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Impact of Radio Irregularity on the Performance of Radio Models in Wireless Sensor Networks

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Abstract **- The aim of this paper is to show the effect of radio irregularity on MAC and routing protocols in wireless sensor networks. It will be observed that most simulation environment for wireless sensor networks assumes a spherical topology for the network environment. Hence the radio model for the simulators use this assumptions in their representation. However based on the results from field experiments on sensor motes, it was observed that varying the DOI and VDOI based on different network setting and heterogeneity of hardware devices will greatly enhance the performance of radio models used in simulation. The idea here is to bridge the gap between spherical radio models used by simulators and the results obtained from on-field experiments. The DOI and VDOI values are built into the MATLAB's PROWLER. The simulation results show the importance of integrating this values in the radio model.**

Keywords: Radio irregularity, anisotropic heterogeneous, path loss, asymmetric, Degree of irregularity (DOI), Variance of Sending power (VSP)

1.INTRODUCTION

Radio irregularity is defined as the changes in radio range and variations in packet loss in different directions as data is been sent from source to destination. This is a major cause forasymmetric linksas seen by upper layers in the protocol stack. Several empirical studies [1], [2], [3] on the Berkeley mote platform have shown that the radio range varies significantly in different directions and the percentage of asymmetric links in a system varies depending on the average distance between nodes.

The impact of radio irregularity on protocol performance can be investigated through life measurements taken in a wireless sensor network environment. This method is hardly employed mainly for two reasons

(i) The complexity and cost of performance evaluations using life measurements escalate, when sensor networks scale up to thousands or more nodes.

(ii) Repeatable results of radio performance are extremely hard to obtain from uncontrolled environments, hence leading to difficulties in system precision and performance evaluation.

As a result, simulation techniques are used as an efficient alterative to evaluate protocol performance. Unfortunately,

Most existing simulations do not take radio irregularity into account. The spherical radio patterns assumed by simulators such as [4] may not approximate real radio properties well enough and hence may lead to an inaccurate estimation of application performance. Several researchers [5], [2] [3], [6] have already shown extensive evidence of radio irregularity in wireless communication. Their main focus is to observe and quantify such phenomena. This aim of this paper is to bridge the gap between spherical radio models used by simulators and the results obtained from on-field experiments. The source of this variance is built into MATLAB's PROWLER in order to obtain a more realistic radio model for wireless sensor networks. An evidence of radio irregularity is shown using empirical data obtained from MICA2 and MICAZ as evidenced in [2], [5]. The results therein demonstrate that the radio pattern is largely random; however, it exhibits a continuous change with incremental changes in direction. Based on experimental data, an improved radio model for simulations, called the Enhanced Radio Irregularity Model (ERIM), is formulated. ERIM takes into account both the anisotropic properties of the propagation media as well as the heterogeneous properties of devices. The model is built into PROWLER in MATLAB in order to improve the results obtained from the simulator.

With the help of the ERIM model, the impact of radio irregularity onMAC, and routing protocol is highlighted. Three routing protocols (LEACH, PEGASIS and GAF), and three MAC protocols(S-MAC, T-MAC AND LMAC) will be used to investigate the effect of radio irregularity in the simulation. The results show the influence of topology variability and sensor heterogeneity on the results obtained from the different protocols used.

The rest of this paper is organized as follows: Section 2 looks into contributions made by other scientist in this field of research. In Section 3, the causes of radio irregularity in wireless sensor networks is highlighted, and based on these conclusions, theERIM radio model was proposed in Section 4. The ERIM model is used in simulations to analyze theimpact of radio irregularity on MAC protocols in Section 5,and routing protocols in Section 6, finally, the paper is concluded in Section 7.

2. RELATED WORK

Different protocols has been formulated for use in the MAC and routing radio channel model for wireless sensor networks. In [4] the authors proposed a contention based MAC protocol (S-MAC) explicitly for wireless sensor networks.In this, they observedthat their proposed method achieves efficient low energy consumption along with good scalability and collision avoidance capability. In [5], the authors introduced ER-MAC (Energy and Rate), an energy aware MAC protocol using TDMA (Time division multiple access) and found that it possesses the natural ability of avoiding extra energy wastage. In this, they use the concept of periodic listen and sleep, in the sense that a sensornode switches off its radio and goes into a sleep mode only when it is in its own time slot and does not have anything to transmit. In [6], a TDMA based MAC protocol that can provide delay guarantee was designed. It is also pointed out in [6] that their proposed approach RT-MAC takes less time relativity by reutilizing the connection channel between two successive channel accessof a sensor node. However, the problem lies in performing a lot of calculations that could exhaust the sensor node itself in some situations. The authors in [7] presents empirical results of extensive link layer measurementswith the eyes nodes, but they do not provide any channel model. The problem of converge-cast in ad-hoc geometric networks is considered in [8], where the authors assume that a transmitting node is capable of detecting collisions within its transmission range and the duration of the time slot was long enough to allow transmission of multiple packets in one time slot. The authors propose some practical considerations for wireless sensor networkalgorithms and provide pointers to remedy the lack of connection [9].

Actually, the impact of radio irregularity is not only confined to the MAC and routing layers, radio irregularity also influences other protocols, such as localization, sensing coverage and topology control protocols. Localization protocols such as DV-HOP [13] and Centroid [14] assume a spherical radio range. The study in [7] shows that the performance of such protocols degrades when the radio range becomes irregular. The sensing coverage scheme in [15] assumes that sensing and communication ranges are spherical. In the presence of radioirregularity, they might not be able to guarantee full coverage and blind areas would occur. The topology control scheme in GAF [16] builds a communication mesh based on the assumption of a spherical range. This might lead to network partition in the presence of a non-spherical range.

3. CAUSES OF RADIO IRREGULARITY

According to [11] there are two major causes of radio irregularity: devices and the propagation media. Device properties include the antenna type (directional or omni-directional), the sending power, antenna gains (at both the transmitter and receiver), receiver sensitivity, and the Signal to Noise-Ratio (SNR) threshold. Media properties include the media type, the background noise and some other environmental factors, such as the temperature and obstacles within the propagation media.

In general, the radio irregularity is caused by the anisotropic properties of the propagation media and the heterogeneous properties of devices. Among all these factors, this paper focuses on the anisotropic path losses and the differences in signal sending power, which are commonly regarded as the key causes of radio irregularity.

Anisotropic Path Losses: The variance in the signal path loss is one of the major causes of radio irregularity. This is due to the uneven surface and the types of obstacles in the network area. When a signal propagates within a medium,it may be reflected, diffracted, and scattered [8]. Reflection occurswhen an electromagnetic signal encounters an object, such as a building whose wavelength is greater than the signal's wavelength. Diffraction occurs when the signal encounters an irregular surface, such as a stone with sharp edges. The signal then pass around obstacle using a longer route. Scattering occurs when the medium through which the electromagnetic wave propagates contains a large number of objects smaller than the signal wavelength. The signal then propagates in different directions.

Another significant reason for anisotropic path loss is hardware differences. A node may have varying antenna gain along all propagation directions, possibly due to hardware manufacturing. Hence, the anisotropic antenna gain of each node also contributes to the anisotropic path loss.

Heterogeneous Sending Powers: Sensor devices may transmit RF signal at different sending powers, even though they are the same kind of devices. This difference may arise from some random factors during the manufacture of sensor devices. Secondly the batteries of different sensor may be depleted at different rates after deployment as a result of different workloads and different environment. Heterogeneous sending powersresult in variable communication ranges, and cause anisotropic connectivity.A simulation model is proposed to handle these radio irregularities. This will then bring about a more realistic radio model for routing in wireless sensor networks.

3.1 Impact of Radio Irregularity

Radio irregularity is an essential reason for asymmetric radio interference and asymmetric links in upper layers of OSI model. It can directly or indirectly affect many aspects of upper layer performance.

Asymmetric radio interference between neighbouring nodes affects the correctness of MAC layer functions. For example, in the presence of radio irregularity, a node might not be able to successfully reserve the wireless channel through RTS and CTS handshaking, this could result that those neighbouring nodes of the receiver, which cannot hear the CTS control packet, might disrupt the receiving node. So, radio irregularity increases the chance of channel reservation failure and reduces the delivery ratios of data frames at the MAC layer. Radio irregularity canalso affect theperformance and even correctness of networking protocols such as [7], [9], [10]. For example, link asymmetry is one of the ways in which radio irregularity manifests itself at the higher layer. Link asymmetry has an adverse impact on protocols that use path reversal techniques to establish an end-to-end connection.

3.2 Impact on MAC Layer

This subsection, discusses the impact of radio irregularity on the operations in the MAC layer. The degree of MAC's performance degradation in the presence of radio irregularity is then investigated.

Most contention-based MAC protocols are based on carrier sensing or handshaking techniques. The impact of radio irregularity on MAC protocols can be explained from the following perspectives:

(1) Impact on Carrier Sensing: Radio irregularity increases the probability of the hidden terminal problem for MAC protocols that use the carrier sensing technique. The hidden terminal problem refers to the situation where a receiver node is unable to receive signals from the sender node because both are not on the same spherical plane. For example, in Figure 1(a), while node B is transmittingpackets to node C, due to the irregularity, node A cannot detect the signal from node B, so node A senses a clear channel and starts to transmit packets.As a result, a collision happens at receiver C. This scenario does not occur if node B has a spherical radio range that covers node A so that A can sense node B's signal and will not send a packet to C and get corrupted. Typical protocols using the carrier sensing technique are CSMA, MACA [11], MACAW [12] and 802.11 DCF

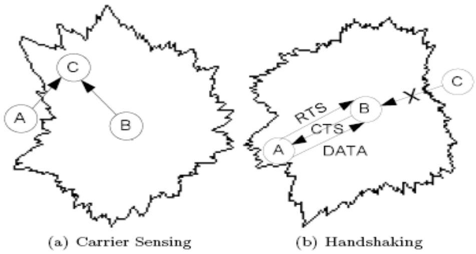

Fig1 Impact on MAC protocols

Table 1: Simulation Configuration

TERRAIN	200m X 200m
Number of nodes	100
Node Placement	Uniform
Application	MATLAB
Packet size	32 bytes
Routing Protocol	LEACH, PEGASIS, GAF
MAC protocol	S-MAC, T-MAC
Radio model	ERIM
Average Radio range	4m
Radio Bandwidth	200kB/sec

(2) Impact on handshaking: The handshaking technique is specially designed to resolve hidden and exposed terminal problems. However, they cannot resolve the hidden and exposed terminal problems due to asymmetry, which can be produced by radio irregularity. This can be demonstrated in an example (Figure 1(b)). We assume that node A sends a RTS message to node B, and then node B responds with a CTS message to node A. Any node overhearing theCTS message is supposed to wait long enough for node A to send out the data packet. If node C can't hear the CTS message from node B while node B can hear node C, there will be a collision if node C sends data. Similar examples can be found for the exposed terminal case.

4. DESCRIPTION OF SIMULATION ENVIRONMENT

The ERIM model is implemented in the MATLAB's PROWLER [13]. MATLAB is a scalable discrete-event simulator.It provides a customizable GUI for entering network parameters (topology, type, number of motes) and animation. There are three modules present in the prowler.The first module is the main module which handles event called by the user (i.e. set clock, send packet) or are fired by the other events (i.e. packet_received, clock_tick, timer_fired). The second one is the radio module that handles both the MAC-layer model and the radio propagation model. Finally, the third module is the application module provides access to user generate events. The simulation configuration will first be described, and then the performance impact under different DOI and different VSP values, are evaluated respectively.Three typical MAC protocols were used in the simulationare S-MAC, T-MAC, and LMACfor case study.

From the results of the experiments in [5], [2], [3] and [6], radio irregularity is a common phenomenon in wireless sensor networks.Therefore, it is essential for simulations of wireless systems to capture such effects. Following is the description of the model that integrates this effects in MATLAB's PROWLER.

4.1 Isotropic Radio Models

In isotropic radio models, the received signal strength is usually represented withthe following formula:
Received Signal Strength = Sending Power –Path_Loss + Fading (1)
The SendingPower of a node is determined by the battery status and the type oftransmitter, amplifier and antenna. Path_Loss describes the signal's energy loss as it travels to the receiver. Many models are used to estimate the Path_Loss, such asthe free-space propagation model, the two-ray model, the Hata model [7], and the two slope log-normal path loss model [17]. All these models are isotropic, meaning that the signal attenuates exactlythe same in all directions. However, from the experiments conducted as well as results obtained by others [1], [2], [3], [6], they all indicate that signals attenuate at different rates in different directions.

To denote the irregularity of a radio pattern, the parameter DOI (degree ofirregularity) is introduced into the ERIM model. The DOI parameter is defined asthe maximum path loss percentage variation per unit degree change in the directionof radio propagation. As shown in Figure 2, when the DOI is set to 0, thereis no range variation, and the communication range is a perfect sphere. However,when we increase the DOI value, the communication range becomes more and moreirregular.

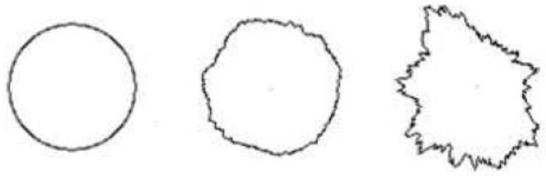

Fig.2. Degree of Irregularity

In order to make the evaluation close to existing hardware proposed for use in wireless sensor network environments, [11], the simulation configuration shown in Table 1 is used. In all experiments, the range of DOI values are set according to the experimental data obtained from MICA2 motes.

4.2 Anisotropy Property in the ERIM Model.

In order to reflect the two main properties of radio irregularity, namely anisotropy and continuous variation, the value of path loss models in Equation 1is adjusted based on DOI values, resulting in the following formula:
Received Signal Strength = Sending Power − DOI Adjusted Path_Loss + Fading
where DOI Adjusted Path_Loss = Path_Loss × K_i (2)
Here K_i is a coefficient to represent the difference in path loss in different directions.Specifically, K_i is the ith degree coefficient, which is calculated as follows:

$$K_I = \begin{cases} 1 & if\ i = 0 \\ K_{i-1} \pm Rand\ X\ DOI & If\ 0 < i < 360 \wedge i \in N \end{cases}$$

Where $|K_0 - K_{359}| \leq DOI$

4.3 Heterogeneity Property in the ERIM Model

Due to different battery statusand hardware differences, the received signal strength can be different from two sending nodes of the same type in the same experimental setting. In ERIM, the variance in signal sending power parameter is used to account for such a difference. A second parameter named VSP (Variance of Sending Power), which is definedas the maximum percentage variance of the signal sending power among different devices is introduced. The new signal sending power is modelled by the following equation:
VSP Adjusted Sending Power = Sending Power × (1 + Rand × VSP) (3)

In Equation 3, the variance of sending power is assumed to fit the normal distribution. This is in conformance with most WSN power model broadly used to estimate battery lifetime distribution and to simulate hardware differences [18], [19], [11].With the two parameters: DOI and VSP, theERIM model can be formulated as follows:

Received Signal Strength = VSP Adjusted Sending Power
−DOI Adjusted Path_Loss + Fading (4)

4.4 DOI Variance in a System.

From empirical data collected in twoMICA2 systems and a MICAZ system, it was observed that sensor devices in a system may have different DOI values, depending on the hardware devices used and the deployment environment. It is not convenient to measure each node's DOI value in a large scale system and assign the measured DOI values to each node in simulation. In order to reflect this fact of DOI variance among different devices in a system, a third parameter VDOI (Variance of DOI) is introduced, which is defined as the maximum percentage variance of DOI values among different devices in a system. It is assumed that the DOI variance in a system fits the normal distribution as explained earlier. So with the distribution as well as the VDOI value, each node in the system can easily get a DOI value.

In performance evaluation of this paper, we first set VDOI as 0 to observe system performance with different DOI values, and then set VDOI greater than 0 to investigate performance sensitivity to different VDOI values.

5. MAC Performance with Different DOI.

The value of VDOI is initially set to 0, here the topology is assumed to be symmetric. In the next subsection, the performance sensitivity of MAC protocol to DOI variance is investigated, by settingVDOI greater than 0.In the initial setup, LEACH, PEGASIS and GAFare used in the routing layer to compare the MAC performance between S-MAC, T-MAC and LMAC. The idea here is to investigate the effect of different routing techniques on the performance of the MAC protocols.

The results show that theMAC loss ratio increases rapidly with the increase of DOI values (Figure 3). However, S-MAC and T-MACyield roughly the same results with the PEGASIS and LEACH routing protocol but slightly worse with the GAFwhile that of LMAC is worse in each case. This can be attributed to the fact that with LMAC a TDMA based MAC protocol, there is high likelihood that a node that has data to be sent is kept idle because transmission is not in its time frame. This can be explained as the fixed time slot for node transmission may not be synchronous with RTS (Ready to send) signal for the node. In the worst scenario no data may be sent which will result in 0% throughput. It should also be noted that MACperformance can be strongly affected by routing, because an incorrect routing decision might lead to the failure at MAC layer. For this reason three routing protocols are used to investigate the effect of routing protocols on radio irregularities in MAC layer.It was observed that the MAC loss ratio increases slightly with the increase of DOI values. Suchdiscrepancy is a strong indication that the radio irregularity has a much largerimpact on routing protocols than MAC protocols.

5.1 Performance Sensitivity to Different VDOI.

This subsection exploreswhether DOI variance in a system has impact on the MAC performance. In thesimulation, DOI value is set as 0.01. VDOI values is varied from 0 to 1, in steps of 0.2. The simulation results is presented in Figure 4. From Figure 4, it can be observed that when VDOI varies from 0 to 1, theaverage single hop loss ratio does not vary much. Thepossible reason is that, statistically, while one portion of nodes have larger DOIvalues and hence more irregular radio, another portion of nodes will have smaller DOI values and hence less irregular radio. So their effects cancel out each other and the system-wide MAC performance is not sensitive to different VDOI values. However it can be seen that the average single hop loss ratio is still much higher when GAF is combined with the MAC protocols than with S-MAC and T-MAC. On the whole the S-MAC protocol behaves best in the face of these variations.

5.2 MAC Performance with Different VSP.

In this experiment, we set theDOI value to 0, which means that the radio range is isotropic. However, differentVSP values make radio ranges different among nodes. This is used to study the effect of heterogeneity of hardware components to MAC performance.

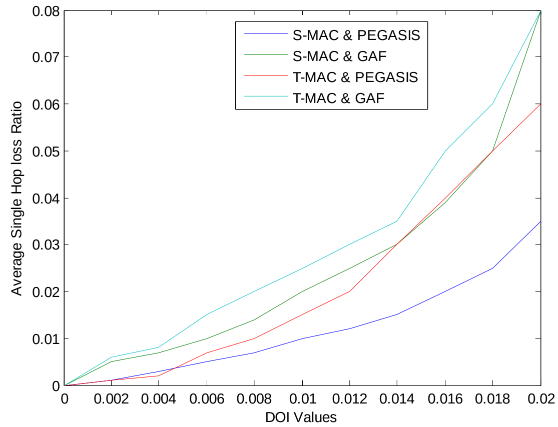

Figure 3: MAC Performance with different DOI Values

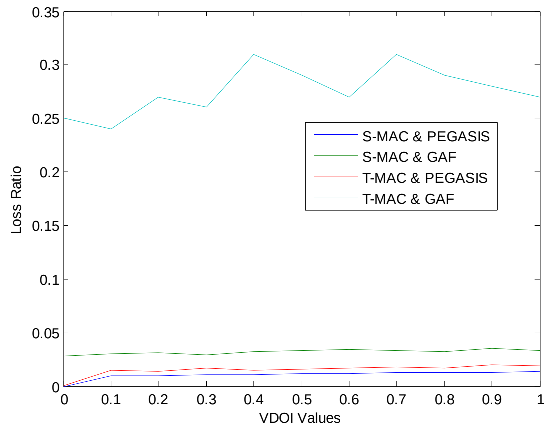

Figure 4: MAC Performance sensitivity to different VDOI Values

The loss ratio increases with the increase of VSP values because the irregularityresults in more asymmetric links. The loss ratio when LEACH and PEGASIS is combined with the MAC protocols is much lower than that when GAF is used, because asymmetric links have a larger impact on GAF than on both LEACH and PEGASIS. This result indicates that varying the VSP values has a much larger impact on routing protocols than on MAC protocols, which is similar to thebehaviour observed by varying the DOI values. This can be explained as follows: the fixed topology employed in GAF makes it highly susceptible to failure in asymmetric topology.

6. IMPACT ON ROUTING LAYER

In this section, we analyze and quantify the impact of radio irregularity on routing protocols. Three techniques widely used in routing protocols are investigated, these are: hierarchical, location based and data centric routing. The analysis shows that routing algorithms that uses both location based and data centric are greatly influenced by radio irregularity. However, the routing algorithms based on hierarchical topology are able to dealwith radio irregularity. The simulation resultsalso show that radio irregularity has a higher impact on GAF than on PEGASIS and LEACH.

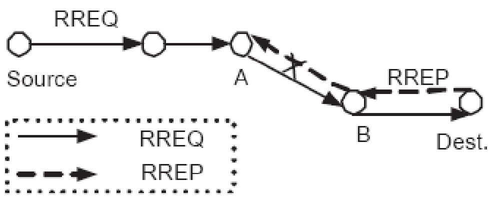

Figure 5 Impact on location based technique

6.1 Logical Analysis of the Impact

In this subsection, the influence of radio irregularity on location based, data centric and hierarchical routing techniques are investigated. The effect is however quantified in two scenario. In the first scenario, path loss difference due to link asymmetry is the main reason of radio irregularity, and in the second scenario, difference in radio sending power is the main reason.

6.2 Impact on Location based Technique.

Protocols that use location based technique are designed on the assumption that sensor nodes are addressed by means of their locations. Location information for sensor nodes is required for sensor networks by most of the routing protocols to calculate the distance between two particular nodes so that energy is conserved.The design of GAF is motivated based on an energy model [20, 21] that considers energyconsumption due to the reception and transmission of packets as well as idle (or listening) time when the radio of a sensor is on to detect the presence of incoming packets. GAF is based on mechanism of turning off unnecessary sensors while keeping a constant level of *routing fidelity*(or uninterrupted connectivity between communicating sensors). In GAF, sensor field is divided into grid squares and every sensor uses its location information, which can be provided by GPS or other location systems [20, 22, 23], to associate itself with a particular grid in which it resides.This kind of association is exploited by GAF to identify the sensors that are equivalent from the perspective of packet forwarding.

Radio irregularity may result in asymmetric links and hence, it may have anadverse impact on protocols that employ location based techniques. For example, in Figure 5, node B can hear node A, but node A cannot hear node B. So even though there is a path from source S to destination D,we cannot assume that thereverse path from D to S exists. So during route discovery, if source S broadcasts aroute request (RREQ) to discover the path to destination D, it may not be possibleto deliver the reply (RREP) message to source S along the reverse path, even thoughnode D replies to the request. In such a case, the route discovery fails.

The above analysis leads one to believe that it would be inappropriate to use anyrouting protocol that uses location based in route discovery, such as GAF, GEAR and MECN. This is so because they would have a very highloss ratio. Similarly the simulation results we present later show that GAFsuffers this fate. However LEACH and PEGASISwork reasonably well despite the asymmetric nature of communication. Thereason is that LEACH and PEGASIS use the hierarchical technique where mostly only nodes in the same vicinity communicates with one another. These routing protocols divide the network area into clusters, thereby limiting long range signals and consequently asymmetry problem. They are also energy efficient which makes them good candidate for routing in wireless sensor networks.

6.3 Impact on Data Centric based Technique

Data-centric protocols differ from traditional address-centric protocols in the manner that the datais sent from source sensors to the sink. In *address-centric* protocols, each source sensor that has the appropriate data responds by sending its data to the sink independently of all other sensors.

However, in *data-centric* protocols, when the source sensors send their data to the sink, intermediate sensors can perform some form of aggregation on the data originating from multiple source sensors and send the aggregated data toward the sink. This process can result in energy savings because of less transmission required to send the data from the sources to the sink. GAF protocol can also be referred to as data centric because sensors in the same grid share the same type of data. Hence for optimal performance each grid senses the same type of data so that data aggregation can be highly utilized.

6.4 Impact on Hierarchical Routing Technique

LEACH Low-energy adaptive clustering hierarchy[26, 27] is the first and most popular energy-efficient hierarchical clustering algorithm for WSNs that was proposed for reducing power consumption. In LEACH, the clustering task is rotated among the nodes, based on duration. Direct communication is used by each cluster head (CH) to forward the data to the base station (BS). It uses clusters to prolong the life of the wireless sensor network. LEACH is based on an *aggregation* (or *fusion)* technique that combines or aggregates the original data into a smaller size (compression) of data that carry only meaningful information to all individual sensors. LEACH divides the a network into several cluster of sensors, which are constructed by using localized coordination and control not only to reduce the amount of data that are transmitted to the sink, but also to make routing and data dissemination more scalable and robust. LEACH uses a randomized rotation of high-energy CH position rather than selecting in static manner, to give a chance to all sensors to act as CHs thereby avoiding battery depletion of an individual sensor which ultimately leads to the death of the node.

The operation of LEACH is divided into rounds having two phases each namely

(i) A setup phase: The first round (i.e. round number zero) is started by each node calculating Threshold value (or probability to become cluster-head) and comparing the threshold value with random no (0 to 1) selected by the cluster. If the threshold value is greater than the random number chosen then the node becomes the cluster-head for this round. Hence the probability of becoming cluster-head in round zero is given as:

$P(n) = p/(1-(p*(r \bmod 1/p)))$

where P(n) = Energy of node/Total Energy of the Cluster
Here p indicates optimum number of cluster-head in a round (5 % as suggested by LEACH) and r denotes round number.Actually during Data Transmission phase of each round every member sends data along with information of its residual energy to their cluster-head and based on this information, the cluster-head decides which node will become the future cluster head. This is done by calculating the probability of becoming cluster head as a function of node energy divided by total energy of the cluster.

6.4 Quantitative Analysis of the Impact

In this sub-section, the performance degradation due to radio irregularity is investigated, through three sets of experiments. The performance metrics used includes:

(i) end-to-end (E2E) loss ratio
(ii) number of control packets i.e. overhead and
(iii) energy consumption.

The performance degradation is analyzed by varying the DOI values.

6.5 Routing Performance with Different DOI.

In this sub-section, the VDOI value is set to 0 to evaluate routing performance with different DOI values. Figure 6 shows that GAF is greatly influenced by radio irregularity. It loses 45% packets when the DOI is 0.02. The reason for this may be attributed to its fixed grid topology. Hence in an asymmetric environment it suffers a high degree of data loss due to the hidden node phenomenon explained earlier.
LEACH and PEGASIS perform well because they divide the network range into clusters. Hence only nodes in close proximity become members of the same cluster. The effect of non symmetry is thus reduced. It can be argued that nodes in the same cluster will be in the same symmetry. They are also energy efficient. This makes hierarchical routing protocols good candidate for use in wireless sensor networks.

In Figure 7, the number of control packets overhead in PEGASIS and LEACH increases with the increase of DOI values but not as high as in GAF . This is because a lot of redundancy is employed in the data packets to determine nodes belonging to the same grid. However in both LEACH and PEGASIS, mostly, only nodes in the same cluster communicates hence the control packets used is minimal.

In Figure 8 LEACHand PEGASIS consume lower energy per delivered byte when compared to GAF, this support the earlier notion on the energy efficient nature of hierarchical routing protocols. It was however observed that GAF does not perform as bad in this regard when compared to its performance in the earlier two experiments conducted in this section. This proofs that GAF is an energy efficient routing protocol but performs badly in an asymmetric network setting. Hence its application is limited only to a spherical topology setting.

Overall LEACH has a slightly higher delay thanPEGASIS, because in PEGASISeach node communicates only with the closest neighbour by adjusting its power signal to be only heard by this closest neighbour. Each Nodes uses signal strength to measure the distance to neighbourhood nodes in order to locate the closest nodes. However LEACH is not equipped with this power signal adjustment, hence it is possible for nodes not in

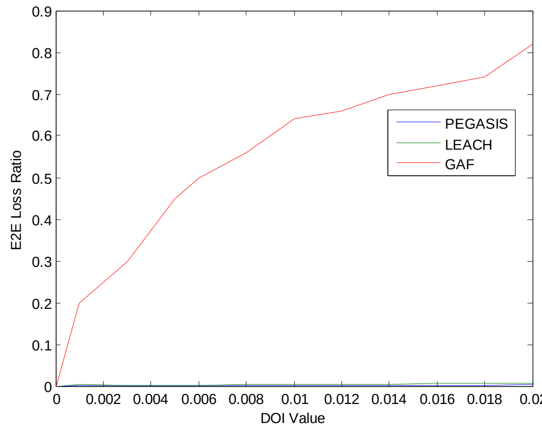

Figure 6a: E2E Loss Ratio Vs DOI

perfect spherical coordinates to be included in the same cluster.

The E2E delay of GAF remains the same because packets in GAF either go through successfullyor get dropped due to its fixed grid topology.

Figure 8 presents the energy consumption normalized according to usefulwork completed. It is measured as the energy consumed for each successfully delivered end-to-end data byte. Figure 8 informs that PEGASIS and LEACH are energy efficient because they do not experience high rate of data loss. As a matter of fact the results obtained suggest that they incurminimal data loss.This shows that they have high data throughput. It also suggests that they are energy efficient, hence they are good candidates for routing in wireless sensor networks.GAFconsumes more energy to deliver a useful data byte through multiple hops, whenthe DOI value increases. This is because the routing is network wide as opposed to the in-cluster routing in hierarchical routing protocol. Also the increased radio irregularity leads toincreased asymmetry links, which result in increased retransmission to deliver thesame amount of useful data. This is evidenced in Figure 8 which shows that GAFdelivers lessuseful data than PEGASIS and LEACH. It was also observed that LEACH delivers less useful data than PEGASIS,with the increase of DOI values. Accordingly, among the three routing protocols,GAF is least energy efficient than PEGASIS and LEACH, and LEACH is less energy efficient than PEGASIS.

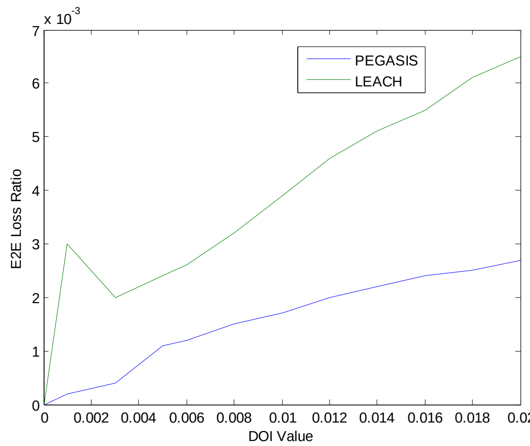

Figure 6b: E2E Loss Ratio magnified for LEACH and PEGASIS

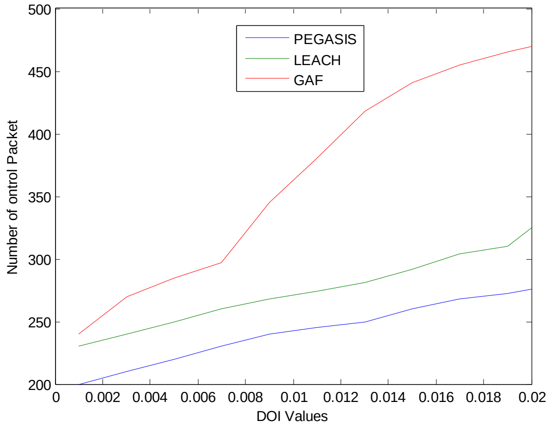

Figure 7: Number of Control Packets Vs DOI

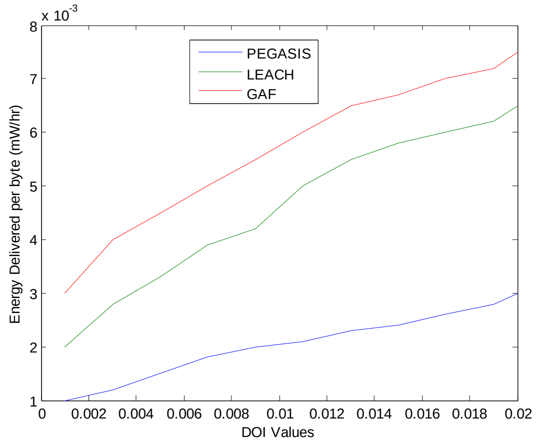

Figure 8: Energy consumption Vs DOI

7. CONCLUSION

This paper has demonstrated the impact of radio irregularity on MAC and routing protocols in wireless sensor networks. The need for routing model in wireless sensor networks to include this variable in their radio model has been highlighted. It was demonstrated that routing algorithm has great impact on the MAC protocol behaviour. Hence appropriate routing protocols must be put in place for any MAC protocol to be effective. Three MAC protocol along with three routing protocol has been used in the simulation. Overall the hierarchical routing protocol has shown high reliability in the face of variation in both symmetry and heterogeneous nodes.

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