Energy Efficient Routing Protocols for Wireless Sensor Networks: A Survey

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Abstract— **This paper provides an up to date evaluation of routing protocols as well as a description of state of the art routing techniques for Wireless Sensor Networks (WSNs) that enhance network lifetime through efficient energy consumption methods. We study the tradeoffs between energy and communication overhead and highlight the advantages and disadvantages of each routing protocol with the purpose of discovering new research directions.**

Keywords - wireless sensor networks; energy efficiency; routing protocols;

I. Introduction

Recent developments and advancements in electronics, communications and sensor technologies that have marked the past decade have determined the evolution of new attractive research directions such as WSNs. A WSN is made up of a large number of sensors nodes organized in a network fashion and deployed in an area of interest with sensing and actuating capabilities. Small size, low power and the ability of wireless communication make WSNs the ideal solution for numerous applications such as remote environmental monitoring, medical healthcare monitoring, military surveillance, etc. The nature of the environment WSNs are placed in, that seldom allows human intervention as well as limited energy resources, pose severe constraints on energy consumption management. Adequate data routing techniques play an important role in the efficiency of WSNs as they contribute to the reduction of energy consumption, latency, data throughput and quality of service. Due to the application specific nature of WSNs, a considerable number of protocols [1] have been developed that address these issues but none have been standardized yet. Currently developed protocols address energy management at all layers of the protocol stack for WSNs ranging from the physical layer to the application layer. For example, at the network layer it is highly desirable to find energy efficient route discovery, data aggregation and correlation techniques in relaying data from sensor nodes to the base station (BS) in order to maximize the lifetime of the network.

Large number of nodes in a WSN makes global addressing schemes nearly impossible, therefore traditional IP based protocols such as TCP and UDP are not suitable. Also, constraints in terms of energy, processing and storage capabilities of nodes are not taken into consideration by traditional protocols. Another challenge is that of mobile nodes in the network that determine frequent and unpredictable changes in network topology therefore position awareness of nodes is crucial as data collection is location dependent. Position awareness methods [2] such as triangulation, multilateration or using Global Positioning Systems (GPS) can be implemented to address this issue. Random deployment and mote mobility are key factors in determining the redundancy [3] of a WSN which can be exploited in routing protocols by using adequate routing techniques such as clustering, data aggregation and correlation in order to improve energy consumption, throughput and bandwidth utilization.

In this paper we propose a classification of energy efficient routing protocols for WSNs into four categories: location aided, data centric, mobility based and heterogeneous routing protocols. We discuss each protocol under this classification with the purpose of identifying advantages and disadvantages as well as future research directions.

II. Power Consumption Model for WSN

In order to understand the necessity of routing protocols and their benefits we briefly describe the power consumption model for WSN devices.

The communications channel can be modeled by using the long distance path loss model [4] and ignoring more complex effects such as fading and multi-path. Thus, the power required by a node to transmit over a distance of d meters can be expressed as:

$$P_T(d) = P_0 \times (d_0 / d)^{\alpha} \quad (1)$$

where P_0 represents the power of the signal received at distance d_0 from the source and α is the path loss exponent which is dependent on the propagation environment and can take values between 2 and 5. Also, using the path loss model and the Friis model the power received at distance d from the node can be expressed as:

$$P_R(d) = P_{tx} / (\beta \times d^{\alpha}) \quad (2)$$

where P_{tx} is the RF power delivered to the antenna of the transmitting node and β is parameter specific to the characteristics of the transmitting and receiving antennas.

Therefore we can determine that the power required to make a single hop transmission between two nodes is equal to $P_T + P_R$. The power required to make a multi hop transmission between n nodes is $(n-1) \times (P_T + P_R)$.

For example the Crossbow IRIS WSN has nodes equipped an Atmel AT86RF230 radio transceiver which consumes 16 mA for receive operations and 17 mA for transmit [5] which is more than twice as much as the processor uses in full operation mode. Powered by a battery of 1500mA and with the radio working at a 50% duty cycle the IRIS node can function for approximately 4 months.

In order to enhance the reduced lifecycle of a WSN as well as address other critical issues such as data throughput, collision avoidance, latency and QoS, suitable protocols must be implemented.

III. ROUTING PROTOCOLS FOR WSN

The numerous applications in which WSNs are used have determined the development of a considerable number of routing protocols which can be classified into different categories:

- Location aided protocols
- Data centric protocols
- Mobility based protocols
- Heterogeneous protocols.

A. Location aided protocols

Location aided protocols use information obtained from either a global positioning system (GPS) (the most common case) or some other method like a localization algorithm [6] for determining the most energy efficient path of data communication between a source node, or cluster head, and a sink. The most accurate solution but not cost effective is equipping all sensor nodes with a GPS receiver. On the other hand, using a localization algorithm induces inaccuracy in estimating the position of sensor nodes.

1) Location based Energy-Aware Reliable routing protocol (LEAR)

The Location based Energy-Aware Reliable routing protocol (LEAR) proposed by Alasem et al. [7] is a cluster based protocol that aims at reducing energy consumption of wireless sensor networks by providing efficient data routing paths depending on the geographical location of sensors in the network. Location information for sensor nodes in LEAR is obtained from devices such as GPS. Each node publishes its position information to all neighboring nodes and each node constructs a routing table based on the distances to its neighbors. When a node wants to send data it checks the routing table and sends it to the neighbor which has the shortest distance to its location. The shortest distance is calculated by comparing the Euclidian distances regarding all neighboring nodes. In order to attain energy efficiency, LEAR uses an Enhanced Greedy Algorithm (EAR) for routing packages from source to destination which is represented in Figure 1.

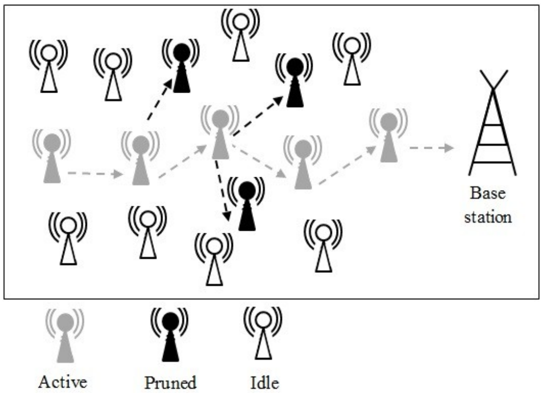

Figure 1. Enhanced Greedy Forwarding Algorithm [7]

EAR is implemented by selecting only forward nodes in the routing path as destination nodes and pruning the nodes behind the active node thus minimizing the path and the number of hops the packet travels in order to reach the destination sink. Pruning of nodes behind active nodes is an efficient method for minimizing the path to the destination thus increasing communication efficiency and lifetime of the network

As LEAR is a protocol that applies to randomly deployed WSNs, cluster heads are not previously elected and any node that has the minimal distance to the source can be selected as the next hop destination as can be seen in Figure 2.

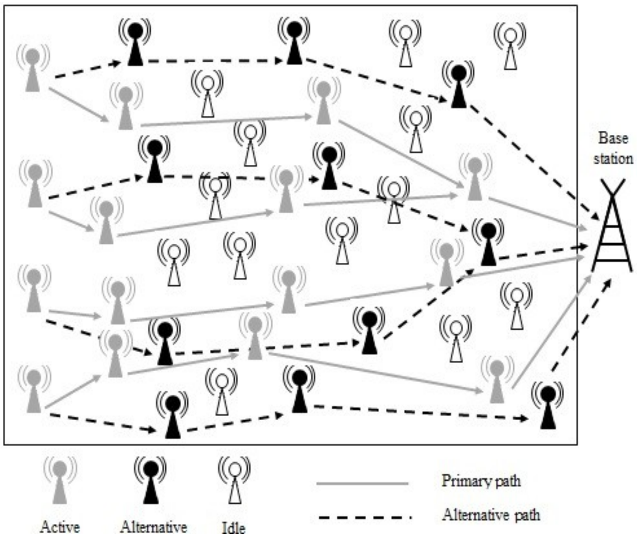

Figure 2. LEAR protocol with clustering [7]

It is also considered that every node is within communication range to the sink and can forward the message itself if required. Each time the distance to the next hop node is smaller than the distance to the sink, the next hop node is chosen as the destination otherwise the message is directly forwarded to the sink.

Simulations performed by the authors have proven that LEAR outperforms other reference protocols such as LEACH [8] and efficiently extends the network lifetime and data delivery of a WSN.

2) Research directions

Several studies have been performed [9,10] on single hop vs. multi hop communication which have proven that single hop communication is more power efficient from the network point of view and the destination node should be chosen as far away from the source node. Taking this into consideration power efficiency can be further enhanced by using an algorithm which chooses the destination node based on longest distance and highest message throughput. Message throughput can be determined by sending a burst of packets to all neighbors, which in turn reply with the number of packets received.

B. Data centric protocols

Randomly deployed and mobile wireless sensor networks are faced with situations where a number of nodes collect similar or sometimes the same data for the same event which they then forward to the same sink node. This increases redundancy and energy consumption of the network as transmitting and receiving data are the most energy consuming operations for sensor nodes, hundreds of times more than computing costs. In order to address these problems adequate data aggregation and compression techniques must be adapted.

1) Data Correlation and Data Aggregation LEACH (DCDA-LEACH)

Xibei et al. [11] have developed an improved LEACH [8] protocol called Data Correlation and Data Aggregation LEACH (DCDA-LEACH) which extends the network lifetime by reducing energy consumption through efficient data aggregation and correlation techniques.

In order to obtain data correlation and aggregation, DCDA-LEACH is divided into rounds.

a) Data-related zoning

During the first round, the base station attains information about the data features of each node. Based on this information the coverage area is divided into belt regions based on the number of hops from the base station. Each belt area is then divided into fan-shaped (atomic) regions made up of sensors that have high data correlation. The fan shaped layout distribution is performed by the base station based on two thresholds: a threshold of data discrepancies and a threshold of angle range. When either threshold is reached an atomic region is obtained. After creating the atomic regions, the base station broadcasts the layout to all nodes of the network. Each node can then calculate the relative angle of its connecting line to the base station and ensure which atomic region it belongs to. Area division performed by DCDA LEACH can be seen in Figure 2.

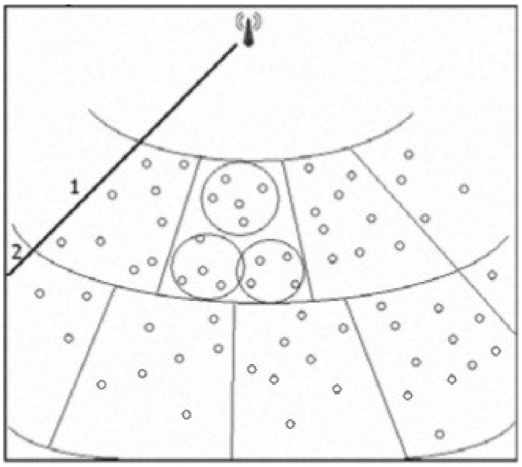

Figure 3. Area division based on data correlation [11]

Dividing the sensing area in such a way allows nodes from the same cluster to have high data correlation and thus cluster heads can perform efficient data aggregation significantly reducing energy consumption.

b) Routing establishment

After area division is performed the cluster heads are elected within the data related areas. Cluster head election is performed the same as in LEACH. After cluster heads are elected each of them broadcasts an advertising message which contains the ID of the region. All nodes that receive the message check to see if the region ID is the same as their own. If not, they ignore the message. If one node receives several advertising messages with the same ID they choose the cluster head with which to communicate based on signal strength. After all nodes have been assigned to a cluster they go to sleep and cluster heads communicate with each other to determine the best communication path to the sink. A spanning tree of cluster heads results which allows easy single hop communication of data from each cluster head to the sink as can be seen in Figure 4.

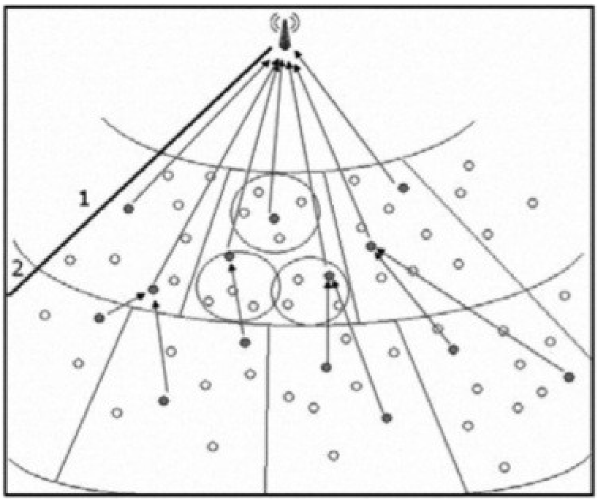

Figure 4. Cluster head tree routing [11]

The division into fan shaped layouts brings power consumption advantages as it reduces the number of cluster heads which communicate directly to the base station and balances the power load of sensor nodes which extends the network lifetime.

c) Timing of data aggregation

Efficient data aggregation is closely related to the waiting time of different nodes before data aggregation on the return path to the cluster head. To address this issue DCDA-LEACH uses a cascading timeout method that determines the timing of data aggregation based on the number of hops to the sink. Nodes with fewer hops to the sink have to wait longer time and those with more hops have to wait shorter time thus resulting in a cascaded waiting time for all nodes of the network. This method is effective from the energetic point of view of the network but also results in increased accuracy and short time delay

2) Research directions

Possible node failure should be taken into consideration as each node performs data aggregation before forwarding the data to the next node on route to the cluster head. If one node fails all data received from previous nodes are lost. This can be avoided by appointing cluster head helper nodes that handle part of data aggregation process and all cluster nodes should send data to either the helper nodes or to the cluster head.

C. Mobility based protocols

Mobility based protocols take into consideration the mobile characteristics of sensor nodes in calculating the best route for transporting a message from a node to a sink. Some networks have sensor nodes that have the ability to move and although this mobility is restricted to a few meters, the nodes might go out of range or new nodes might come within communication range. This important aspect must be taken into consideration when designing an energy efficient protocol.

1) Energy Aware Geographic Routing Protocol (EAGRP)

To address the mobility problem in sensor networks Elrahim et al. [12] have developed an efficient data forwarding protocol called Energy Aware Geographic Routing Protocol (EAGRP). This protocol takes into consideration the distances between nodes as well as the energy level of each node before choosing the correct path to send a message. This is done by calculating the average distance of all neighboring nodes of a “sender” node and their energy levels. Based on these characteristics the node that has the maximum energy and which is located at a distance equal to or less than the average distance to all neighboring nodes is selected as the next destination. In order to address the mobility issue, before a node decides to send a message it also checks that it is still in the same neighborhood. If it has moved greater than a distance referred to as “flooding distance” it will send out a flood of the new position and determine the coordinates of the new quadrant it has moved to. It then sends out a flood with its new position to all neighbors that need to know. The selection of the adequate neighbor with the corresponding energy level and nearest distance is made and this node will receive the packet. The procedure is repeated until the packet reaches its destination.

Simulation results have proven EARGP more efficient in terms of energy consumption, packet delivery, throughput and delay compared to several routing protocols used for WSNs and MANETs such as Dynamic Source Routing (DSR), Ad hoc On-demand Distance Vector Routing (AODV) and Greedy Perimeter Stateless Routing (GPSR).

2) Research directions

As the base station is considered to have very high power resources (sometimes connected directly to a power source) an algorithm can be devised that would increase the power efficiency of the network by creating a motion pattern for the network nodes. All nodes have to be synchronized. Each node will have to periodically publish its position to the base station. After a certain amount of time, when the base station has acquired enough position data it can create a motion pattern recognition for all network nodes. Using this pattern it can create transmission timetables for all nodes which include the time to send and the ID of the node to send to in order to obtain the optimum transmit path. These timetables will be published to each individual node.

D. Heterogeneous protocols

Heterogeneous wireless sensor networks are made up of sensor nodes with different hardware characteristics that perform specific tasks, sometimes others than the majority of nodes in the network. Such nodes may be submitted to intense or limited functionalities as they can dispose of more or less energy than other nodes. The unique characteristics of individual sensor nodes must be taken into consideration when designing energy efficient routing protocols for WSNs.

1) Energy Efficient Cluster Head Election Protocol (LEACH-HPR)

L.Han has developed LEACH-HPR [13], an energy efficient cluster head election protocol for heterogeneous WSNs that uses a minimum spanning tree algorithm to construct efficient inter cluster routing. The heterogeneous WSN proposed by Han is made up of three types of nodes, type A, B and C, where node A has the least energy, node B has medium energy and node C has the most energy. The network organizes itself into clusters governed by a cluster head node that gathers data from all nodes in the same cluster, processes it and then forwards it to the base station if it is in range or to the closest cluster head otherwise.

The cluster head selection phase is done as follows. Each node assigns an internal timer with a value inverse proportional to the energy level it has left. While the timer counts down, each node listens to the transmission medium for any messages from neighboring nodes. If no message is received, the node whose timer counts down the fastest assigns itself as the cluster head by transmitting a message to all neighbors. The message contains the nodes’ ID, the amount of energy it has left and a header identifier that distinguishes the message as an announcement message. Each node determines the cluster it belongs to by selecting the cluster head that has the most energy and which is closer to it based on the received signal strength of the announcement message. After a node decides to join a cluster it broadcasts a join-request message to the cluster head that contains the nodes' ID and the cluster head's ID.

In order to reduce the energy consumed by cluster heads, each of them elects an assistant from the remaining nodes of the cluster that has the purpose of fusing gathered data and assigning tasks to the other nodes. The cluster head assistant is chosen to be the cluster node with the most remaining energy. The strategy of using this collaboration of cluster head and cluster head assistant greatly improves energy consumption and prolongs the network lifetime.

To address the problem of cluster head nodes that cannot communicate directly to the base station, a multi hop routing approach is used. In order to determine the optimum path from a cluster head to the base station a greedy algorithm that finds a minimum spanning tree for a connected weighted graph is used, Prim's algorithm in which the weights are represented by the remainder energy of the interim cluster head nodes.

Simulation results have proven that using efficient cluster head election methods combined with an improved Prim algorithm LEACH-HPR significantly balances and reduces energy consumption thus prolonging the network lifetime.

2) Research directions

In randomly distributed WSNs, dynamic cluster head election can be prone to errors as marginal nodes can be left out of the newly formed clusters. To overcome this problem network topology must be taken into consideration when creating new clusters. One solution is to create a map of the network by using location devices or location determination algorithms and taking care not to leave out nodes when creating new clusters. Another solution is to divide the whole network coverage area into smaller areas and elect cluster head nodes within these newly created areas.

IV. CONCLUSIONS

Adequate data routing techniques play an important role in the efficiency of WSNs as they contribute to the reduction of energy consumption and latency but also provide high data throughput and quality of service. In this paper we have provided an evaluation of state of the art routing protocols which we have classified into four categories namely location aided, data centric, mobility based and protocols for heterogeneous networks.

We have observed that these protocols are hybrid and they fit under more than one category. To address this issue we have realized a comparison of these protocols which can be seen in Table 1.

We have also described advantages and disadvantages for each protocol and provided future research directions which can be used to further improve these protocols and which can be applied to the creation of new routing protocols.

Other research directions can be addressed such as:

- Exploring the density of nodes in a network. Randomly deployed networks can have high density of nodes in certain areas. Using intelligent task distribution, cluster head nodes can assign helper nodes to perform certain tasks and thus distribute the work load.
- Applying proper sleep/wake timetables the redundancy of the network can be decreased as nodes to close to each other can provide duplicate measurement results.
- Using time and localization synchronization to support distributed and collaborative processing
- As the work load is not evenly distributed some nodes may die and leave the network. Using appropriate reconfiguration and neighborhood updates at predefined intervals can make the network very easy to maintain and adaptive to topology changes.
- Localization: equipping sensor nodes with GPS is not always possible as such devices only work outdoors and in absence of obstructions. Other methods such as trilateration/multilateration do not provide enough accuracy as needed in WSNs. Therefore there is a need for developing other methods of establishing a coordinate system.
- Currently developed protocols address mainly the issue of energy efficiency and data throughput. WSNs are also used in many military applications therefore transmission and data security is an issue that cannot be overlooked.

Even though the performance of these protocols is good with regards to energy efficiency further research is needed to address issues such as quality of service which can ensure guaranteed bandwidth throughout the network.

TABLE I. COMPARISON OF ROUTING PROTOCOLS

Protocol	*Classification*	*Negotiation Based*	*Mobility*	*Position Awareness*	*Multipath*	*Query based*	*Data aggregation*	*Scalability*	*QoS*
LEAR	Higherarchical	No	Possible	Yes	Yes	Yes	No	No	No
DCDA-LEACH	Higherarchical	Yes	No	Yes	No	No	Yes	No	No
EAGRP	Flat	Yes	Yes	No	Yes	Yes	No	Yes	No
LEACH-HPR	Higherarchical	Yes	No	Yes	Yes	Yes	No	Yes	No

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