Improved Clustering Routing Protocol for Low-Energy Adaptive Cluster-Based Routing in Wireless Sensor Network

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ABSTRACT

Advancement in wireless sensor network (WSN) technology and sensor instrumentation has contributed to the development of novel protocols which are designed specifically for WSN, where conservation of energy is of utmost importance. Though, the performance of the cluster-based routing protocols is limited by problems related to determining an accurate and energy-efficient radio model for the sensor nodes in the network. A number of radio models have been proposed to improve the performance of WSN clustering routing protocols but the basic assumptions and inaccurate configuration of these radio models make them ineffective and most time lead to poor utilization of the limited energy and computational resources. This paper addresses this challenge by proposing an improved radio model that incorporates specialized data transmission schemes, stepwise energy level and capable of adapting to frequent changes in the position of the motes without hindering the reliability of the data transmission to the sink, despite fluctuations due to signal interference. The proposed radio model was incorporated into the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol and called LEACH-IMP. The proposed LEACH-IMP shows a better performance in terms of the energy consumption, number of packets received, signal interference and network lifetime when compared to LEACH routing protocol.

Keywords: Clustering Routing Protocols; Motes, Wireless Sensor Network; Sink; Radio Model

INTRODUCTION

Advances in wireless communication, digital electronics, digital signal processing and radio technology has proliferated the development of miniaturized smart sensor devices such as the sensor mote which are used for tracking, detecting and monitoring remote events [1, 2]. This sensor motes are usually deployed to form a network being referred to as Wireless Sensor Network (WSN),with a wide range of application among which includes wild fire monitoring, tactical surveillance, weather monitoring, wildlife migration tracking, and ubiquitous computing [1, 3].

The WSN which is made up of numerous motes may be deployed in an area, where it is difficult to replace dead nodes or even recharge their in-built batteries. Thus, a major concern in WSN is maximizing network lifetime by minimizing the energy consumption by sensor motes without compromising the reliability of the information acquired by the network. Several approaches have been proposed for increasing the lifespan of the network, among which includes low duty cycle that involves the strategic turning on and off of the sensor radio based on the sensing demand of the network [4], data fusion[5], data aggregation, data compression and data filtering [6]. However, the challenge associated with determining an accurate and energy efficient radio model for the sensor motes in the network towards maximizing the network lifetime has received little consideration.

It is note that one of the most energy draining task in WSN is the radio operation, during transmission and reception of data [2, 7] and as such cannot be overlook during WSN protocol design. In addressing this issue associated with the radio propagation model, the free space pathloss radio model that operates based on the assumption of short inter-nodal distance between the sensor motes and a clear line-of-sight path between the transmitter and receiver [8], has been proposed. However, it has been shown that the assumption of short inter-nodal distance between motes is impractical. As large discrepancy is being observed in the reported readings by protocols that incorporated the free space pathloss radio model in their design and the actual energy consumed by the network during transmission and reception of data [9, 10]. These misleading readings that was as a result of the inaccurate configuration of the free space pathloss radio model parameters often leads to improper utilization of the limited energy and computational resources[11, 12].

This paper presents an improved radio model for clustering routing protocol. The proposed radio model was incorporated into the design of the proposed LEACH-IMP, which is capable of reporting reliable data to the sink despite fluctuations in the network signal strengths. The rest of the paper is structured as follows: A review of some clustering routing protocols and their radio model is presented in Section II. The proposed system model is presented in section III. Section IV presents the simulation results while conclusion and future work is presented in section V.

Clustering Routing Protocols and Radio Models

In WSN, radio propagation model involves the investigation of how the choice of physical layer parameters affects the energy consumption of the sensor motes and the overall network. This is crucial in understanding the process of the data transmission and reception of the network and in the design of robust routing protocols capable of guaranteeing reliable communication. It is assumed in many designed clustering routing protocols that the radio operation is expensive. Hence, there is need to design clustering routing protocol to reduce the transmit distances and minimize the number of radio operations (transmission and reception) for each message. The energy dissipation of the entire clustering networks greatly depends on the choice of the radio model parameter. Thus, the need for the careful and effective selection of the radio model parameters to ensure the longevity of the network and reliable environmental monitoring when used for both civil and military applications.

Radio Models

There are two types of radio model in WSN, namely the free space pathloss and the second-order radio model.

Free Space Pathloss Radio Model

The free space pathloss radio model was designed on the assumption of a single clear line of sight between the transmitter and the receiver in an ideal propagation condition. In this model, the communication radius is basically modelled as a circle around the transmitter with the receiver able to receive all transmitted packet when it is within the communication radius else it losses all sent packet from the transmitter when it is outside the coverage radius of the transmitter [13, 14]. The received signal power P_r in (*dB*) at a distance *d* from the transmitter [14], is shown in (1):

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

where, P_t is the transmitted signal power, G_t and G_r are the transmitter and receiver antenna gain respectively. The loss l in (dB) is expressed as

$$l = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{2}$$

Therefore, P_r in (*dB*) in equation 1 can be expressed as:

$$P_r = P_t + G_t + G_r - 20\log_{10}(d) - 20\log_{10}(f) - 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{3}$$

where, f *is* the signal frequency, d is the distance from the transmitter and c is the speed of light in Vacuum.

The free space pathloss radio model is often used in most hierarchical routing protocols that include the Low-Energy Adaptive Clustering Hierarchy (LEACH) [13]. Furthermore, it is suitable for used in health applications and medical body area networks as reported in the Vital Sign project where dedicated sensor motes were deployed manually for patient identification [2]. The radio model sensitivity is high due to the short inter-nodal distance between sensor motes. Also, the radio model reduced the energy consumption of the network due to the short inter nodal distance which reduces the time of transmission and reception of signal. Though, the accuracy of the radio model is low due to the dependency of the received power on the transmission distance, but it's less complex as it was designed on the assumption of line of sight without the possibility of having any hindrances along the propagation path.

Second-Order Radio Model

The second order radio model was designed with the assumption of direct line of sight between motes though with wider coverage distance compared to the free space pathloss radio model. This model gives a more accurate prediction at long distance [14, 15]. However, a misleading result may be obtained for shorter distance due to the wider inter-nodal distance for which it is designed for as well as the effects of ground reflection propagation path. The received power is predicted as a deterministic function of distance by designing the communication range as an ideal circle[16, 17]. The received power P_r in decibel (dB) at distance *d* meter (m) can be expressed as [18, 19]:

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

Where, h_t and h_r are the transmitting and receiving antennas heights respectively. The parameter σ, is an estimation of the amount of multiple interferences modeled as shown in (5) and *n* is the percentage of the total amount of multiple interferences with a value within 20 to 30 that will be accounted for in the model [18].

$$\sigma = \sum\nolimits_{\text{int}}\left[\sigma_{\text{int}}\right] \tag{5}$$

Where, int is interference in the environment that attenuates the signal by a constant factor σ_{int} and [ ] represent integer numbers.

This radio model is designed for used in application with wider intermodal distance between motes compared to the free space pathloss model[14, 16]. Furthermore, it is more complex, with low sensitivity and energy awareness due to the longer time needed for the transmission and reception of signal. Though with an improved accuracy compared to that of the free space path loss. It is mostly used for environmental monitoring applications and system [14].

Clustering Routing Protocols

Threshold-Sensitive Energy-Efficient Sensor Network (TEEN) and Adaptive Periodic Threshold-Sensitive Energy-Efficient Sensor Network (APTEEN) were proposed for time-critical applications [20]. In Teen, the sensor motes closer to each other are grouped in the same cluster during the cluster formation and Cluster Heads (CH) are selected for each cluster, with higher priority given to CHs closer to the sink. A hard threshold value was used in triggering the radio of the motes for data transmission to CHs, while a soft threshold was used in reducing the data transmission when there was no considerable changes in the sensed attribute[21]. The threshold value in APTEEN was set based on the user demands and application type. Though, the cluster formation as well as CH election was made by the sink while the elected CHs distribute the thresholds, Attributes, Schedule and Count Time parameters. Also, a range of flexibility was introduced in APTEEN clustering protocol among which allowed users to set the count time interval which minimizes the energy consumption. Nevertheless, the process of cluster formation, threshold management and query formation in both approaches were complex and require high overhead. Furthermore, there was limited coverage area during transmission of data due to the use of the free space pathloss radio model, which may degrade the scalability and the performance of wireless simulators. More so, a misleading result may be obtained due to an unsuitable configuration of model parameters.

The Energy consumption in WSN was reduced by an adaptive and self-organizing protocol called LEACH [13]. It conserves energy by the randomized rotation of CHs, which enable the even distribution of energy dissipation among all sensor motes. It involved the use of two different phases namely; the set-up phase where motes select a random number between the range of 0 and 1, and the steady phase. A sensor mote is elected as a CH if the selected value exceeds the specified threshold [22]. This approach which uses the free space pathloss radio model has the merit of enhanced data aggregation which improved the network lifetime by minimizing the rate of redundant data transmission. However, in a dense network scenario, the LEACH protocol faced the challenge of scalability due to the use of a single-hop communication that drains the energy of the sensor motes, and ineffective for long distance communications.

A power-efficient gathering in sensor information system (PEGASIS) which was an extended version of LEACH was presented in [23]. It uses a multi-hop communication technique for data transmission from the source node to the sink. This was achieved by sending sensed data to the nearest neighbors that eventually transmit the sensed data to the sink. PEGASIS is more robust to node failure when compared to LEACH routing protocol. Though, it used free space pathloss radio model but employs equal distribution of the network energy resources among all sensor nodes as the energy efficient strategy [24], thereby enhancing the network lifetime. However, the extra overhead introduced by the cluster splitting algorithm during cluster formation drains the network energy. The radio propagation model assumes the first-order radio model just like that of LEACH.

A Geographic Adaptive Fidelity (GAF) routing protocol that split the networks into virtual grid, with a global position system used by nodes to associate themselves with a location on the virtual grid after the protocol initialization is presented in [25]. Though, a node is selected as the leader node in conveying data to other nodes in the network. However, the leader node does not have the capability of aggregating data as found in most other clustering routing protocol. The network lifespan is enhanced as the number of sensor nodes increases by conserving energy in form of discovering corresponding nodes and turning off idle nodes. However, the utilization of GPS technology that is energy-draining and expensive for a huge and dynamic network is one of the scalability issues with this algorithm.

A routing protocol designed for used under critical surveillance condition system called the periodic, event-driven and query-based (PEQ) protocol was presented in [26]. The use of hop level of motes to minimize redundant data transmission is the basic idea behind PEQ algorithm. It configured the entire network based on the shortest path from each mote to the sink. The configuration process was initialized by the sink by broadcasting the hop value, time-stamp and source address of the nearest neighbor. Afterwards, the hop level is send to the next neighboring nodes by the nodes haven stored the increment. At each node, the hop value was compared to the one in the packet. It updates the packet and retransmits it, if the hop value is greater. The process continued until the whole network was configured [26].

A Hierarchical periodic, event-driven and query-based protocol (CPEQ), which was an improved version of PEQ was proposed in [22]. CHs are allocated based on the energy resources of the sensor motes in each cluster. Thus, motes with high energy are selected as CH [22]. It used the second order radio model with a multi-hop communication technique in dense network, which have the merit of effective long-distance communication. The used of the optimal routing path ensured low latency and reduced the energy consumption. PEQ just like the CPEQ algorithm have the merit of low latency, support reliability and low energy consumption. Nevertheless, a major drawback of this protocol was the flooding of the network by configuration broadcast messages. Furthermore, the energy resource of the network may be mismanaged, due to the redundant transmission and reception of data as the network size grows bigger.

PROPOSED SYSTEM MODEL

The proposed system model comprises of the description of the designed network architecture, the proposed radio operation model as well as the data transmission scheme for the proposed LEACH-IMP routing protocol.

Description of the Network Architecture

In WSN, the two basic components involved in the network designed are the sensor nodes (motes) and the base station (sink). In this work, it was assumed that homogenous motes with an initial amount of energy for each mote in the network were deployed in an industrial environment with presence of obstruction in the communication path. Also, it is assumed that the motes sensed the environment at a constant rate and relay such information to the sink using TDMA scheduling. Though, the sink has the location information of all the motes in the network. Furthermore, for practical purpose, it was assumed that a programmable power control technique was incorporated into the design with an averagely reliable MAC layer transmission quality.

In cluster formation, the sink logically clustered the motes for efficient event monitoring and data collection. Motes within the same cluster performs the sensing tasks and forwarded the sensed data to elected CH. The CHs aggregates the received data from cluster member and relay it directly to the sink or via other CH nodes if necessary. The received data from the motes are being processed by the sink and retransmitted via wire or wireless network access to the end user. In the proposed LEACH-IMP protocol, the sink act as a central controller that performs the essential tasks of determining the suitable type of hierarchical cluster formation among CHs given different network conditions.

Radio Operation Model

In the design of the proposed mathematical model for the radio operation, some important metrics were considered, among which include the antenna orientation, the effect of obstructions and interference, the coverage connectivity of the WSN, relative distance between the transmitting and receiving motes, as well as the incorporation of stepwise energy levels. The total pathloss $L(d)$ for the proposed radio operation is model as[18, 27]

$$L(d) = \begin{cases} L_1(d_o) + 10\beta_1 \log_{10}\left(\frac{d}{d_o}\right) + F(\delta_1), & \text{if } d \leq d_{th} \\ L_2(d_o) + 10\beta_2 \log_{10}\left(\frac{d}{d_o}\right) + F(\delta_2), & \text{if } d > d_{th} \end{cases} \quad (5)$$

where, $L_1(d_o)$ and $L_2(d_o)$ are the pathloss with reference to distance d_o for the free space path loss and second order radio model respectively. Similarly, β_1 and β_2 are the pathloss factor for the free space path loss and second order radio model respectively. The fading effect $F(\delta)$ is denoted as a function of attenuation (δ_1) and (δ_2) caused by interference for the free space path loss and second order radio model respectively, with the threshold distance denoted as, d_{th}. The threshold distance was set to cater for the effect of multipath propagation as a result of interference caused by the presence of obstructions as well as to incorporate flexibility in the radio model. This threshold distance was set to 0.95m, in order to allow the radio model to dynamically switch between the free space path loss in (3) and the second order scenario in (4) based on the inter-nodal distance between the motes. Hence, if $d \leq d_{th}$ the free space pathloss radio model will be used, but if $d > d_{th}$ then the second order radio model will be used. Beyond this threshold distance, the pathloss factor increases, and this means that the probability of having a good line-of-sight will gradually decrease with increasing distance from the sink.

The stepwise energy was incorporated into the radio model design in order to make the model practical and conform to practical hardware design constraints. The stepwise energy level implementation is expressed in (6)

$$E_{tx}^{k} \in \{E_{tx}\} \quad (6)$$

where, k the step is approximated

as shown in (7), with E_{tx} being the transmit energy of the mote, and U denotes the unit by which E_{tx} increases

$$k \approx \left\lfloor \frac{E_{tx}}{U} \right\rfloor \quad (7)$$

It is note that the energy readings of motes are calibrated to the appropriate level based on computed appropriate step. This ensures the conservation of the battery and storage resources of motes.

The energy consumption model in the proposed LEACH-IMP protocol is an improvement over existing clustering based routing protocols [13]. To operate the radio electronic of the proposed LEACH-IMP, energy resources are consumed by the transmitter and receiver of the motes as shown in Figure 1.

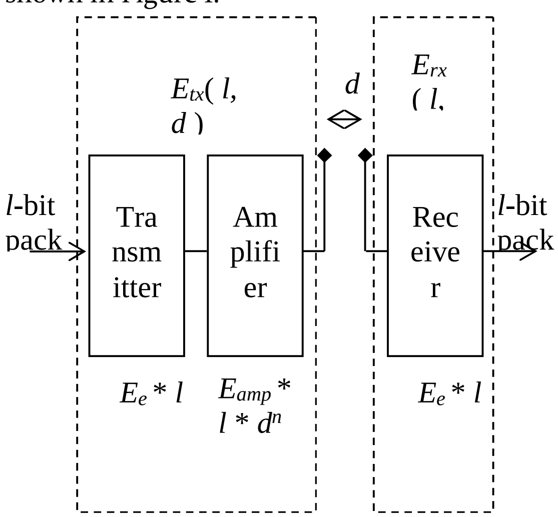

Figure 1: Radio Energy Consumption Model in LEACH-IMP

The free space path loss and the second order radio model were incorporated in the radio communication model of the proposed LEACH-IMP protocol based on the distance between the transmitting and the receiving motes. An energy control method was used for the incorporation of these radio models by carefully tuning the energy of the amplifier. As seen in figure 1, d^n is the energy loss due to channel transmission based on either the free space pathloss or the second order radio model being utilized. The utilization of the energy control ensures that if the distance (d) is less than or equal to a threshold distance (d_{th}), the free space pathloss radio model is adopted. However, if the distance (d) is greater than the threshold distance (d_{th}), the second order radio model is utilized. Thus, the energy consumption during the transmission and reception of an l-bit message between two nodes separated by a distance d are given by equation (8) and (9) respectively:

$$E_{tx}^{k}(l,d) = E_e \times l + E_{amp}(d) \times l \quad (8)$$

$$E_{rx}\left(l,\theta\right) = E_e \times l \quad (9)$$

where, $E_{tx}^{k}(l,d)$ denotes the total energy dissipated in the transmitter of the source node, and $E_{rx}\left(l,\theta\right)$ represents the energy consumed in the receiver. The electronics energy E_e is the per bit energy dissipations for transmission and receptions, which depends on some parameters like signal modulation, signal spreading, filtering and digital coding. The required energy by the transmit amplifier needed for maintaining an acceptable signal to noise ratio for acceptable data message transfer is denoted as $E_{amp}\left(d\right)$. In approximating the pathloss during the data transmission, the free space pathloss and the second order radio model were adopted. The energy required by the transmit amplifier $E_{amp}\left(d\right)$ using these two models is expressed in (10).

$$E_{amp}\left(d\right) = \begin{cases} E_s \times d^2, & if \ d \le d_{th} \\ E_l \times d^4, & if \ d > d_{th} \end{cases} \quad (10)$$

where, E_s and E_l denotes the consumed energy for short and long-range transmission distance respectively.

Model for Data Transmission Scheme

In the proposed LEACH-IMP, data are routed from the motes to the sink in a many to one data traffic pattern. Data are communicated among motes in the same cluster using direct communication. Multi-hop communication technique is utilized, when data are to be forwarded among CHs. The LEACH-IMP takes the advantage of the two mechanisms by integrating both the single-hop and multi-hop routing, which makes it different from other routing protocols.

In the proposed LEACH-IMP, a pseudo code was used to differentiate between signal transmissions by motes within the same cluster from that of other clusters. In addition to this, another pseudo code was employed after the data aggregation process is completed to relay the message to the CH nearest to the sink or directly to the sink. TDMA was used to avoid transmission collision among motes within the same cluster and that from other clusters during communication among CHS. This was done by the sink which determined the time slot schedule in TDMA.

Statistically correlated data signals are combined into a smaller single set of data using a simple data fusion technique during data aggregations phase. This ensures the effective conservation of the limited memory and processing resources as well as maintaining a close accuracy between the compressed dataset and the original data signals. The CHs are responsible in aggregating the *K* packets of data received from *K* motes in their respective clusters into a single packet.

In WSN, data frame is the structure and organization of the packet transferred. The most essential operation in a round is the effective management of a frame, which is scheduled by TDMA time slots. The TDMA time slots are allotted for communication among motes in the same cluster (intra-cluster), among different CHs (inter-cluster) and from the nearest CH to the sink (end-to-end) transmissions. This implies that an apportioned time slot is specified for each sensor node in order for it to be able to transmit data to their respective CHs. Furthermore, the CHs are allotted one-time slots for forwarding the aggregated datasets to the sink for further processing and analysis by the end user.

The number of transmitted frames in a round (*FR*) depends on the throughput bandwidth of the wireless channel (*TPB*), the number of bits contained in the specified frame (N_b), and the round duration (*R*). The number of transmitted frames is computed using (11) [28]:

$$FR = \frac{TPB}{N_b \times R} \tag{11}$$

Equation (11) can be expanded by using the knowledge that the number of bits contained in a given frame (N_b) is the product of the number of slots contained in the frame (*S*) and the packet length (*L*). Therefore, equation (11) can be expanded as:

$$FR = \frac{TPB}{S \times L \times R} \tag{12}$$

The structure and organization of a frame in the mechanism of the LEACH-IMP protocol with respect to a time line is presented in Figure 2.

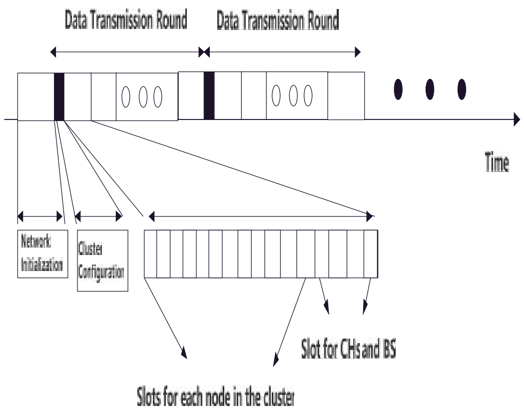

Figure 2: Organization and Structure of Frame in Proposed LEACH-IMP

SIMULATION RESULTS

OMNeT++ was utilized for the simulation process, which provides graphical user interface for the development of protocol and selection of features. While, MATLAB was used for the analysis of results obtained from OMNeT++. A clustered WSN field of 100m by 100m was considered for the purpose of simulation. The main simulation parameter settings are summarized in table 1. The performance measures employed in this work are energy consumption, number of packets received, signal interference and network lifetime. The performance of each of this metrics for the propose LEACH-IMP were evaluated by comparing it to the original LEACH routing protocol as shown in figure 3, 4, 5, and 6 respectively.

TABLE 1: SUMMARY OF SIMULATION PARAMETERS

Parameter	Value
WSN Area, $A = N \times N$	100 m x 100 m = 10,000 m^2
Number of nodes, n	100
Average percentage of nodes per cluster	0.061%
Probability of becoming cluster head, P_{opt}	0.1
Size of message, l	4000 bits
Pathloss exponents (β_1, β_2)	2.09, 4.01
Fading exponent ($F(\delta_1)$, $F(\delta_2)$)	0.28, 0.67
Threshold distance d_{th}	0.95m
Average radio transmission coverage d_{max}	2.35m
Electronics energy, E_e	50 nJ/bit
Short-range transmission energy, E_s	10 pJ/bit/m^2
Long-range transmission energy, E_l	0.0013 pJ/bit/m^4
Initial energy for sensor nodes, E_o	0.5 J

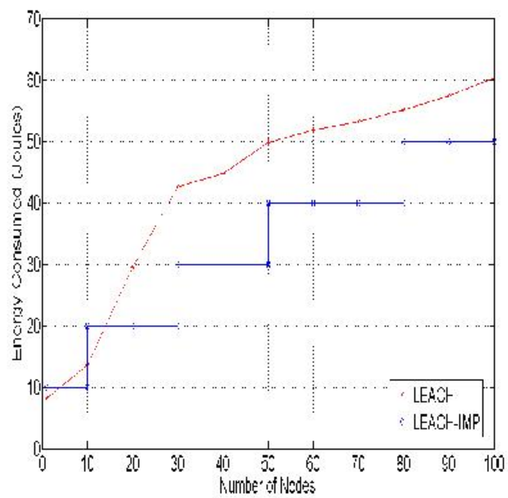

FIGURE 3: Comparative Plot of LEACH-IMP and LEACH Energy Consumption

Observed from Figure 3, that the LEACH protocol performs better in terms of energy consumption when there are fewer number of nodes in the network. However, as the numbers of nodes increases, as the network grows bigger, the proposed LEACH-IMP performs better by consuming less energy due to the incorporation of the step wise energy level.

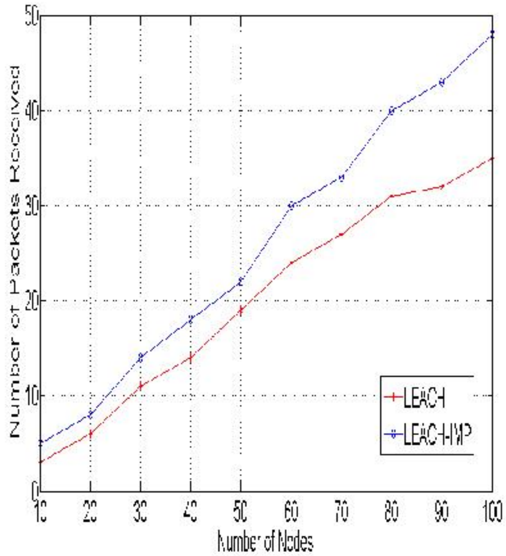

figure 4: comparative plot of leach-imp and leach number of packets Received

The poor performance of the LEACH-IMP when there are fewer numbers of nodes in the network may be attributed to its computational complexities, processing costs and overhead. Nevertheless, as the number of nodes increases, load balancing becomes a crucial factor that must be maintained in the network. This was provided by the proposed LEACH-IMP whose benefits outweigh its complexity and overhead. An improvement of 30.72% was recorded by the proposed LEACH-IMP when compared to that of LEACH protocol in terms of the average energy consumption. Similarly, observe from figure 4 that LEACH-IMP has better packet delivery with less number of failed nodes when compared to the LEACH protocol. This improvement by LEACH-IMP can be attributed to the incorporation of the specialized data transmission schemes and threshold-sensitive dynamic setting of allowed number of transmissions in its design. The LEACH-IMP recorded 29.21% improvement in terms of the number of packets received at the end of the network operation. It was observed that the signal interference in LEACH-IMP protocol increases as the inter-nodal distance between the nodes increases. However, it is comparatively lesser when compared to LEACH protocol (see figure 5). This improved achievement of the LEACH-IMP protocol with about 9.28% in terms of signal interference over LEACH can be attributed to the incorporated improved radio model that supports dynamic inter nodal distance, capable of accounting for the effect of signal fluctuation (discussed in section IV) in the LEACH-IMP protocol. Observe that for the first few rounds in the network; the LEACH protocol performs better than the LEACH-IMP (see figure 6). This may be attributed to the less computation complexities and overheads of the LEACH protocol. However, as the number of rounds increases with more network operation, the merit of the proposed LEACH-IMP outweighs its overhead and complexity thus, showing better network lifetime performance.

CONCLUSION AND FUTURE WORK

This paper examined the performance of an improved radio model for energy efficient clustering routing in WSN. The developed radio model was incorporated into the design of a new routing protocol called LEACH-IMP. The performance of the proposed LEACH-IMP was evaluated by simulation. The results obtained were benchmarked against standard clustering routing protocols called LEACH in terms of the energy consumption, number of packets received, signal interference and network lifetime, with the LEACH-IMP showing better performance. Future research work will examine the development of a testbed for the practical implementation of the proposed LEACH-IMP. In addition, techniques for preserving the privacy of the transmitting node will be explored as well as its utilization for pipeline monitoring.

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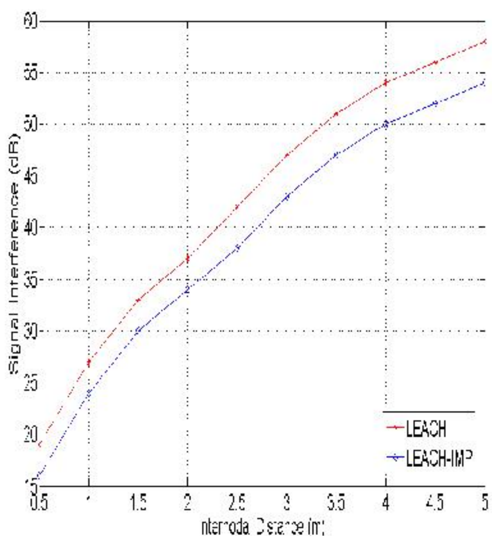

Figure 5: Comparative plot of LEACH-IMP and LEACH Signal Interference

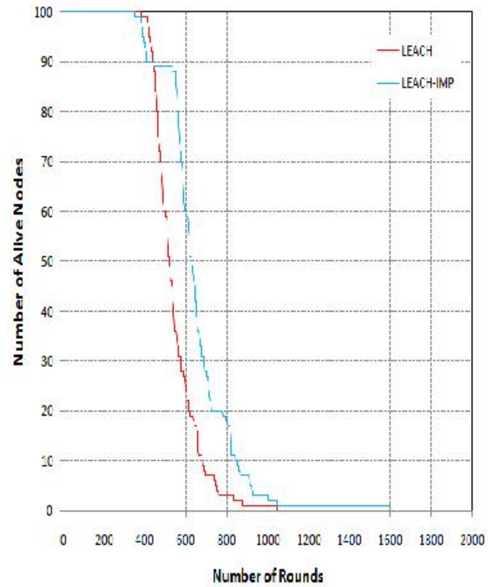

Figure 6: Comparative plot of LEACH-IMP and LEACH Network Lifetime

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