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Enhanced Clustering Routing Protocol for Power-Efficient Gathering in Wireless Sensor Network

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Abstract: Wireless sensor network (WSN) is a new and fast advancing technology, which is opening up many opportunities in the field of remote sensing and data monitoring. In spite of the numerous applications of WSN, issues related to determining a suitable and accurate radio model that will foster energy conservation in the network limit the performance of WSN routing protocols. A number of radio models have been proposed to address this issue. However, the underlying assumptions and inaccurate configuration of these radio models make them impractical and often lead to mismanagement of scarce energy and computational resources. This paper addresses this problem by proposing an enhanced radio model that adapts to the frequent changes in the location of the sensor nodes and is robust enough to report reliable data to the base station despite fluctuations due to interference. The impact of incorporating stepwise energy level and specialized data transmission schemes in the proposed radio model is also investigated in this paper. The performance of the proposed radio model is evaluated using OMNET++ and MATLAB and the results obtained is benchmarked against PEGASIS. It is shown by simulation that the novel LEACH-IMP performs better with respect to energy consumption, number of links faults, number of packets received, signal attenuation, and network lifetime.

Keywords: Wireless Sensor Network, Radio Model, Power-Efficient Gathering Technique, Cluster-Based Routing Protocol, Data Transmission and Sensor Nodes.

1. Introduction

WSN is a fast advancing technology, which is comparatively novel and has opened up many opportunities in the field of remote sensing and data monitoring. Recent advances in digital signal processing, digital electronics, nanotechnology, micro-electro-mechanical systems (MEMS) technology, wireless communications and radio technology have tremendously led to the development of smart and miniaturized sensor devices [1]. Contemporary advancement in modern technology made the idea of WSN viable as it has opened up numerous possibilities in using motes for tracking, monitoring and detecting remote events. Applications of WSN includes wildlife migration tracking, wild fire monitoring, reconnaissance and tactical surveillance, weather monitoring and ubiquitous computing [2], [3].

There is an increasing demand for wireless sensor networks. However, the performance of sensor networks is limited by problems related to determining an accurate and energy-efficient radio model for the sensor nodes in the network. In addition to this, radio model issues cannot be overlooked in WSN protocol design because the most energy consuming functions are radio operations, i.e., data transmission and reception [1], [4]. The first order radio model has been proposed to address the aforementioned issues. The first order radio model operates by assuming that there is only one clear line-of-sight path in the ideal propagation condition between transmitter and receiver due to the short inter-nodal distance between the sensor nodes [5]. However, it has been shown that the assumption of short distance between sensors nodes is impractical. This is because network engineers who incorporate this model in their protocol design observe much discrepancy between the readings that protocol reports and what is actually occurring in the WSN field [6]. Most especially, the reported readings of energy consumed during transmission and reception have been shown by researchers to be largely different from the actual amount of energy consumed in the network. These misleading readings which are as a result of the inaccurate configuration of the first order model parameters often leads to mismanagement of scarce energy and computational resources [7].

This paper presents an enhanced radio model for cluster-based routing protocol, which is assessed to be robust enough to report reliable data to the central monitoring system for the end user despite the fluctuations in signal strength. The remainder of the paper is organized as follows: Section 2 presents related works. Section 3 presents model for radio operation, section 4 present simulation results and Section 5 concludes this paper.

2. Related Work

First-Order Radio Model

The first order radio model is often used in most of the cluster based routing protocols such as the Low-Energy Adaptive Clustering Hierarchy (LEACH) [4], [8]. 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 first order model. All the packets are received from the transmitter if a receiver is within the circular range else, it loses all packets [9]. The received signal power P_r in (dB) for first order radio model at a distance d from the transmitter is expressed as [8], [10]:

$$P_r = P_t + G_t + G_r - loss \tag{1}$$

Where, P_t is the transmitted signal power. G_t and G_r are the antenna gains of the transmitter and the receiver respectively.

Therefore, P_r in (dB) in equation 1 can be expressed as [8], [10]:

$$P_r = P_t + G_t + G_r - 20\log_{10}(d) - 20\log_{10}(f) - 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{2}$$

Where, P_t is the transmitted signal power. G_t and G_r are the antenna gains of the transmitter and the receiver respectively, d is the distance from the transmitter, f *is* the signal frequency, and c is the speed of light in Vacuum.

Area of Practical Application: The first order radio model is more suitable for health applications and medical body area networks. One of such applications was developed in the Vital Sign project where dedicated sensors (UC Berkeley motes running on TinyOS software) are manually deployed for patient identification [8].

Size of Network: The size of the network is usually small, for only ten to twenty sensor nodes are being deployed as a result the deployment area is small. The sensor nodes are used to monitor single event for short period of time, the data required is not much since it is designed for small-scale application [9], [11].

Mode of Deployment: The mode of deployment of sensor nodes is manual in order to ensure accurate positioning of the sensor nodes.

Inter-nodal Distance: The inter-nodal distance between the sensor nodes is very small usually 0.2 to 0.7 meter [8]. Consequently, the probability of having any form of interference is very low since the sensor nodes are being deployed very close to each other with small distances between the nodes [9].

Radio Model Complexity: The radio model design is not complex since there is no any form of obstacle that might cause the signal to be reflected, refracted or cause any other form of noticeable signal interference, which might result in additional signal attenuation between the sensor nodes [9].

Radio Model Accuracy: The first order radio model accuracy is low as a result of the received power dependency on distance consequently if the inter-nodal distance between the sensor nodes is increased it might cause additional signal attenuation or even result in the complete attenuation of the signal [9], [12].

Radio Model Sensitivity: The radio model is very sensitive because of the proximity of the sensor nodes to each other that is as a result of the short inter-nodal distance which minimize the possibility of having any signal interference which might cause additional signal attenuation [9], [12].

Energy Awareness: Energy is consumed most during radio operation such as the transmission and reception of signal [9]. In this radio model that stipulates short inter-nodal distance between the sensor nodes, this means that the time of transmission and reception is short as a result the energy expended on the transmission and reception of signal is small. Therefore, this radio model is designed for minimizing energy. Hence, it is energy aware [8], [13].

Second Order Radio Model (Type I)

The second order radio model (Type I) is used in some cluster based routing protocol such as the Geographic Adaptive Fidelity (GAF) [14]. A single line-of-sight path between two nodes is often the only means of propagation. This model gives a more accurate prediction at a comparatively long distance than the first-order radio model [8], [9]. However, a misleading result may be obtained for short distance because of the wider inter-nodal distance and the effects of the reflected signal paths. This model predicts the received power as a deterministic function of distance by representing the communication range as an ideal circle [15], [16]. The received power P_r at distance d can be expressed as [10], [11]:

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2 \sigma}{n d^4 L} \tag{3}$$

Where, P_t is the transmitted signal power, G_t and G_r are the antenna gains of the transmitter and the receiver respectively, h_t and h_r are the heights of the transmitting and receiving antennas respectively, σ is an estimation of the amount of multiple interferences and L *(*$L \geq 1$*)* is the system loss.

The received power P_r (in dB) can be expressed as [10], [17]:

$$P_r = P_t + 10\log_{10}(\sigma) + 10\log_{10}(G_l) + 20\log_{10}(h_t h_r) - 10\log_{10}(n) - 40\log_{10}(d) \tag{4}$$

The parameter σ is an estimation of the amount of multiple interferences and n, a value within 20 to 30, is the percentage of the total amount of multiple interferences that will be accounted for in the model [9], [10]. It was assumed that $int \in INT$ is interference in the environment that attenuates the signal by a constant factor σ_{int}. It was also assumed that $INT_{s,d}$ is the set of all interferences or obstructions intersecting the virtual line-of-sight between the source node (s) and receiving node (d) [8], [13]. Based on these, the parameter σ was modeled as [10], [12]:

$$\sigma = \sum_{int \in INT_{s,d}} [\sigma_{int}] \tag{5}$$

Area of Practical Application: The second order radio model (Type I) is designed for applications where the inter-nodal distance between one sensor node and another is estimably of medium length and the WSN is averagely of medium size [8], [15]. The second order radio model (type I) is more suitable for environmental monitoring applications and systems. One of such applications was developed in the Hawaiian Remote Ecological project where dedicated sensors (embedded computers running on open source COTS software and relying on external power source and GPS receivers) are manually deployed for remote visual surveillance of rare, threatened or endangered plant species and the prevailing weather condition [9], [18]. The users of this application conduct real-time monitoring of important phenomena such as the presence of insects or pollinators, human intrusion, consumption by herbivores and other weather factors pertinent to the plant condition. Therefore, this WSN application alerts the system administrator by rapidly and accurately detecting, tracking and reporting any form of threats to the plant species [12], [19].

Size of Network: The size of the network is often of medium size, for only thirty to seventy sensor nodes are being deployed as a result the deployment area is of medium size [8]. The sensor nodes are used to monitor multiple events for a period of time. The data acquired is comparatively larger than WSN application using the first-order radio model and it is usually designed for medium scale application [12], [13].

Mode of Deployment: The mode of deployment of sensor nodes is manual and usually once in order not to tamper with the optimal location and positioning of sensor nodes for the acquisition of data [9].

Inter-nodal Distance: The inter-nodal distance between the sensor nodes is comparatively wider than WSN application using the first–order radio model. The inter-nodal distance is usually within 0.8m to 2m, it is incorporated in the design of second order radio model to be able to accounts for the effects of interference and the reflected signal is almost parallel to the line of sight signal between the sensor nodes [8], [16].

Radio Model Complexity: The radio model design is comparatively more complex than that of the first-order radio model. This is because of the presence of interference and the likelihood of having multiple signal paths, though the probability of having a multiple signal path is low due to the inter-nodal distance, which is often between 0.8m to 2m [9], [18]. As such, the sensor nodes are close to each other though relatively wider than that of the first-order radio model. However, the radio model was design to be able to account for noticeable interference [11], [19].

Radio Model Accuracy: The second order radio model accuracy (type I) is comparatively better than that of the first-order radio model because the radio-model can accounts for interference and signal reflection due to multiple signal paths [8]. However, the inter-nodal distance is not that wide for an increase in the inter-nodal distance may result in additional signal attenuation. Hence, the radio model accuracy can be rated as more accurate than the first-order radio model [12], [16].

Radio Model Sensitivity: The radio model sensitivity is low due to comparatively wide inter-nodal distance between the sensor nodes which may cause additional signal attenuation due to the presence of interference and reflected signals due to multiple signal paths [8], [9].

Energy Awareness: This radio model stipulates a comparatively wider inter-nodal distance between the sensor nodes than that of the first-order radio model [9]. This implies that the time of transmission and reception of signal is relatively longer than that of the first-order radio model. Consequently, the energy expended on the transmission and reception of signal is much. Hence, its energy awareness is low [16], [20].

Second Order Radio Model (Type II)

The second-order radio model was able to overcome the effects of multiple signal paths and signal interference, which creates randomness in the received signal power measured over a certain distance [11], [17]. Nodes can only probabilistically communicate when near the edge of the communication range. This model gives a more accurate prediction at a comparatively long distance than the second-order radio model (type I). However, misleading results may be obtained for short distance because of the long inter-nodal distance length [9], [13]. The received power P_r at distance d is expressed as [10], [16]:

$$P_r = \frac{P_t G_t G_r \sigma}{L_t L_r L(d)} \tag{6}$$

Where, P_t is the transmitted signal power, G_t and G_r are the antenna gains of the transmitter and the receiver respectively, σ is an estimation of the amount of multiple interferences, L_t is the transmitter loss, L_r is the receiver loss and $L(d)$ is the path loss.

The received power P_r at distance d in equation (6) can also be expressed as [10], [12]:

$$P_r = P_t - loss + interference \tag{7}$$

The loss at distance d with reference distance d_o can be expressed as [10], [20]:

$$loss = L(d_0) + 10\log\left(\frac{d}{d_0}\right)^{\beta} = L(d_0) + 10\beta\log\left(\frac{d}{d_0}\right) \tag{8}$$

Where, β is the path loss exponent and is usually empirically determined by field measurement. The estimation of the amount of multiple interferences σ is expressed as [10], [17]:

$$\sigma = \sum_{int \in INT_{s,d}} [\sigma_{int}] \tag{9}$$

Where it was assumed that $int \in INT$ is interference in the environment that attenuates the signal by a constant factor σ_{int} and it was also assumed that $INT_{s,d}$ is the set of all interferences or obstructions intersecting the virtual line-of-sight between the source node (*s*) and receiving node (*d*).

Therefore, the received signal power P_r at distance d with distance d_0 as the reference distance is fully expressed as [10], [16]:

$$P_r = P_t - L(d_0) + 10\beta\log\left(\frac{d}{d_0}\right) + \sum_{int \in INT_{s,d}} [\sigma_{int}]$$

Where, P_t is the transmitted signal power, $L(d_0)$ is the path loss, β is the path loss exponent and is usually empirically determined by field measurement.

Area of Practical Application: The second order radio model (type II) is designed for applications where the intermodal distance between one sensor node and another is comparatively larger and the size of the WSN is comparatively bigger than that of the second order radio model (type I) [9], [15]. The second order radio model (type II) is more suitable for military applications, surveillance and reconnaissance systems. One of such applications is the Object Tracking project developed at the Institute for Pervasive Computing, ETH Zurich, Switzerland [8], [18]. In this WSN application, dedicated sensors (UC Berkeley smart dust motes running on COTS software) are deployed automatically and randomly to unobtrusively monitor real-world events in a simulated battlefield with excellent quality and scalability [16], [20]. The designers of this application utilized remote-controlled toy cars (carriers for the motes) for tracking the location of military forces, presence of hostile gadgets and other real-world battlefield phenomena. In such a scenario, this WSN application frequently monitor the environment and alerts the central military base by rapidly and accurately detecting, tracking and reporting any form of threats or breach of security [12], [13].

Size of Network: The size of the network is comparatively bigger than that of the second order radio model (type I) for usually within 100 to 200 sensor nodes are being deployed in an area, which make the size of the WSN bigger [9]. The sensor nodes are used to monitor multiple events for a period of time. The data acquired is relatively larger than WSN application using the second order radio model and it is usually designed for large-scale application [12], [13].

Mode of Deployment: The sensor nodes are deployed automatically and randomly to unobtrusively monitor real-world events in a simulated battlefield with excellent quality and scalability [8].

Inter-nodal Distance: The inter-nodal distance between the sensor nodes is comparatively wider than WSN application using the second-order radio model (type I). The inter-nodal distance is usually within 3m to 10m, it is incorporated in its design to be able to accounts for the effects of signal interference and multiple signal paths.

Radio Model Complexity: The radio model design is very complex when compared to the first-order and second order (type I) radio model. This is because the radio model design put into consideration the effects of signal interference as a result of obstruction of signal due to the presence of objects and also multiple signal paths, which may cause additional signal attenuation [11]. The high degree of signal interference and multiple signal paths was as a result of the wide inter-nodal distance between the sensor nodes [9], [19].

Radio Model Accuracy: The second order radio model accuracy (type II) is comparatively better than that of the second order radio model (type I) because the radio model can account for signal interference due to signal obstruction as a result of the presence of noticeable object and also the effects of multiple signal paths [8]. However, misleading results may be obtained for short inter-nodal distance and also due to the presence of minute signal interference such as soil and moisture particles, which may cause additional signal attenuation [13], [16].

Radio Model Sensitivity: The radio model sensitivity is low due to the comparatively wide inter-nodal distance between the sensor nodes and the inability of the radio model to account fully for signal interference and the effects of multiple signal paths [8], [16].

Energy Awareness: This radio model stipulates a comparatively wider inter-nodal distance between the sensor nodes than that of the first-order and the second-order (type I) radio model [9]. This implies that the time of transmission and reception of signal is relatively longer than that of the first-order and second order (type I) radio model. Consequently, the energy expended on the transmission and reception of signal is very much. Hence, its energy awareness is low [16], [20].

Cluster-Based Routing Protocols

The low-energy adaptive clustering hierarchy (LEACH) protocol uses the first order radio model. The use of randomized rotation of cluster heads so as to facilitate the even distribution of energy dissipation among all sensor nodes involved is the underlying idea behind LEACH. 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. A sensor node is elected as a cluster head if the selected number exceeds the specified threshold [21].

The Time Division Multiple Access (TDMA) is the principle used by the cluster heads to allocate the time for sending data after cluster formation. A single-hop communication is used by LEACH [21]. The use of 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 causes the scalability problem facing the use of LEACH in a dense network scenario.

The power-efficient gathering in sensor information system (PEGASIS) protocol uses the first order radio model. It is an extended version of LEACH protocol. In PEGASIS, Sensor nodes transmit data to their nearest neighbors, which eventually transmit the data captured by the sensor nodes to the base station. The merit of PEGASIS over LEACH is it being more robust to node failures than LEACH. In PEGASIS, the equal distribution of the network energy resources among all the sensor nodes was the energy efficient strategy employed for the selection of cluster head [22]. Like LEACH, the cluster configuration is centrally managed by base station and the WSN is logically divided into clusters headed by CHs.

In PEGASIS, a multi-hop communication is used for data transmission to the BS. This implies that data is not being directly transmitted to the BS but conveyed via neighboring CHs to the BS. The CH closest to the BS is tasked with the responsibility of the aggregated data transmission to the BS [22]. The network lifetime is increased by the dynamic clustering utilized by PEGASIS. Furthermore, the network lifetime is further enhanced and the energy dissipation is reduced by performing local data aggregation. However, if PEGASIS is utilized in large-scale networks it faces scalability problems. This is due to the extra overhead as a result of the dynamic clustering network function. In addition, the scarce energy resources of the sensor nodes may be further drained by the periodic broadcast of updates and exchange of network queries. Recently, researchers have shown that there exist the possibility that some sensor nodes may not have any CHs in their vicinity with LEACH and PEGASIS. This is a great set back because the network will not be able to utilize the energy resources of such nodes and use them for data transmission.

The threshold-sensitive energy-efficient sensor network (TEEN) protocol uses the first order radio model. For time-critical applications, TEEN (Threshold-Sensitive Energy-Efficient Sensor Network) and APTEEN (Adaptive Periodic Threshold-Sensitive Energy-Efficient Sensor Network) were proposed [23], [24]. TEEN protocol was developed to respond to abrupt changes in the sensed attributes. At the start, nodes nearer to each other are grouped as clusters during the cluster formation. Higher priority is assigned to CHs of clusters closer to the sink, while lower priority is assigned to CHs of clusters farther from the sink. Hard and soft threshold are the two threshold disseminated by cluster heads to cluster members after cluster formation. The hard threshold is the minimum possible value of the sensed attribute that will trigger nodes to turn on their radio for transmitting data to their CHs. The transmission of data by nodes will begin if the following conditions are satisfy: (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, when there are no considerable changes in the sensed attributes the soft threshold helps in reducing transmissions of data [25].

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 bases use by APTEEN in changing the threshold values used in TEEN. Cluster formation is made by the BS and elected CHs 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 CHs to save energy [25]. Redundant data transmission is prevented by reducing the number of transmission by the soft and hard threshold, which leads to energy conservation. A wide range of flexibility is provided by APTEEN, which enable 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 complexity and overhead related to (1) cluster formation and (2) threshold management and query handling are the common weakness of both TEEN and APTEEN.

The geographic adaptive fidelity protocol (GAF) uses the second order radio model. (GAF) is a protocol initially developed for mobile ad hoc networks (MANETs) but realized to be useful for sensor networks [14]. In each grid area, a node serves as a leader to convey data to other nodes, which is the basic idea behind GAF. These leader nodes do not perform data aggregation like other cluster routing protocols. 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 [14].

This protocol conserves energy by discovering corresponding nodes and turning off idle nodes. Consequently, as the number of sensor nodes increases in GAF, the network life span is considerably increased as well. 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, in order to support mobility this algorithm determines the travel time. When nodes are deployed in areas with unfavorable environmental conditions, it might be difficult or nearly impossible to estimate the travel time in larger networks.

The periodic, event-driven and query-based routing protocol uses the first order radio model. The improved version of the periodic, event-driven and query-based routing protocol called the cluster-based periodic, event-driven and query-based (CPEQ) uses the second order radio model. (PEQ) protocol is intended for used when sensor networks are deployed and operated under critical condition as surveillance systems [26]. The use of hop level of sensor nodes to minimize redundant data transmission is the basic idea behind PEQ algorithm.

The shortest distance from each sensor node to the sink was determined and this is the bases for configuring the entire network by the protocol. The broadcast of the hop value, time-stamp, and source address by sink to the nearest neighbors initiate the configuration process. Afterwards, the hop level is send to the next neighboring nodes by the nodes haven stored the increment. 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 [21].

In a large network scenario, PEQ uses multi-hop communication, which is simple and effective for long distance communication [21]. 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 setback. When the WSN 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.

An improved version of the PEQ is the (CPEQ) where energy resources of the sensor nodes is the criteria for electing CHs, therefore, sensor nodes with more energy resources are selected as cluster heads [21]. CHs form clusters and cluster members communicate with their respective CHs. 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 CHs is the only difference. The cluster head selection process is based on LEACH.

Redundancy is reduced by data aggregation performed on the incoming data by CHs. Afterward, the aggregated data will be transmitted by the CHs to the sink via the shortest path. The event and data delivery process is similar to the one used in PEQ. All the advantages of PEQ are also possessed by this algorithm, specifically, Low energy consumption, Support for low latency and Support for reliability and simplicity. The aggregation of data, which conserve 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 setback. High amount of energy will be wasted in the transmission of and listening to unwanted or unnecessary packets in a highly dense network scenario.

The inter-cluster communication based energy-aware routing protocol (ICE) uses the second order radio model. (ICE) algorithm is a protocol designed for periodic, event-driven and query-based networks [26]. CHs and nodes nearest to each other within two adjacent clusters help in forwarding the message to the CHs, which in turn route it to the BS. The use of the node-node inter-cluster communications combination facilitates data transmission via short transmissions, which help to minimize the energy consumption. The setup phase begins this protocol where the network is configured just like in the PEQ and CPEQ protocols. The CH selection is based on LEACH. The process of cluster configuration is initiated by CHs broadcasting notifications to neighboring nodes, which 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 CHs [27].

This protocol has the merits of CPEQ and PEQ, namely; support for reliability, data aggregation, 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. There is the possibility of occurrence of redundant transmission and reception of packets. In a scenario where the network size is increasingly growing and becoming more dynamic, the network management can be difficult and costly.

3. Proposed Model for Radio Operation

This novel analytical model takes into consideration the important factor that the design of motes is constrained by having stepwise energy levels. The proposed analytical model also takes into account four significant factors, which affect signal propagation in WSN environment, namely; (1) the impact of interference and obstructions, (2) orientation of the antenna, (3) relative distance between the sending and receiving nodes, and (4) connectivity and coverage of the WSN.

The mathematical analysis is presented by first offering a novel set of equations, which are generalized expressions for the second order radio model type II as [9], [10]:

$$L(d) = \begin{cases} L(d_o)_1 + 10\beta_1 \log_{10}\left(\frac{d}{d_o}\right) + F(\delta)_1, & if\ d \leq d_{th} \\ L(d_o)_2 + 10\beta_2 \log_{10}\left(\frac{d}{d_o}\right) + F(\delta)_2, & if\ d > d_{th} \end{cases} \tag{11}$$

In the equation above for the total path loss $L(d)$, $L(d_o)$ is the path loss with respect to distance d_o, β is the path loss factor, $F(\delta)$ is the fading effect represented as a function of attenuation (δ) caused by interception and d_{th} is the threshold distance. The attenuation (δ) can be modeled as a function of the dielectric properties of the soil particles. The real and imaginary components of the dielectric properties of the soil particles can be derived by employing the Peplinski's principle [28]. The Peplinski principle defines the complex parameters of the propagation constant of the electromagnetic wave traversing soil particles [28]. In this research, simplified expressions for these complex parameters are derived as:

$$\epsilon = \epsilon_{real} - j\epsilon_{imag} \tag{12}$$

ϵ_{real} and ϵ_{imag} are expressed as shown in equation (13) and (14) respectively.

$$\epsilon_{real} = 1.15\left(1 + \frac{d_b}{d_s}\left(\epsilon_{soil/water}\right)^k + \left(v_{wc} \times \epsilon_{water}^{real}\right)^k - v_{wc}\right)^{k^{-1}} - 0.68$$

$$\epsilon_{imag} = \left(v_{wc} \times \epsilon_{water}^{imag}\right)^k \tag{14}$$

Where, $\epsilon_{soil/water}$ is the complex dielectric constant of soil mixed with water particles, while v_{wc} is the volume of the water content contained in the soil and d_b is the bulk density of the soil (measured in g/cm^3). d_s is the specific density of the soil particles which is approximately 2.66 g/cm^3 and k is an adjustable constant that is used as a fitting parameter to make the model averagely close to practical conditions in a WSN field. This parameter is in the range of (0.45, 0.75). Furthermore, ϵ_{water}^{real} and ϵ_{water}^{imag} are the real and imaginary parts of dielectric constant of the water particles. The attenuation (δ) is modeled in accordance with the Pelpinski principle as:

$$\delta = \omega\left(\frac{\mu_{soil}\,\epsilon_{real}}{2}\left(\left(1 + \left(\frac{\epsilon_{imag}}{\epsilon_{real}}\right)^2\right)^{\frac{1}{2}} - 1\right)\right)^{\frac{1}{2}} \tag{15}$$

From the above equation, ω is the angular frequency and μ_{soil} is the magnetic permeability of the soil particles.
The attenuation function is modeled by assuming that each obstruction $o_i \in O$ in the environment surrounding the nodes in the WSN attenuates the transmitted signal by a factor of δ_i. The source of obstruction is limited to soil particles in order to keep the model simple and practical. As a result, the transmitted signal will be affected by soil depth (undulation), concentration of water particles in the soil and the electrical conductivity of the soil. By letting $O_{s,t}$ be the set of all obstructions intersecting the virtual communication line between source node (s) and destination node (t), the fading effect can be mathematically expressed as:

$$F(\delta) = \textstyle\sum_{i \in O_{s,t}} (\delta_i \times d + R(\Gamma)_i) \tag{16}$$

From the above equation, $R(\Gamma)$ is the additional attenuation as a result of signal reflection. This function is carefully modeled as a logarithmic function in order to have a gradual and moderate attenuation effect and not a rapid and high attenuation effect, which is not practical. This function is formally expressed as [10], [29]:

$$R(\Gamma) = 10\log_{10}\left(\frac{2}{1+\Gamma^{-1}}\right) \tag{17}$$

From the above equation, Γ is the reflection coefficient, which can be formulated by employing the Fresnel equation. Assuming that the incident wave generated by a sensor node and the reflected wave are represented respectively in equation (3.8) and (3.9):

$$H_i(z,t) = \frac{A_i}{Z_1} e^{j(\omega t - c_1 z)} \tag{18}$$

$$H_r(z,t) = \frac{B_r}{Z_2} e^{j(\omega t + c_2 z)} \tag{19}$$

Where c_i is the wave number as the wave traverses region 1 and 2, A_i and B_r represents the propagation constant of incident wave in the $-z$ direction and the propagation constant of the reflected wave in the $+z$ direction, and Z_i is the electromagnetic impedance for the two waves. The reflection coefficient can be calculated as:

$$\Gamma = \frac{B_r}{A_i} = 1 - T = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \tag{20}$$

From the above equation, T is the transmission coefficient. The electromagnetic impedance is expressed as [10], [29]:

$$Z_* = \left(\frac{\mu_{soil} \times \mu_0}{\epsilon \times \epsilon_0}\right)^{\frac{1}{2}} \tag{21}$$

From the above equation, μ_0 is the magnetic permeability of free space which is $4\pi \times 10^{-7}$ Hm^{-1}, ϵ_0 is the dielectric permittivity of free space which is 8.854×10^{-12} Fm^{-1} and μ_r is the magnetic permeability of the soil particles. The magnetic permeability is usually neglected and set to 1 for practical purposes. The reflection coefficient can thus be simplified as shown in equation (22):

$$\Gamma = \frac{B_r}{A_i} = 1 - T = \left(\frac{1-\sqrt{\epsilon}}{1+\sqrt{\epsilon}}\right)^2 \approx \left(\frac{1-\sqrt{\epsilon_{real}}}{1+\sqrt{\epsilon_{real}}}\right)^2 \quad (22)$$

From the above equation, the imaginary component is neglected in order to maintain simplicity but there is a possibility of introducing error in the range (0.002, 0.007) at frequencies around 2.4 GHz.

In the context of this research, the threshold distance is modeled to cater for the effect of multipath propagation as a result of interference due to the presence of obstructions. In the case of WSN, where the antennas of the sensor nodes are positioned slightly above the ground, the signal transmitted to the receiving node will experience reflection from undulating topographies, large soil particles, small water basins and other forms of obstructions. This will lead to a large multipath signal. The effect of this multipath is modeled by the threshold distance which is the square root of the ratio of the receive signal strength (RSSI) of the second order radio model type I to the first order radio model. The mathematical equations for the second order radio model type I and the first order radio model are as given in equation (3.13) and (3.14) respectively [8], [10]:

$$P_{2nd} = P_{tx} G_{tx} G_{rx} \left(\frac{h_{tx} h_{rx}}{d^2}\right)^2 \quad (23)$$

$$P_{1st} = P_{tx} G_{tx} G_{rx} \left(\frac{\lambda_s}{4\pi d}\right)^2 \quad (24)$$

From the equation above, λ_s is the wavelength of the transmitted signal, h_{rx} and h_{tx} are the respective antenna heights of the receiving and transmitting sensor nodes, G_{rx} and G_{tx} are the respective antenna gains of the receiving and transmitting sensor nodes, and P_{tx} is the transmit power of the sensor node.

The threshold distance is thereby computed as shown in:

$$d_{th} = \sqrt{\frac{P_{tx} G_{tx} G_{rx} \left(\frac{h_{tx} h_{rx}}{d^2}\right)^2}{P_{tx} G_{tx} G_{rx} \left(\frac{\lambda_s}{4\pi d}\right)^2}}$$

$$d_{th} = \sqrt{\left(\frac{\frac{h_{tx} h_{rx}}{d^2}}{\frac{\lambda_s}{4\pi d}}\right)^2}$$

$$d_{th} = \frac{4\pi h_{tx} h_{rx}}{d \cdot \lambda_s} = \frac{2(2\pi f_c) h_{tx} h_{rx}}{d \cdot c}$$

$$d_{th} = \frac{2\omega_c h_{tx} h_{rx}}{d \cdot c} \quad (25)$$

From the above equation, f_c (or ω_c) is the carrier frequency and c is the speed by which the signal is propagated. Beyond this threshold distance, the path loss factor increases, and this means that the probability of having a good line-of-sight will gradually decrease with increasing distance from the BS. Before deriving the mathematical expressions for the transmission, it is necessary to expound on how stepwise energy levels is incorporated in this analytical model. The formal expression for the stepwise energy level implementation is:

$$E_{tx}^{k} \in \{E_{tx}\} \quad (26)$$

Where k is approximated as:

$$k \approx \left\lceil \frac{E_{tx}}{U} \right\rceil \quad (27)$$

From the above equation, k is the step, E_{tx} is the transmit energy of the sensor node and U is the unit by which E_{tx} increases.

The implication of the equation above is that the stepwise energy values are members of the huge range of continuous energy values. Stepwise energy level is chosen in order to make the model practical and conform with practical hardware design constraints. Most mote designs have specified energy values according to varying steps. Therefore, the sensor energy readings are calibrated to the appropriate level by calculating the appropriate step. This is done to conserve the limited storage and battery resources of the motes. For example, a WSN that consist of motes with maximum individual energy resources of around 97 µJ and the motes are designed to accommodate 7 steps. Due to the fact that E_{tx} cannot exceed 97 µJ, U will be 10, meaning that the energy values will be in tens. If at a given point in time, the transmit energy is 37 µJ, this value will not be used directly but the corresponding step will first be ascertained which is $k \approx 3$. The predefined transmit energy at $k = 3$ will then be used.

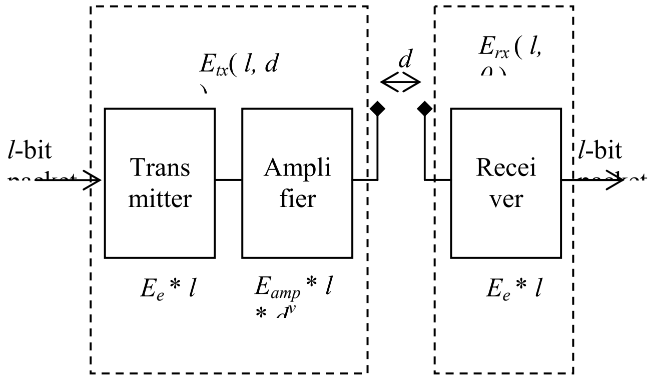

Figure 3.1: Radio Energy Consumption Model in LEACH-IMP

Based on the figure above, the radio energy can be modeled as written in equation (27):

(28)

Where,

$$E_{tx}^{k}(l,d) = \begin{cases} E_{rx}(l,\theta)_1 + (l \times E_e) + (l \times E_s \times L(d)_1), & if\ d \le d_{th} \\ E_{rx}(l,\theta)_2 + (l \times E_e) + (l \times E_l \times L(d)_2), & if\ d > d_{th} \end{cases}$$

(29)

From equation (28), the electronics energy (E_e) depends on parameters such as signal modulation, signal spreading, filtering and digital coding. E_s is the energy consumed for short-range transmission distance and E_l is the energy consumed for long-range transmission distance. The amplifier energy, $E_s \times L(d$ or $E_l \times L(d$, depends on the bit-error rate and the distance to the receiver. It must be mentioned that the orientation of the receiver's antenna is taken into consideration in this model as denoted in the model as E_rx (l,θ)

4. Simulation Results

In this research work, a clustered wireless sensor network is simulated in a field of 100m by 100m dimensions using MATLAB and OMNET++. The total number of sensors n = 100. The Short-range transmission energy, Es is set to 10 pJ/bit/m^2, the Long-range transmission energy, E_l is 0.0013 pJ/bit/m2 and the Initial energy for sensor nodes, E0 0.5 Joule. The average percentage of nodes per cluster is 0.061%. The size of the message packet that sensor nodes forward to aggregators as well as the size of message packet that aggregators forward to the sink is 4000 bits. The performance measures employed in this work are energy consumption, number of links fault or path failure, number of packets received, signal attenuation, and network lifetime.

Analysis of Energy Consumption: This performance metric is evaluated as the total amount of energy consumed from the initiation of the network operation till the death of the last alive node in the entire sensor network. it is observed that the LEACH-IMP technique has better energy consumption performance compared to the PEGASIS protocol when the number of nodes increases. However, when there is few numbers of nodes, the PEGASIS protocol consumes lesser energy than the LEACH-IMP. A possible explanation for this is because of the unsuitability and computational complexities of the LEACH-IMP technique for WSN with few number of sensor nodes. . This explains why PEGASIS has better energy consumption performance than LEACH-IMP when there is few numbers of nodes in the WSN. However, when there is larger number of sensor nodes in the WSNs, load balancing becomes an essential factor that must be maintained and the benefits of the LEACH-IMP technique noticeably outweigh the overhead and complexity costs. This is due to the appropriate energy level or step chooses by the LEACH-IMP technique, which is based on the induced path loss and inter-nodal distance. Furthermore, aside from minimizing energy consumption, this approach is more practical and applicable in current stage of mote design such as CC2420 chip. This helps in closing the gap between simulation and real experimentation.

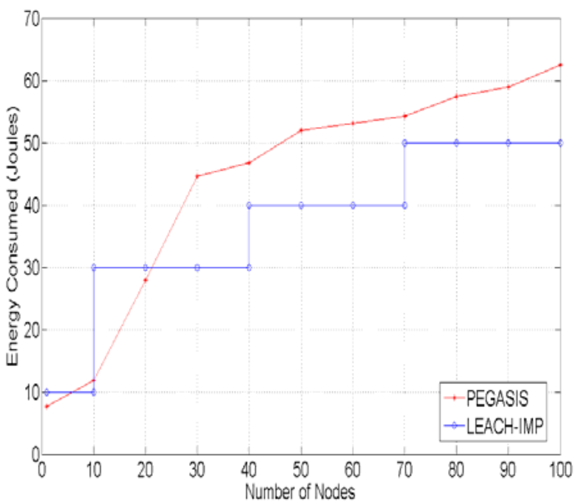

Figure 1. Energy Consumption

Analysis of Number of Link Faults or Path Failures: This performance metric is evaluated as the total number of broken links or path failures in the entire sensor network. It is observed that LEACH-IMP and PEGASIS have the same number of link faults. When there are few numbers of nodes in the network (between 10 to 20) but the performance of LEACH-IMP improved and the number of link faults become lesser than PEGASIS with larger number of sensor nodes in the network. A logical explanation for this is because of the algorithmic complexity, processing costs, overhead and computational complexities introduced by the LEACH-IMP technique. This makes it unsuitable and tasking for WSN with few numbers of sensor nodes and this substantiates why PEGASIS and LEACH-IMP have the same number of link faults in the small-scale network scenario. On the other hand, when network size becomes larger, the strengths of the LEACH-IMP technique outweigh the overhead and complexity costs. This is because LEACH-IMP utilizes three specialized data transmission schemes, namely; (1) intra-cluster communication, (2) inter-cluster communication and (3) end-to-end communication schemes. These specialized communication schemes are devised in order for the WSN to properly manage transmission tasks and ensure fair distribution of load among participating sensor nodes. This helps to ensure that the total amount of transmission going on in the network is not more than the maximum allowable capacity of the WSN and as a result, data flooding and other forms of routing path blockage and failure is significantly minimized.

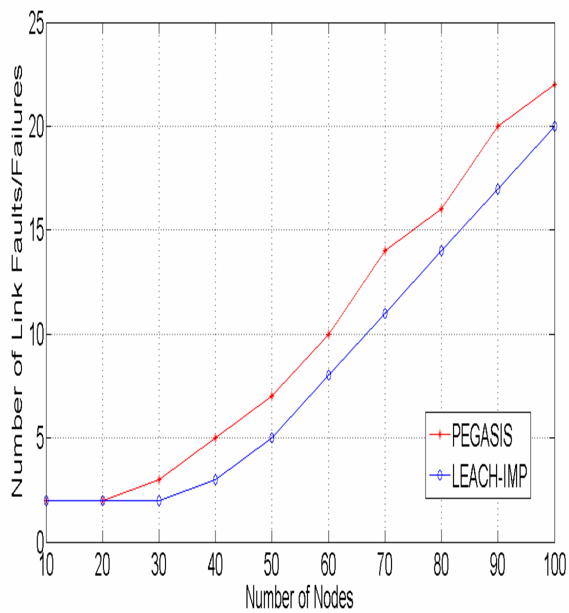

Figure 2. Number of Link Faults or Path Failures

Analysis of Number of Packets Received: This performance metric is evaluated as the total sum of packets sent from nodes to their respective CHs and the total amount of packets sent from CHs to the sink. It is observe that LEACH-IMP technique has better number of packets received as the number of sensor nodes increases when compared to the PEGASIS protocol. However, when there is few numbers of nodes, PEGASIS has higher number of packets received than LEACH-IMP. A possible explanation for this is because of the introduced overhead and complexity costs by LEACH-IMP for networks with fewer number of sensor nodes. This explains why PEGASIS has higher packets received than LEACH-IMP when there are fewer numbers of nodes in the WSN. However, as the network size grows bigger due to the addition of more sensor nodes, the benefits of LEACH-IMP outweigh the complexity costs and overheads. This is due to the flexibility and robustness of LEACH-IMP. As the network size grows larger with the addition of more sensor nodes, LEACH-IMP allows the utilization of specialized transmission schemes, which allows the WSN to flexibly switch and adapt to different scenarios for the successful delivery of packets to the destination. Therefore, this substantiates the reason why LEACH-IMP is able to account for higher number of packets successfully received.

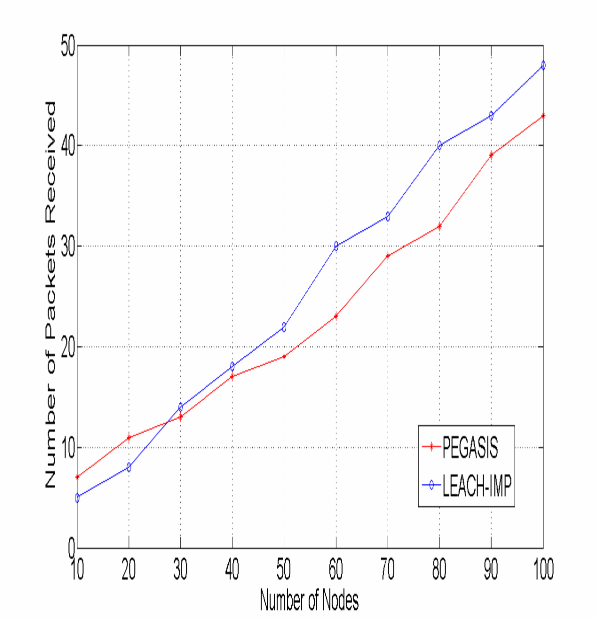

Figure 3. Number of Packets Received

Analysis of Signal Attenuation: This performance metrics is evaluated as the average attenuation per inter-nodal distance for the whole period where the WSN is considerably active. It is observed that LEACH-IMP and PEGASIS have the same amount of signal attenuation when there is little inter-nodal distance (between 0.5 to 1.5) but the performance of LEACH-IMP improved and the signal attenuation becomes lesser than PEGASIS with increasing inter-nodal distance. A possible explanation for this is as a result of the processing costs, overhead and computational complexities introduced by the LEACH-IMP technique. This makes it unsuitable and tasking for WSN with little inter-nodal distance and this substantiates why PEGASIS and LEACH-IMP have the same amount of signal attenuation in the small-scale network scenario. On the other hand, when the inter-nodal distance becomes larger, the accuracy and strengths of LEACH-IMP overshadow the computational complexities, processing costs and overhead. The reduced signal attenuation in LEACH-IMP is because of the accurate and enhanced radio model of the LEACH-IMP technique. This novel radio model allows flexible orientation of antenna, supports dynamic inter-nodal distance, supports dynamic network coverage and accounts for the effect of fluctuation in received signal strength. Therefore, this substantiates the reason why LEACH-IMP has reduced signal attenuation.

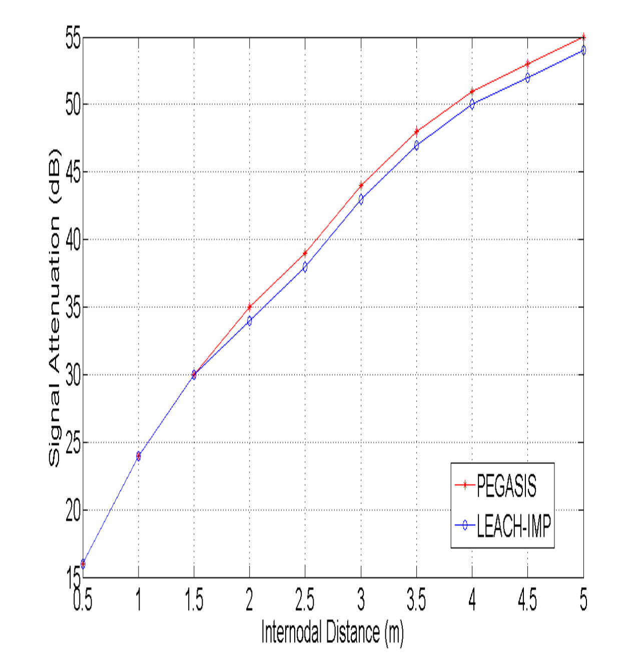

Figure 4. Signal Attenuation

Analysis of Network Lifetime: This performance metric is evaluated as the time interval from the initiation of the network operation by the sensor nodes until the death of the last alive node. It is observed that PEGASIS displays better network lifetime performance than LEACH-IMP for the first few rounds. However, LEACH-IMP exhibits better network lifetime performance as the number of rounds increases. A logical explanation for this is because of the introduced computational complexities, overhead and processing costs of LEACH-IMP, which is not suitable for WSN with fewer numbers of rounds. This explains why PEGASIS has better network lifetime performance than LEACH-IMP for the first few rounds in the WSN. However, as the number of rounds increases due to more network operations and tasks, the efficiency, accuracy and other benefits of LEACH-IMP considerably outweigh the overhead and complexity costs. This is because LEACH-IMP strategically and dynamically selects the appropriate energy level or step based on the induced path loss, inter-nodal distance and network load. Therefore, the limited energy resources are conserved and this explains why the lifetime of the WSN is longer for LEACH-IMP.

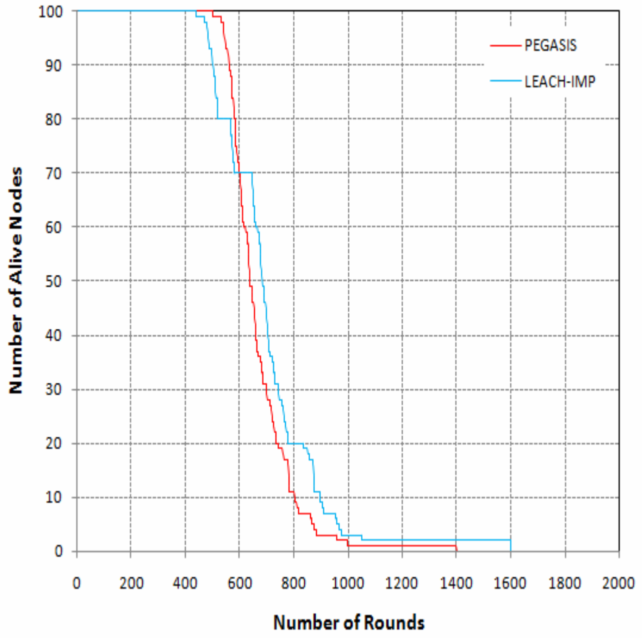

Figure 5. Network Lifetime

5. Conclusion and Future Work

This paper investigates the performance of an enhanced radio model for energy efficient cluster-based routing for sensor network. A systematic study of the impact of utilizing an enhanced radio model technique for cluster-based routing in WSN is carried out in this research. This enhanced radio model was used to develop a novel routing protocol called LEACH-IMP. The performance of the novel routing protocol utilizing the enhanced radio model has been evaluated using OMNET++ and MATLAB. The results obtained were benchmarked against standard cluster-based routing protocol PEGASIS in terms of energy consumption, number of links faults, number of packets received, signal attenuation, and network lifetime. It has been shown by simulation that the LEACH-IMP techniques displays better performance in comparison with existing clustering routing protocol with respect to the aforementioned performance metrics. The practical implementation of the LEACH-IMP technique on a WSN testbed for real-time monitoring application can be study in future. This aims to further substantiate and validate the acquired simulation results.

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References

[1] Oliveira, L., and Rodrigues, J. “Wireless Sensor Networks: a Survey on Environmental Monitoring,” Journal of Communications, North America, vol. 6, no. 2, pp. 143-151, 2011.

[2] Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., and Cayirci, E. “Wireless Sensor Networks: A Survey, Computer Networks,” vol. 8, no. 4, pp. 393-422, March, 2002.

[3] Karapistoli, E., Pavlidou, F. N., Graugopoulus, I., and Tsetsinas, I. “An Overview of the IEEE 802.15.4a Standard” IEEE Communication Magazine, vol. 48, no. 1, pp. 47-53, 2010.

[4] Heinzelman, W. R., Chandrakasan, A. and Balakrishnan, H. “Energy-Efficient Communication Protocol for Wireless Microsensor Networks,” In Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS 2000), vol. 2, 10 pp., 4-7, January, 2000.

[5] Ye, W., Heidemann, J., and Estrin, D. “Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks,” IEEE/ACM Transactions on Networks, vol. 12, no. 3, pp. 493-506, 2004.

[6] Alejandro, M. S., Jose-Maria, M. P., Esteban, E. L., Javier, V. A., Leandro, J. L., and Joan, G. H. “An Accurate Radio Channel Model for Wireless Sensor Networks Simulation,” Journal of Communications and Networks, vol. 7, no. 4, pp. 401- 407, December, 2005.

[7] Mallinson, M., Hussain, S., and Park, J. H. “Investigating Wireless Sensor Network Lifetime Using a Realistic Radio Communication Model," In Proceedings of MUE, pp.433-437. 2008.

[8] Iyengar, S. S., Parameshwaran, N., Phoha, V. V., Balakrishnan, N., and Okoye, C. D. “Fundamentals of Sensor Network Programming - Applications and Technology,” Wiley-IEEE Press, New Jersey, USA, 2010.

[9] Dargie, W., and Poellabauer, C. “Fundamentals of Wireless Sensor Networks- Theory and Practice,” Wiley Series on Wireless Communications and Mobile Computing, John Wiley and Sons, West Sussex, United Kingdom, 2010.

[10] Sobh, T., Elleithy, K., and Mahmood, A. “Novel Algorithms and Techniques in Telecommunications and Networking,” Springer Dordrecht Heidelberg, London, New York, (2010).

[11] Mukhopadhyay S. C., and Leung, H. “Advances in Wireless Sensors and Sensor Networks,” Springer-Verlag Berlin Heidelberg, New York, USA, 2010.

[12] Gaura, E., Girod, L., Brusey, J., Allen M., and Challen, G. “Wireless Sensor Networks – Deployments and Design Frameworks,” Springer Dordrecht Heidelberg, London, New York, 2010.

[13] Buratti, C., Martalo, M., Verdone, R., and Ferrari, G. Signals and Communication Technology - Sensor Networks with IEEE 802.15.4 Systems, Distributed Processing, MAC, and Connectivity, Springer Dordrecht Heidelberg, London, New York, 2011.

[14] Xu, Y., Heidemann, J., and Estrin, D. “Geography-Informed Energy Conservation For Ad Hoc Routing,” In Proceedings of the Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2001), Rome, Italy, pp. 70-84, July, 2001.

[15] Dishongh, T. J., and McGrath, M. “Wireless Sensor Networks for HealthCare Applications,” Artech House, Norwood, USA, 2010.

[16] Gauger, M. “Integration of Wireless Sensor Networks in Pervasive Computing Scenarios,” Logos Verlag, Berlin, Germany, 2010.

[17] Marron, J. P., Voigt, T., Corke P., and Mottola, L. “Real-World Wireless Sensor Networks,” -Verlag Berlin Heidelberg, New York, USA, 2010.

[18] Ballal, P., and Lewis, F. L. “Wireless Sensor Network Design – A practitioners Guide,” VDM Verlag Dr. Müller, Saarbrücken, Germany, 2010.
[19] Al-Majeed, S. S., Hu C. L., and Nagamalai, D. “Advances in Wireless, Mobile Networks and Applications,” Springer Dordrecht Heidelberg, London, New York, 2011.
[20] Ferrari, G. “Signals and Communication Technology - Sensor Networks Where Theory Meets Practice,” Springer Heidelberg Dordrecht, London, New York, 2010.
[21] Martirosyan, A., Boukerche, A., and Pazzi, R. W. N. “Energy Aware and Cluster-Based Routing Protocols for Large-Scale Ambient Sensor Networks,” In Proceedings of the First International Conference on Ambient Media and Systems, Quebec, Canada, 2008.
[22] Muruganathan, S., Bhasin, R., Ma, D., and Fapojuwo, A. “A Centralized Energy-Efficient Routing Protocol for Wireless Sensor Networks,” IEEE Communications Magazine, vol. 43, issue. 3, pp. 8-13, March, 2005.
[23] Manjeshwar, A., and Agarwal, D. P. “TEEN: A Routing Protocol For Enhanced Efficiency In Wireless Sensor Networks,” In Proceedings of the 15th International Parallel and Distributed Computing Symposium (IPDPS 2002), pp. 2009-2015, April, 2001.
[24] Manjeshwar, A., and Agarwal, D. P. “APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks,” In Proceedings of the 16th International Parallel and Distributed Processing Symposium (IPDPS 2002), pp. 195-202, August, 2002.
[25] Singh, S. K., Singh, M. P., and Singh, D. K. “A survey of Energy-Efficient Hierarchical Cluster-based Routing in Wireless Sensor Networks,” International Journal of Advanced Networking and Application (IJANA), vol. 02, issue. 02, pp. 570–580, 2010.
[26] Boukerche, A., Pazzi R. W. N., and Araujo, R. B. “HPEQ – A Hierarchical Periodic, Event-driven and Query-based Wireless Sensor Network Protocol,” In Proceedings of the IEEE Conference on Local Computer Networks, pp. 560-567, November, 2005.
[27] Nikoletseas, S., and Rolim, J. D. P. “Theoretical Aspects of Distributed Computing in Sensor Networks,” Springer Dordrecht Heidelberg, London, New York, 2010.
[28] Peplinski, N., Ulaby, F., and Dobson, M. “Dielectric properties of soils in the 0.3-1.3-GHz range,” IEEE Trans. Geoscience and Remote Sensing, vol. 33, no. 3, pp. 803-807, May, 1995.
[29] Lorrain, P., Corson, D. P., and Lorrain, F. “Electromagnetic Fields and Waves,” 3rd ed. W.H. Freeman, New York, 1998.