Energy Efficient Dynamic Routing Protocol for Wireless Sensor Networks

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Abstract. One of the most significant challenges for Wireless Sensor Networks (WSN) is long-lived sensor nodes and minimization in overall power consumption, As the nodes spend substantial energy in sending and receiving data, a robust and power-aware routing protocol can maximize the network lifetime. In this paper, a cluster based dynamic and energy efficient routing scheme with optimal transmission range (DEOR) for wireless sensor networks is proposed in order to maximize the network lifetime. In this protocol, nodes are classified in different ranks depending on the nature of their power consumption in terms of both direct communication to the Base Station and optimal transmission range. Each node maintains a routing table to choose the next hop node to relay the data and after successful transmission it updates that routing table. Computer simulation of this dynamic routing protocol has been done and a better outcome has been observed compared to one of the multihop routing strategies.

Keywords: Wireless Sensor Network, Energy Hole Problem, Optimal Transmission Range, Routing Table.

1 Introduction

Wireless Sensor Network (WSN) is a rising and enabling technology for low-cost and unattended monitoring of a wide range of application areas like environment, industry, health and space. The recent advances in micro-electro-mechanical systems and integrated digital electronics have promoted wireless communication, sensing and processing combined together in a tiny device, called a sensor node or mote. These sensor nodes are low-powered, economically cheap, and multifunctional, that can monitor and respond to changes in target parameters of the environment in which they were deployed.

A typical WSN consists of a number of sensor nodes that communicate with each other via wireless channels to perform a common task, and sensed data are gathered in a previously assigned sink node or gateway called the Base Station (BS). Usually, the

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BS is a more powerful device than the deployed sensor nodes and plays a vital role administering the whole network, such as decision making, routing table updating etc. In WSN, collected data from a remote sensor node can either be sent to BS directly or by using other intermediary nodes. From a group of node, some times a node is selected as Clusterhead (CH) to gather local data from others and then pass it to other node or BS.

WSN has some unique features such as limited power and bandwidth, stringent memory capacity and small scale processing ability etc. These features have caused many challenges to WSN that demanded energy efficiency in all levels of network implementation, ensuring quality of service. Effective and proper use of the energy resources of sensor nodes and maximizing the network lifetime are important design parameters for the network topology and routing protocol [1]. Therefore, in this paper we address the topic of energy efficient data routing protocol in a homogeneous WSN consisting of a large number of static sensor nodes deployed randomly in a 2D field and a static sink or Base Station used to collect data from sensor nodes.

Most sensor nodes are equipped with limited energy reserves. For instance, Mica2 of Crossbow sensor board uses a 1.5 Amp-Hour (Ah) 3 Volt battery [2]. On the other hand, sensors are unattended and in most cases it is not feasible to change the power supply. In terms of power consumption, the most power consuming task is data transmission. Approximately 80% of power consumed in each sensor node is used for data transmission [3]. Because of the nature of node distribution, the traffic load is not evenly distributed over the network [4]. The CHs that are closer to the BS relay more traffic than the other nodes and have a tendency to die first, creating a gap around the BS. As a consequence, the rest of the nodes in the network become unavailable to the BS and the whole network become useless. These CHs are called 'hot spot' and the problem has been identified as the hot spot problem or self-induced black hole effect.

We address the problems mentioned above, and propose a cluster based dynamic and energy efficient routing scheme with optimal transmission range (DEOR) that ensures quality of service and balanced energy consumption among different areas of the network. In our proposed scheme, we try to confine each node's transmission range to achieve optimal power consumption, and based on that, we divide the network into several energy bands and classify accordingly. The CHs of one energy band will dynamically select the next CH of an adjacent band depending on the cost function calculated based on certain parameters. We performed computer simulations of the proposed scheme and present the result of the simulations to prove the effectiveness and compare it with a greedy algorithm based routing protocol. The numerical results show that our proposed scheme offers attractive energy efficiency.

2 Related Works

Energy efficient routing in sensor networks is a challenging problem because of its resource constraints and the nature of operation. Many proposals have been made so far addressing these problems.

LEACH [5] is a well known hierarchical cluster-based routing protocol where cluster formation is dynamic and clusterheads are chosen based on probabilistic value. The key features of LEACH are: (i) dynamic formation of clusters and CH based on localized coordination and control, (ii) data aggregation to reduce size of data, (iii) one hop communication to the sink or Base Station. Single hop routing adopted by LEACH is not practical in many applications where the sensor field is large. Moreover, since the nodes situated far away from the BS consume comparatively more energy, the network size shrinks as time passes.

PEGASIS[6] forms a chain of nodes to transmit data to BS. It uses a greedy algorithm to select the member node of the chain and each node sends and receives from neighbour nodes and only one node is selected from that chain to transmit data to BS. In each round, a randomly chosen sensor node acts as CH and transmits data to BS. When a sensor fails or dies because of low battery power, the chain is reconstructed using the same greedy algorithm. This protocol tried to overcome the shortcomings of LEACH but it can not minimize the number of hops which eventually incurs extra energy.

The concept of LEACH has been extended in HEED [7] by using residual energy and node density in a cluster. In the paper [8], the authors propose a cluster based protocol, Even Energy Dissipation Protocol (EEDP), for data gathering from CH. It tries to balance the energy consumption of all the CHs of the entire network instead of CH rotation inside the cluster. In this protocol, multiple chains composed of CH are formed and sensor data are passed to the base station using those chains. The algorithms OFFIS and 2L-OFFIS [9], have considered some parameters such as distance, remaining battery power, link usage to select the next hop node in multihop routing. Using a Fuzzy Inference System, the next hop node is selected among some candidate nodes and this selection procedure constitutes the optimized route from source to sink. This protocol also suffers from the hot spot problem.

The paper is organized as follows. Section 3 provides the energy model of a sensor node and the overall power consumption trends of the sensor networks describing the energy hole problem. In section 4, the solution to the energy hole problem and the description of our proposed protocol is presented. Section 5 presents the results of the simulation program of our proposed protocol. The protocol has been compared with PEGASIS and better outcome has been gained. In Section 6, the conclusions of this paper are drawn.

3 Problem Formulation

We notice that overall energy consumption in various locations in a WSN is different irrespective of the deployment strategy. If the network follows the direct communication method, nodes far away from BS drain out more energy than the nearer ones. This section presents the mathematical explanation of the contradictory phenomena of WSN where we first present the energy model and then the mathematical model.

3.1 Energy Model

The energy consumed by a sensor node is used in three ways- transmitting, receiving and processing. We use the same energy model mentioned in LEACH [5]. If the data rate is b bits/second, to transmit a data packet of b bits over a distance d, the corresponding power consumption for transmission and receiving are as follows;

$$P_{Tx} = \beta_1 b + \beta_2 d^{\alpha} b, P_{Rx} = \beta_1 b$$

Here, $\beta_1 = 50$ nJ/bit is the amount of energy dissipated by the radio to run the transmitter or receiver circuitry and $\beta_2 = 100$ pJ/bit/m^2 is the transmit amplifier power. α is the path exponent that indicates the rate at which the path loss increases with distance. Typically we consider α takes the values 2, 3 or 4 in wireless communications which actually depends on the environment. Therefore, it is understandable that while transmitting, the radio circuitry consumes more power than receiving data.

To transmit a message from one node to another node within transmission range R is the total of energy spent to send and to receive. Then we can express the total energy, E_{n2n}, to send b bit data as

$$E_{n2n} = b(2\beta_1 + \beta_2 d^{\alpha})$$

Our energy model only considers the power for transmitting and receiving, excluding power for processing and sensing tasks which are negligible and depend on computational hardware architecture and processing complexity.

3.2 The Energy Hole Problem

The imbalanced traffic distribution in WSN creates a bottleneck problem which is referred to as the Energy Hole Problem [10], which degrades the performance and the lifetime of the WSN. In[4] and [10] the authors explained the nature of the energy hole problem with the help of simulation and mathematical analysis. According to [10], the per node traffic load near the BS is

$$Load_{innermost\_band} = \frac{M^2}{\pi} b$$

and the per node energy consumption rate (ECR) is

$$ECR_{innermost\_band} = \alpha_1 b + \gamma_1 (\frac{M^2}{\pi} - 1) b + (\beta_1 + \beta_2 d^k) \frac{M^2}{\pi} b$$

Here the authors assumed that the sensor field is divided into M concentric bands and γ_1 is the energy dissipated by the radio when receiving data.

Following the same model in [10], if we divide the sensing field into M concentric bands, we can calculate the probable difference in the number of sensor nodes in each band. The area differences between the bands are

$$\pi 3r^2, \pi 5r^2, \pi 7r^2, ...$$

if we assume the radius of the bands are increased by r. If the node density is δ and if it is uniform throughout the network we can say that the number of nodes in each band increases as the radius of the network increases. Therefore, the total initial energy in each band, $B_x, x \in [1.M]$,has a significant impact on the lifetime of the network and we can say that

$$E_{init}(B_1) < E_{init}(B_2) < E_{init}(B_3) < .. < E_{init}(B_{M-1}) < E_{init}(B_M)$$

On the other hand, nodes in the inner bands are relaying more data than the other nodes in the outer bands. So these two phenomena of WSN are responsible to create energy hole or hot spot problem.

4 Description of DEOR Protocol

In this section, we first define some assumptions, and then we describe the band formation across the network, cost function calculation and dynamic route selection, as well as the role of Base Station (BS).

4.1 Assumptions

In this work, we assume a sensor network where *n* static but identical sensor nodes are deployed randomly and uniformly in the 2D circular sensing field. Once deployed, this network must work unattended and all its resources are non-renewable. All nodes have the same initial energy and same resources to carry on their sensing, computing and communication activities with the same maximum transmission range. We assume that the transceiver is equipped with omni directional antennas and data can be sent to every node around it within transmission range. The BS is static and could either be placed at the centre or just outside the sensing field. The nodes in the network are location aware and able to communicate with at least one neighbour node. We implement our routing protocol in a multi-hop WSN that is data from any part of the network can be sent to BS via multi-hop. Furthermore, each node is assigned a unique ID and a database of these IDs is kept in BS. The nodes are able to compute their residual energy, buffer size, and channel quality (based on Signal to Noise Ratio) with neighbour nodes. Additionally, we assume that there is an ideal MAC layer protocol implemented in the node protocol stack so that there is no collision and retransmission. Therefore, our technique basically works on network layer of the protocol stack.

4.2 Power Optimal Transmission Range

A wireless link is a broadcast mechanism, and increasing the power to transmit a data packet results in interference with other nodes in the network and draining the battery of the node. Therefore, it is necessary to use the optimum energy to transmit data packets to the next neighbour node so that it does not consume maximum power. A node can reach to another node using its maximum capability with the expense of shorter life-time while shorter transmission rang demands more hops. However, power consumption also increases with the number of hops as well. The strength of transmitting power used by a node determines the bit rate of a wireless link [1]. The bit error rate can be reduced if the transmitting power is increased up to a predefined level to restrain the noise interference. So we need tradeoffs choosing suitable transmission range for data communication. Many researches has been done so far to distinguish the optimal transmission range to prolong the node lifetime and it can be summarized that selecting an appropriate transmission range which is energy efficient is heavily dependant on the application and the environment of the network.

At this stage we refer to two research works [11] and [12] which tried to figure out the maximum and minimum limits of node transmission range and also the generalized optimal transmission range for a particular route. In [11] the authors formulated a routing scheme with optimal power management in terms of transmission range. In this work, end-to-end frame error rate from source node to destination node is defined which acts as the base to formulate a power-cost equation at any error rate.

In [12], the authors tried to specify the boundaries of optimal transmission range based on the data rate generated by the sender nodes. According to the authors, the boundary of the transmission range *R* can be defined as

$$R_{\min} = \max\left[\sqrt{\frac{2.E_{elec}}{\varepsilon_{amp}}}, 2.R_s\right], R_{\max} = \min\left[R_{MAX}, \frac{L}{\sqrt{\alpha\pi}}\right]$$

where R_{MAX}, R_s, E_{elec}, ε_{amp}, α ,and L stand for the physically maximum transmission range of a sensor node, sensing range of a node, energy to run the transmitter or receiver circuitry, transmit amplifier power, the ratio of average Voronoi cell size to the area size of the neighbour nodes and length of a square shaped sensing field respectively.

For calculating the optimal transmission range that makes the minimum power consumption in topology management, the total data rate (λ) of the network must be bound. If $\overline{P}$ is the total power dissipated by all nodes during the lifetime, the conditions that make the optimal transmission range in the boundary as previous equations are given by

$$\frac{\partial}{\partial R}\overline{P}(R_{\min}, \lambda) < 0, \frac{\partial}{\partial R}\overline{P}(R_{\max}, \lambda) > 0$$

Therefore, it is possible to preset an optimal transmission range for routing scheme which is adjustable based on the environment and the sensor network application. In our routing protocol, we propose to use optimal transmission range, denoted as R_{mn_cst}, for the link *i* that dissipates minimum power to exceed SNR threshold of ψ. A high level of power used for transmission can acquire better link quality and high SNR but that drains the battery of the node very quickly. Hence the nodes must use an optimal transmission for hop to hop data transmission.

4.3 Band Classification among Nodes

We propose to divide the sensing field into different circular regions or bands, B_i. These bands are formed based on the node-to-Base Station distance which makes the basis of power consumption. As we are assuming the sensing field as a circle of radius r_{BS} and BS is situated at the centre, theoretically we can partition the whole sensing field with radius, r_{BS}, into M different but adjacent bands. But in a real life scenario, this partition might not work ideally because of attenuating factors present in the environment. Therefore, we propose this band classification among nodes to be launched by the BS. The BS has the information about the sensing place of interest and hence the sensor field radius. Thus, it theoretically divides the field into some adjacent bands and assigns the width of each band.

In section 3.2, we found that the area differences among the bands (and hence among the circles) is increased continuously if the radius of each concentric circle is increased by r. If we wish to keep the area of each band equal, we must have to reorganise and control the width of each band. Let us assume, we have M circles $C_i, i \in [1, M]$ with radius $r_j, j \in [1, M]$ and area $A_{C_i}, i \in [1, M]$. We also assume that the sensor field is divided into M adjacent bands $B_x, x \in [1, M]$ with width $w_y, y \in [1,5]$ and area $A_{B_x}, x \in [1, M]$. Since we want $A_{B_1} = A_{B_2} = \ldots = A_{B_M}$, we need to choose different widths of different bands based on r_1. Now we get

$$A_{B_1} = A_{C_1} = \pi r_1^{\,2}, A_{B_2} = A_{C_2} - A_{C_1}, \ldots\ldots A_{B_M} = A_{C_M} - A_{C_{M-1}}$$

and it is possible to derive the width of each band based on r_1. Thus we finally obtain

$$w_1 = r_1, w_2 = (\sqrt{2} - 1)r_1, w_3 = (\sqrt{3} - \sqrt{2})r_1, w_4 = (2 - \sqrt{3})r_1, w_5 = (\sqrt{5} - 2)r_1, \ldots\ldots..$$

and so on.

The whole sensor field can be depicted as figure1.

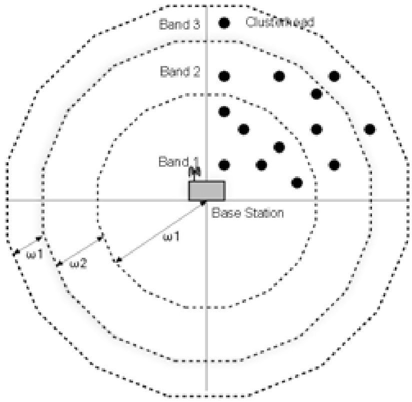

Fig. 1. A sensor field that is divided into bands of variable width

Before the band formation takes place, the BS has prior information about the sensing field size and nodes' capabilities such as radio range, processing ability, initial battery power and energy dissipation due to data transmission in ideal conditions. Consequently the BS decides the number of bands and their widths for a specific WSN application in that particular geographic location with the resources available. At the time of deployment, the threshold value of SNR, ψ, is defined with all the nodes individually so that nodes can communicate with their neighbour nodes with undistorted data.

4.4 Routing Table

Each CH maintains a routing table containing data about neighbour nodes of adjacent band closer to the BS. The routing table contains *node_id*, *cluster_head*, *neighbour_distance(* $d_{i,j}$ *)*, *BS_distance(* $d_{j,BS}$ *)*, *hop_support(* h *)*,and *residual_energy(* e_j *)* as the fields which represent node id, clusterhead indicator, distance with neighbour node, distance with BS, number of nodes from previous band are being hosted, residual energy of a CH of the next downstream band respectively.

In each round of data transmission, the sender, *i*, uses the cost function mentioned below to determine the best neighbour CH, *j*, to send the data:

$$C_{i,j} = W_1.d_{i,j} + W_2.d_{j,BS} + W_3.h_j + W_4.e_j$$

Here, W is the weight which is adaptive and dependent on network application. These weights can be changed dynamically by the BS if situation demands. Before relaying the data, the sender CH always executes its cost function and the record of a node that provides the lowest cost from that database is chosen as best candidate. Hence, the next hop of the route is determined. After every z rounds, all CH nodes that form a route chain to BS include their residual energy, load condition (to upgrade *hop_support*) with the data packets so that BS gets information about all the CHs and it can update all the clusterhead nodes by broadcasting the message. The routing algorithm for z rounds is given below;

Algorithm. Routing Decision Making

Require: The updated data in the routing table about the CH of next downstream band and the weight value for W_1, W_2, W_3, W_4

i: The sender node
j: The candidate neighbour node
z: The number of operational round defined by BS
k: The number of record in the table
$d_{i,j}$: The distance between node *i* and *j*.
$d_{j,BS}$: The distance between BS and node *j*.
h_j : The number of hosted CH in the previous round
e_j : The residual energy of the candidate neighbour CH
$C_{i,j}$: The cost for a route
next_hop: NULL
max_cost: 0
for (1 to *z*)
    if(*next_hop*== NULL)
        for(1 to *k*) calculate $C_{i,j} = W_1.d_{i,j} + W_2.d_{j,BS} + W_3.h_j + W_4.e_j$;
            if($C_{i,j} \geq$ *max_cost*) *max_cost*= $C_{i,j}$; **end if**
        end for
    end if
    next_hop=*i*; send(data to node *i*)
end for
next_hop= NULL; read(received UPDATE message); update(routing table)

For instance, in figure 2, CH1 and CH2 are making decision about the next hops. CH1 can send data to three CHs of the next band which are CH3, CH4, and CH5. But the cost function prefers CH4 as the next hop and it is sending data to CH4. Similarly, CH3 is the best next hop node for CH2 to relay the data.

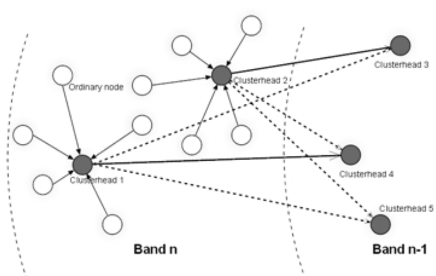

Fig. 2. Routing decision making in the network

5 Simulation Results

The proposed scheme has been tested in a simulator written in C++ and programmed for this proposed scheme. We compared the proposed scheme with another routing scheme called PEGASIS [6] where each CH relays the data to the nearest neighbour. In simulation result reveals that if the number of hop to BS is decreased, significant energy efficiency can be gained.

5.1 Node Placement and Initialization

In the simulation, 100 nodes are considered in an area of 100×75 square units. We use Cartesian coordinates to locate the sensors. These sensor nodes represent the CHs of the actual network field. The BS is located at origin (0, 0). Initially, in our simulation, we assume a simple model according to [5] where the radio dissipates $E_{elec} =$ 50nJ/bit to run the transmitter or receiver circuitry and $\varepsilon_{amp} =$ 100pJ/bit/m^2.

5.2 Power Consumption Comparison

Total energy consumed to send a data packet of size 32bit has been calculated in this simulation for both the PEGASIS and DEOR. We run the simulation for all 100 nodes individually to send data to BS. The result for one-round data transmission from every node is shown in figure 3.

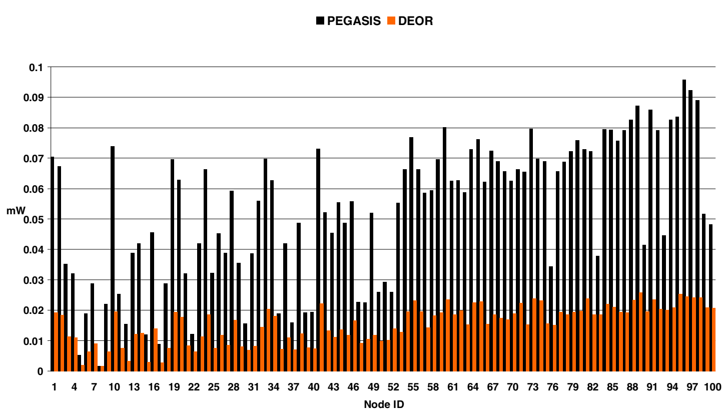

Fig. 3. Comparison of per node energy consumption in case of communication with the Base Station

From the figure 3 it can be inferred that the average energy gain is 30% and in some cases more than 50% gain is achieved.

5.3 Route Selection

In PEGASIS, the next neighbour node is chosen using Greedy Algorithm. In that case, the closest neighbour node of the sender node is chosen every time for that particular chain. But in our proposed routing, the next neighbour node is chosen with the help of a routing table that chooses the best candidate for the next hop based on cost function. The proposed routing scheme reduces the number of hop needed to reach to BS. Selected routes from nodes 1, 75, 89 and 100 for PEGASIS and DEOR are given in figures 4 and 5 respectively.

From figure 4 and 5 it is quite clear that our proposed protocol takes less hops and uses the shortest route to send data to base station. Moreover, our protocol chooses different CH nodes for different routes near the BS that eliminates the hot spot problem.

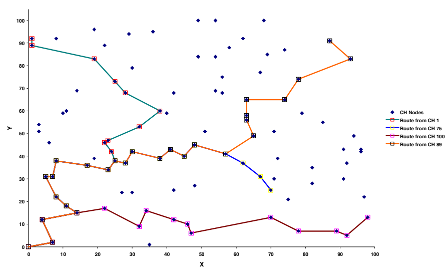

Fig. 4. Example routes selected by PEGASIS

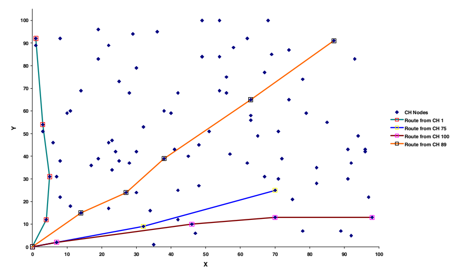

Fig. 5. Example routes selected by DEOR

6 Conclusion

In this paper, we proposed a dynamic routing protocol with optimal transmission range for wireless sensor networks that minimizes the number of hops and hence consumes less energy compared to a multihop routing protocol of its kind. This strategy achieves an even distribution of energy consumption based on its dynamic decision for selecting next relay node. Moreover, this technique is aware of the location of the next relay node and also able to prioritize the network demand depending on the application.

This protocol proposes a concentric model of bands, where the centre is base station, in order to classify the energy consumption of different nodes in different areas of the sensor field. Our simulation result shows that network life time is maximized if we adopt DEOR protocol. Our next target is to propose a rotation scheme with nodes in different bands to get a more healthy balance among the nodes.

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