by this protocol [3, 4, 11].

Analysis of Performance: In a large network scenario, PEQ uses multi-hop communication which is simple and effective for long distance communication. Energy consumption is reduced and low latency is ensured by using optimal path routing. An ACK-based repair mechanism is used to maintained reliability.

However, the flooding and broadcasting of configuration and subscription messages is a major concern. When the network grows larger and becomes more dynamic it becomes a major problem. In such scenario, there will be mismanagement of the scarce energy resources due to redundant transmission and reception of data.

Radio model: In PEQ, radio propagation model assumes that the distance between the sensors is too short hence there is limited radio range. This is in accordance with the first order radio model proposed for LEACH. This can degrades performance and scalability of wireless simulators. More so, a deceptive result may be gotten due to an inappropriate configuration of model parameters.

2.5. Clustering Periodic, Event Driven and Query based Routing Protocol

In Clustering Periodic, Event-driven and Query-based (CPEQ) protocol, a sensor node with more energy is selected as cluster heads. Cluster heads form clusters and cluster members communicate with their respective cluster heads [3, 4, 11].

Mechanism of Operation: Just like in the PEQ protocol, this protocol starts with network configuration. The propagation of an additional field to specify the percentage of nodes that can become cluster heads is the only difference. The cluster head selection process is based on LEACH [3, 4, 11].

The next stage after selecting the cluster heads is the cluster configuration stage, where broadcasting notifications is used by cluster heads to form their clusters. This is the same process as in the configuration phase of PEQ. Whenever an event is sensed by a node, they relay it to their respective cluster heads. This data routing scheme is also similar to the one used in PEQ. Furthermore, just like in the PEQ algorithm CPEQ also employs an ACK-based path repair mechanism. [3, 4, 11].

The cluster heads performed data aggregation on the incoming data to reduce redundancy. Afterward, the aggregated data will be transmitted by the cluster heads to the sink via the shortest path. The event and data delivery process is similar to the one employed in PEQ [3, 4, 11].

Analysis of Performance: All the strengths of PEQ is also possessed by this algorithm, specifically; low energy consumption, support for low latency; support for reliability and simplicity. The aggregation of data which saves energy by reducing repetitive data transmission is another merit of this algorithm.

However, the redundant transmission and reception of packets in the configuration process is a major concern. High amount of energy will be wasted in the transmission of and listening to unwanted or unnecessary packets in a highly-dense network scenario.

Radio model: In CPEQ, radio propagation model assumes that the distance between the sensors is very short hence limited radio range device is used. Hence there is limited radio communication range; this is similar to the first order radio model proposed by LEACH. This can degrades performance and scalability of wireless simulators. More so, due to an inappropriate configuration of model parameters, a misleading result may be gotten.

2.6. Energy Efficient Inter-cluster Communication based Routing Protocol

A protocol designed for periodic, event-driven and query-based networks is the Energy Efficient Inter-cluster Communication based (ICE) algorithm. Cluster heads and nodes nearest to each other within two adjacent clusters help to accomplished message routing. As a result, data transmission is carried out via short transmissions [3, 4, 12].

Mechanism of Operation: The setup phase begins this protocol where the network is configured just like in the PEQ and CPEQ protocol. The cluster head selection is based on LEACH [3, 4, 12].

The cluster configuration process where cluster heads form clusters by broadcasting notifications to neighboring nodes is similar to that of the CPEQ algorithm. The discovery of free nodes which do not belong to any cluster is a unique property of this protocol. Notification messages are sent to adjacent nodes by free nodes. These neighboring nodes forward their requests to their cluster heads [3, 4, 12].

An improved version of the ACK-based path repair mechanism employed in PEQ and CPEQ is used in this algorithm. One of the adjacent clusters is selected to help relay the data, whenever a cluster member has data to send to the sink. A node belonging to an adjacent cluster will receive the transmitted data and that node will send the message to its cluster head. The data is finally delivered to the sink by following this sequence [3, 4, 12].

Analysis of Performance: This protocol has the merits of CPEQ and PEQ, namely; data aggregation, support for reliability, simplicity and support for low latency. Using nearest neighbors, energy is conserved as a result of short-range transmissions. The use of multipath routing ensures load balancing, network longevity and fault tolerance. Quality of Service (QoS) is provided using the least-cost path and Notifications are prioritized.

However, the inability to form a logical line for clustering is a drawback. This implies that no nearest neighbors will be discovered and data transmission will be negatively affected. Redundant transmission and reception of packets are highly likely to occur. In a scenario where the network size is increasingly growing and becoming more dynamic, the network management can be costly and difficult.

Radio model: In ICE, radio propagation model assumes that the distance between the sensors is very short hence there is limited radio communication range. This is similar to the first order radio model proposed for LEACH. This can degrades performance and scalability of wireless simulators. More so, a misleading result may be gotten due to an inappropriate configuration of model parameters.

3. Radio Propagation Models in Wireless Sensor Networks

3.1. Free Space Path-Loss Radio Model

Free space path-loss radio propagation model used in wireless sensor network is popularly known as the first order radio model in LEACH and many other cluster-based routing protocols [7, 9]. It assumes that there is only one clear line-of-sight path in the ideal propagation condition between the transmitter and receiver. The communication range is basically represented as a circle around the transmitter in the free space model. All the packets are received from the transmitter if a receiver is within the circular range else, it loses all packets [7, 8, 13]. The received signal power in free space at distance *d* from the transmitter can be calculated by using the equation below:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi^2) d^2 L}, \tag{1}$$

where, P_t is the transmitted signal power. G_t and G_r are the antenna gains of the transmitter and the receiver respectively. L $(L \geq 1)$ is the system loss and λ is the wavelength [7, 13].

3.2. Two-Ray Ground Reflection Model

This is also known as the second-order model and it is used in GAF which considers both the direct path and the ground reflection path. A single line-of-sight path between two nodes is often the only means of propagation [10]. This model gives a more accurate prediction at a long distance than the free space path-loss radio model [14]. However, due to the oscillation caused by the constructive and destructive combination of the two rays, a misleading result may be obtained for short distance [13]. The predicted received power at distance d is obtained by the equation below

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L}, \tag{2}$$

where, h_t and h_r are the heights of the transmitting and receiving antennas respectively. This model predicts the received power as a deterministic function of distance by representing the communication range as an ideal circle [10, 13].

3.3. Shadowing Model

This model was recently adopted by researchers in sensor network as the third order model [14], the model was able to overcome the effect of multipath propagation also called fading effect which results in the random variable obtained for the received power at certain distance [13, 14]. Nodes can only probabilistically communicate when near the edge of the communication range thus extending the ideal circle model to a richer statistic model [13]. The model consists of two parts namely the path loss model and the log-normal random variable. The first part known as the path loss model uses a close-in distance d_0 as reference in predicting the mean received power at distance d [13], denoted by $Pr(d)$ which is computed relative to $Pr(d_0)$ [13, 14] as shown below:

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10log\left(\frac{d}{d_0}\right)^{\beta}, \tag{3}$$

where β is usually empirically determined by field measurement and is called the path loss exponent.

The variation of the received power at certain distance is being reflected by the second part of the shadowing model which is a log-normal random variable and of Gaussian distribution if measured in dB [13]. The complete log-normal shadowing model is represented below:

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta log\left(\frac{d}{d_0}\right) + X_{dB}, \tag{4}$$

where, X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB} known as the shadowing deviation [13].

4. Numerical Results

The performance metrics of the radio model on energy consumption and network lifetime for the clustering sensor network is examined; a clustering wireless sensor network is simulated in a field of dimensions 50 m by 50 m using MATLAB and OMNET++. The total number of sensors node deployed is n=100. The initial energy of a lower energy node is set to E_0 = 0.5 Joules. The energy dissipated by the transceiver, cluster head and amplifier are 50 nJ/bit, 5 nJ/bit/report and 10 pJ/bit/m^2 respectively. The message packet size that sensor nodes forward to cluster-head as well as the message packet size that cluster-head forward to the sink is 2000 bits. The performance metrics used in this work are energy consumption and network lifetime. Two of the clustering routing protocols are used for comparison thus the Low-Energy Adaptive Clustering Hierarchy (LEACH) is selected because it uses the First-Order radio model just like other clustering routing protocols discussed above except the Geographic Adaptive Fidelity Protocol (GAF) which uses the second-order radio model. Hence LEACH and GAF are being compared.

4.1 Energy Consumption Analysis

This metric is measured as the total amount of energy exhausted in the entire sensor network from the start of the network operation till the last alive node is dead. In Fig. 1 and Fig. 2 (below), it is observed that the energy available for the sensor network decreases gradually as the time round increases, however it is seen in Fig. 1 (LEACH) that energy is expended faster than that of Fig. 2 (GAF) thus shortening the lifespan of the network. one of the factor which account for the longevity of the network lifespan of Fig. 2 below (GAF) is the used of the second-order radio model and other enhancements in the protocol which cater for a better allocation and management of energy among sensor nodes than the first-order radio model employed in LEACH and thus it exhibits a better performance on average when compared to that of LEACH.

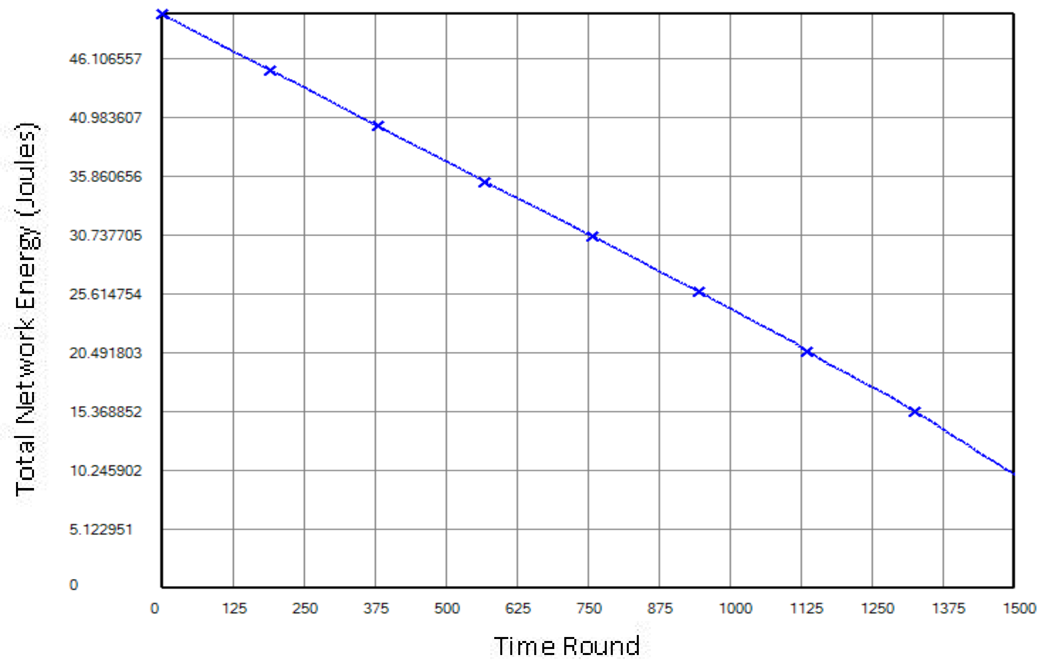

Fig. 1. Total Network Energy for LEACH.

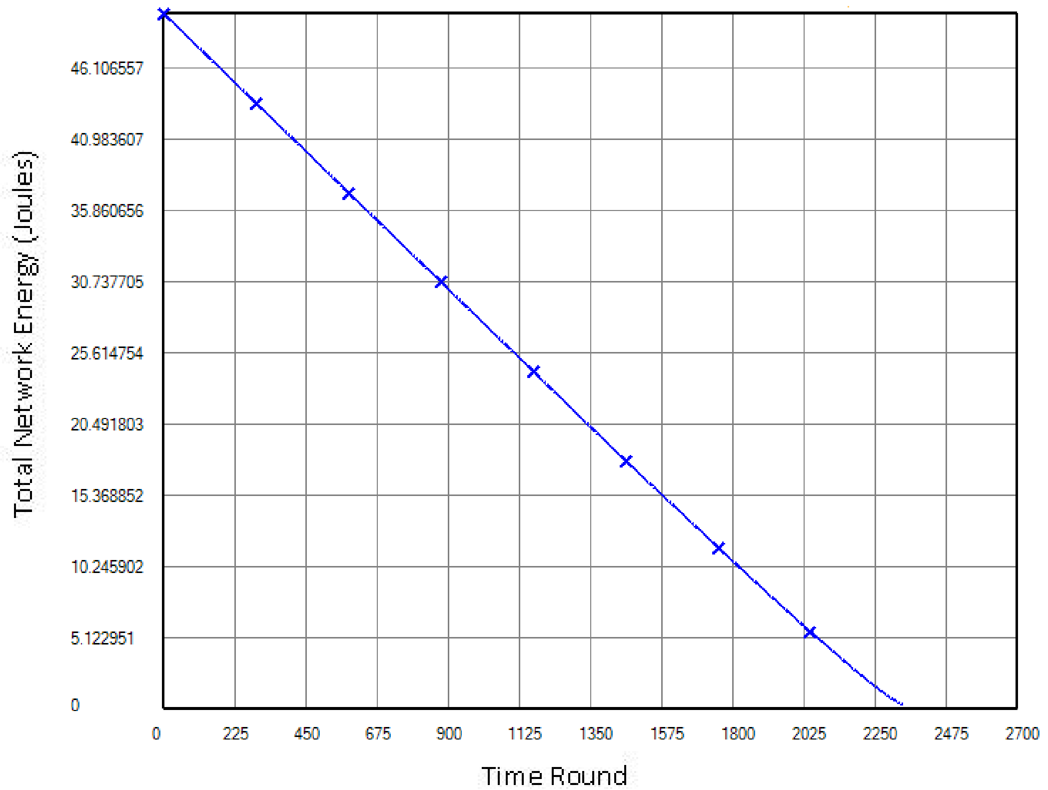

Fig. 2. Total Network Energy for GAF.

4.2. Network Lifetime Analysis

This metric is measured as the time interval from the commencement of operation by the sensor nodes until the last alive node is dead. As shown in Fig. 3 (LEACH) and Fig. 4 (GAF) below. It is observed that the network lifetime for LEACH is shorter than that of GAF for it is seen from Fig. 3 that after about 1,512 time rounds about 60 % of the sensor nodes were already dead and thus terminating the lifespan of the sensor network while in Fig. 4 it is seen that before the dead of the 60 % of sensor node which lead to the termination of the sensor network, it was after about 2,375 time rounds. Thus we can deduce that the network lifetime of GAF in Fig. 4 is longer due to the employment of the second-order radio model and other enhancements in the protocol which provide a better allocation and management of energy among sensor nodes compared to that of LEACH in Fig. 3 that uses the first-order radio model.

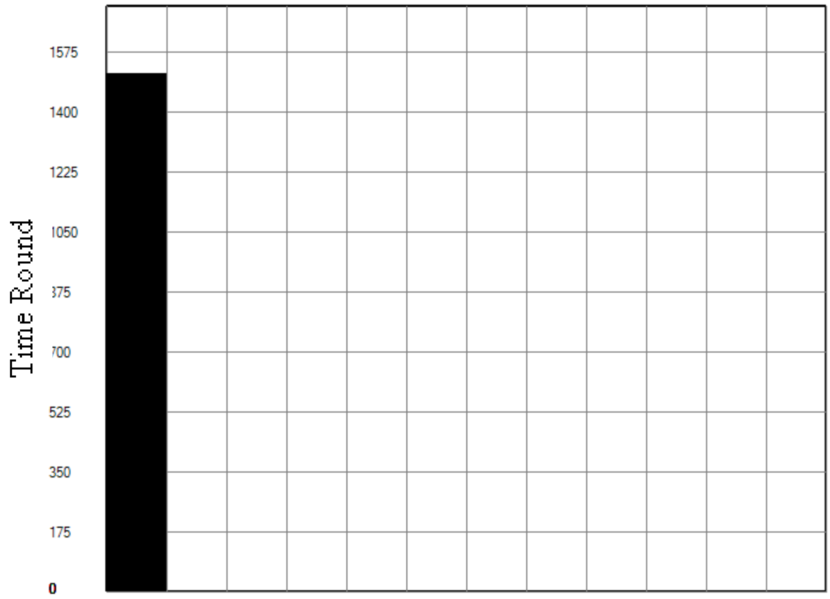

Fig. 3. Network Lifetime.

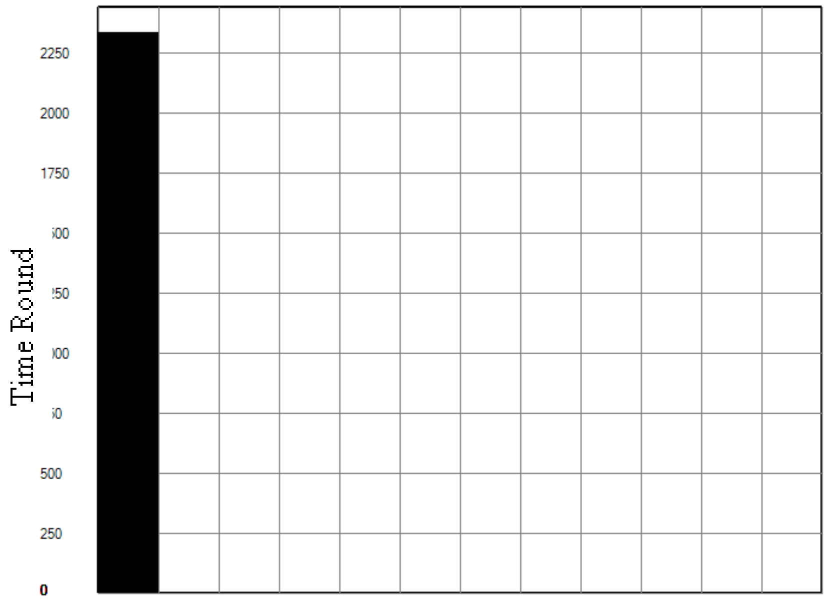

Fig. 4. Network Lifetime.

5. Summary of Features

In this section, a summary of the key features of the investigated clustering routing protocols and their radio propagation model is presented in the table below for easy and quick comparison.

Table 1. Summary of Features.

	Radio Propagation Model	Radio Model Simplicity	Radio Model Accuracy	Radio Model Energy-Efficiency	Radio Model Sensitivity	Multipath	Query-based	Energy Awareness	Optimal Route	Fault Tolerance
LEACH	FIRST-ORDER	HIGH	LOW	LOW	LOW	NO	NO	YES	NO	NO
TEEN	FIRST-ORDER	HIGH	LOW	LOW	LOW	NO	NO	YES	NO	NO
APTEEN	FIRST-ORDER	HIGH	LOW	LOW	LOW	NO	NO	YES	NO	NO
GAF	SECOND-ORDER	LOW	MEDIUM	MEDIUM	MEDIUM	NO	NO	YES	NO	NO
PEQ	FIRST-ORDER	HIGH	LOW	LOW	LOW	YES	YES	YES	YES	YES
CPEQ	FIRST-ORDER	HIGH	LOW	LOW	LOW	YES	YES	YES	YES	YES
ICE	FIRST-ORDER	HIGH	LOW	LOW	LOW	YES	YES	YES	YES	YES

6. Conclusion

Radio modeling has attracted considerable attention of researchers in the field of wireless sensor networks. Sensor nodes are organized in clustering sensor networks such that propagation of message is achieved with minimal energy to the sink via cluster heads. Recently, researchers have shown that an improved radio propagation model will assist in conserving energy and improving network lifetime. This paper investigated some selected clustering routing protocols, outlined their key features and analysis of their radio model performance. LEACH is ineffective for large-scale sensor networks due to the assumption of limited radio communication range and short inter-node distance. Other routing techniques address this challenging issue by considering the performance of multi-hop communication. Most of the routing techniques use a LEACH-type first order radio model except GAF which uses a two-ray ground model which accounts for the effects of fading and multipathing on designing an accurate radio model. The key issues that need further investigation are energy-efficient radio propagation modeling, designing a realistic radio model that accurately describes practical scenarios, tradeoff between simplicity and accuracy and finding optimal radio model, network reliability and fault tolerance.

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Guide for Contributors

Aims and Scope

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Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
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