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HIERARCHICAL ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS

Harneet Kour*

Abstract: Due to recent advancement and changes in wireless sensor network, various routing protocols have emerged. Hierarchical-based routing is a cluster based routing in which high energy nodes are randomly selected for processing and sending data while low energy nodes are used for sensing and send information to the cluster heads. This property of hierarchical-based routing contributes greatly to the network scalability, lifetime and minimum energy. In this paper, we will discuss various hierarchical routing protocols in wireless sensor networks.

Keywords: Wireless Sensor Network, clustering, LEACH, SEP, HEED, PEGASIS, TEEN, APTEEN, DEEC, MECN

1. INTRODUCTION

A wireless sensor network (WSN) can be defined as a network consists of low-size and low-complex devices called as sensor nodes that can sense the environment and gather the information from the monitoring field and communicate through wireless links; the data collected is forwarded, via multiple hops relaying to a sink (also called as controller or monitor) that can use it locally, or is connected to other networks [1]. A sensor node usually consists of four sub-systems [2] *i.e.* sensing unit, processing unit, communication unit and power supply unit.

In WSN, the sensor nodes are deployed in a sensor field. The deployment of the sensor nodes can be random (i.e. dropped from the aircraft), regular (i.e. well planned or fixed) or mobile sensor nodes can be used. Sensor nodes coordinate among themselves to produce high-quality information about the physical environment. Each sensor node bases its decisions on its mission, the information it currently has, and its knowledge of its computing, communication, and energy resources. Each sensor nodes collect the data and route the data to the base station. All of the nodes are not necessarily communicating at any particular time and nodes can only communicate with a few nearby nodes. The network has a routing protocol to control the routing of data messages between nodes. The routing protocol also attempts to get messages to the base station in an energy-efficient manner.

The base station is a master node. Data sensed by the network is routed back to a base station. The base station is a larger computer where data from the sensor network will be compiled and processed. The base station may communicate with the Remote Controller node via Internet or Satellite [2, 3]. Human operators controlling the sensor network send commands and receive responses through the base station.

* Department of Information Technology & Engg., Baba Ghulam Shah Badshah University, Rajouri, J&K, India. *E-mail: harneet_105@yahoo.co.in*

2. ROUTING TECHNIQUES

The basic operation of wireless sensor networks is to gather the sensed data and transmit it to the base station for further processing. The general scenario in these networks is during data gathering the intermediate nodes can aggregate the data in order to avoid redundant transfers. The order in which the data or the aggregated data is transmitted from the source node to the base station is the problem of routing.

3. DESIGN ISSUES IN WSN

The design of routing protocols in WSNs is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved in WSNs. In the following, we summarize some of the routing challenges and design issues that affect the routing process in WSNs [7, 8].

Node deployment: It is application-dependent and can be either manual (deterministic) or randomized. In manual deployment, the sensors are manually placed and data is routed through predetermined paths. However, in random node deployment, the sensor nodes are scattered randomly, creating an ad hoc routing infrastructure. If the resultant distribution of nodes is not uniform, optimal clustering becomes necessary to allow connectivity and enable energy-efficient network operation. Inter sensor communication is normally within short transmission ranges due to energy and bandwidth limitations. Therefore, it is most likely that a route will consist of multiple wireless hops.

Energy consumption without losing accuracy: Sensor nodes are tightly constrained in terms of energy, processing, and storage capacities, so they require careful resource management. The lifetime of nodes is a critical issue because of the limited battery lifetime. In multi-hop networks, the malfunctioning of some sensor nodes due to power failure can cause significant topological changes, and might require rerouting of packets and reorganization of the network.

Data reporting method: It is application-dependent and also depends on the time criticality of the data. Data reporting can be categorized as either time-driven, event driven, query-driven, or a hybrid of all these methods. In time-driven delivery method, it requires periodic data monitoring and sensor nodes will periodically turn on their sensors and transmitters, sense the environment, and transmit the data of interest at constant time intervals. In event-driven methods, sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute due to the occurrence of a certain event. In and query-driven method, sensor nodes respond to a query generated by the BS or another node in the network. They are well suited to time-critical applications. A combination of the previous methods is also possible. The routing protocol is highly influenced by the data reporting method in terms of energy consumption and route calculations.

Node/link heterogeneity: In many researches, all sensor nodes were assumed to be homogeneous (i.e., have equal capacities in terms of computation, communication, and power) but depending on the application a sensor node can have a different role or capability. For example, some applications might require a diverse mixture of sensors for monitoring temperature, pressure, and humidity of the surrounding environment, detecting motion via acoustic signatures, and capturing images or video tracking of moving objects. Either these special sensors can be deployed independently or the different functionalities can be included in the same sensor nodes. Even data reading and reporting can be generated from these sensors at different rates, subject to diverse QoS constraints, and can follow multiple data reporting models.

Fault tolerance: Some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, medium access control (MAC) and routing protocols must accommodate formation of new links and routes to the data collection BSs. This may require actively adjusting transmit powers and signaling rates on the existing links to reduce energy consumption, or rerouting packets through regions of the network where more energy is available. Therefore, multiple levels of redundancy may be needed in a fault-tolerant sensor network.

Scalability: Routing scheme must be able to work with a huge number of sensor nodes. In addition, sensor network routing protocols should be scalable enough to respond to events in the environment.

Network dynamics: In many applications both the base station or sensor nodes can be mobile. The routing protocol should consider this eventuality, making the design more complicated.

Transmission media: The traditional problems associated with a wireless channel (e.g., fading, high error rate) may also affect the operation of the sensor network. In general, the required bandwidth of sensor data will be low, on the order of 1-100 kb/s. Related to the transmission media is the design of MAC. One approach to MAC design for sensor networks is to use time-division multiple access (TDMA)-based protocols that conserve more energy than contention-based protocols like carrier sense multiple access (CSMA) (e.g., IEEE 802.11). Bluetooth technology can also be used.

Connectivity: High node density in sensor networks precludes them from being completely isolated from each other and sensor nodes are expected to be highly connected. However, it may not prevent the network topology from being variable and the network size from reducing due to sensor node failures. In addition, connectivity depends on the possibly random distribution of nodes.

Coverage: A given sensor's view of the environment is limited in both range and accuracy; it can only cover a limited physical area of the environment. Hence, area coverage is also an important design parameter in WSNs.

Data aggregation: Data sensed by many sensors in WSNs is typically based on common phenomena, so there is a high probability that this data has some redundancy, which needs to be exploited by the routing protocols to improve energy and bandwidth utilization. Data aggregation is the combination of data from different sources according to a certain aggregation function (e.g. duplicate suppression, minima, maxima and average). This technique has been used to achieve energy efficiency and data transfer optimization in a number of routing protocols. Signal processing methods can also be used for data aggregation. In this case, it is referred to as data fusion where a node is capable of producing a more accurate output signal by using some techniques such as beamforming to combine the incoming signals and reducing the noise in these signals.

Quality of service: In many applications, conservation of energy is considered relatively more important than the quality of data sent. Hence, as energy is depleted, the network may be required to reduce the quality of results in order to reduce energy dissipation in the nodes (energy-aware routing protocol).

4. CLASSIFICATION OF ROUTING PROTOCOLS

Routing protocols in wireless sensor network [7] might differ depending on the application (Protocol Operation-based) and network architecture (Network-Structure-based) as shown in Figure 1.

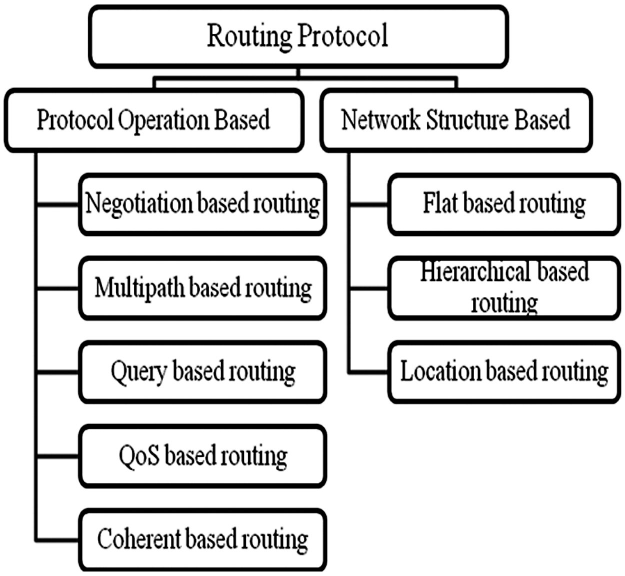

Figure 1: Classification of Routing Protocols in WSN

Depending on the protocol operation we can divide routing protocols in:

Negotiation Based Routing: These protocols use high-level data descriptors in order to eliminate redundant data transmissions through negotiation. The necessary decisions are based on available resources and local interactions. Examples are: Sensor Protocols for Information via Negotiation (SPIN), SPAN, Virtual Grid Architecture routing (VGA) and Sequential Assignment Routing (SAR) protocol.

Multipath Based Routing: Multipaths are used rather than single path in order to enhance the network performance. These protocols offer fault tolerance by having at least one alternate path (from source to sink) and thus, increasing energy consumption and traffic generation. These paths are kept alive by sending periodic messages. Directed Diffusion is a good for robust multipath routing and delivery.

Query Based Routing: In these protocols, the destination nodes propagate a query for data (sensing task or interest) from a node through the network. The node containing this data sends it back to the node that has initiated the query. Examples are: Directed Diffusion, Sensor Protocols for Information via Negotiation (SPIN), Rumor Routing, Gradient-Based Routing (GBR).

QoS Based Routing: In these protocols, the network has to balance between energy consumption and data quality. The network has to satisfy certain QoS metrics (delay, energy, bandwidth, etc.) when delivering data to the BS. Examples are: Sequential Assignment Routing (SAR) and SPEED are QoS based routing protocols.

Coherent Based Routing: In these protocols, the entity of local data processing on the nodes distinguish between coherent (minimum processing) and non-coherent (full processing) routing protocols.

Based on network structure, the routing protocols can be classified as:

Flat Based Routing: in these protocols, each node plays the same role and sensor nodes collaborate to perform the sensing task. Examples are: Sensor Protocols for Information via Negotiation (SPIN), Directed Diffusion, Rumor Routing, Gradient-Based Routing (GBR), Minimum Cost Forwarding Algorithm (MCFA), Constrained Anisotropic Diffusion Routing (CADR), ACtive QUery forwarding In sensoR nEtworks (ACQUIRE).

Hierarchical (Cluster-based) Routing: In these protocols, higher-energy nodes are used to process and send the information, while low-energy nodes are used to perform the sensing in the proximity of the target. The creation of clusters and assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. Hierarchical routing is an efficient way to lower energy consumption within a cluster, performing data aggregation and fusion in order to decrease the number of transmitted messages to the sink node. Examples are: Low Energy Adaptive Clustering Hierarchy (LEACH), Threshold sensitive Energy Efficient sensor Network (TEEN), AdaPtive Threshold sensitive Energy Efficient sensor Network Protocol (APTEEN), Power Efficient Gathering in Sensor Information Systems (PEGASIS), Hybrid Energy Efficient Distributed Protocol (HEED), Stable Election Protocol (SEP).

Location Based Routing: In these protocols, sensor nodes are addressed by means of their locations. The distance between neighbouring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighbouring nodes can be obtained by exchanging such information between neighbours or by communicating with a satellite using GPS. To save energy, some location-based schemes demand that nodes should go to sleep if there is no activity. Examples are: Geographic Adaptive Fidelity (GAF), Geographic and Energy Aware Routing (GEAR), SPAN, Greedy Other Adaptive Face Routing (GOAFR).

5. HIERARCHICAL ROUTING PROTOCOL

The nodes in a sensor network often need to organize themselves into clusters.

Clustering allows hierarchical structures to be built on the nodes and enables more efficient use of scarce resources, such as frequency spectrum, bandwidth, and power [4].The main parts of clustering scheme are [5]:

Sensor Node: A sensor node is the core component of a WSN. Sensor nodes can take on multiple roles in a network, such as simple sensing; data storage; routing; and data processing.

Clusters: Clusters are the organizational unit for WSNs. The dense nature of these networks requires the need for them to be broken down into clusters to simplify tasks such a communication.

Cluster-heads: Cluster-heads are the organization leader of a cluster. They often are required to organize activities in the cluster. These tasks include but are not limited to data-aggregation and organizing the communication schedule of a cluster.

Base Station: The base station is at the upper level of the hierarchical WSN. It provides the communication link between the sensor network and the end-user.

End User: The data in a sensor network can be used for a wide-range of applications [3]. Therefore, a particular application may make use of the network data over the internet, using a PDA, or even a desktop computer. In a queried sensor network (where the required data is gathered from a query sent through the network). This query is generated by the end user.

The main aim of hierarchical routing is to efficiently maintain the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the sink. Cluster formation is typically based on the energy reserve of sensors and sensor's proximity to the cluster head [8, 22, and 10].

Low Energy Adaptive Clustering Hierarchy (LEACH) [11]: In 2000, W. R. Heinzelman, A. P. Chandrakasan and H. Balakrishnan proposed this protocol. It is one of the most popular hierarchical routing algorithms for sensor networks. The idea is to form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. This will save energy since the transmissions will only be done by such cluster heads rather than all sensor nodes. Optimal number of cluster heads is estimated to be 5% of the total number of nodes. All the data processing such as data fusion and aggregation are local to the cluster. Cluster heads change randomly over time in order to balance the energy dissipation of nodes. This decision is made by the node choosing a random number between 0 and 1. The node becomes a cluster head for the current round if the number is less than the following threshold [11]:

$$T(n) = \begin{cases} \dfrac{p}{1 - p \times (r \bmod \frac{1}{p})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

where p is the desired percentage of cluster heads (e.g. 0.05), r is = the current round, and G is the set of nodes that have not been cluster heads in the last $1/p$ rounds.

LEACH achieves over a factor of 7 reduction in energy dissipation compared to direct communication. The nodes die randomly and dynamic clustering increases lifetime of the system. LEACH is completely distributed and requires no global knowledge of network. However, LEACH uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption.

An enhancement over the LEACH protocol was proposed in 2002, called as *LEACH-C* [12], is a centralized version. It adjusts cluster head selection from distributed to central. In each round of LEACH-C, a node needs to send its residual energy and location information to the BS. Based on the received information, the BS can uniformly distribute the cluster heads throughout the topology and adjust the size of each cluster. The BS also adjusts the probability of selecting cluster heads according to each node's residual energy Because the base station carries out energy intensive tasks, such as cluster formation and cluster head selection, a great reduction in energy dissipation can be achieved for sensor nodes.

Power Efficient GAthering in Sensor Information Systems (PEGASIS) [15]: In 2002, S. Lindsey and C. Raghavendra proposed this protocol. It is an improved version of LEACH. Instead of forming clusters, it is based on forming chains of sensor nodes. One node is responsible for routing the aggregated data to the sink. Each node aggregates the collected data with its own data, and then passes the aggregated data to the next ring. The difference from LEACH is to employ multi hop transmission and selecting only one node to transmit to the sink or base station. Since the overhead caused by dynamic cluster formation is eliminated, multi hop transmission and data aggregation is employed, PEGASIS outperforms the LEACH. However excessive delay is introduced for distant nodes, especially for large networks and single leader can be a bottleneck.

Threshold sensitive Energy Efficient sensor Network Protocol (TEEN) [13]: In 2001, A. Manjeshwar and D. P. Agarwal proposed this protocol. Closer nodes form clusters, with a cluster heads to transmit the collected data to one upper layer. Forming the clusters, cluster heads broadcast two threshold values. First one is hard threshold; it is minimum possible value of an attribute to trigger a sensor node. Hard threshold allows nodes transmit the event, if the event occurs in the range of interest. Therefore a significant reduction of the transmission delay occurs. Unless a change of minimum soft threshold occurs, the nodes don't send a new data packet. Employing soft threshold prevents from the redundant data transmission. Since the protocol is to be responsive to the sudden changes in the sensed attribute, it is suitable for time-critical applications.

AdaPtive Threshold sensitive Energy Efficient sensor Network Protocol (APTEEN) [14]: In 2002, A. Manjeshwar and D. P. Agarwal proposed this protocol. The protocol is an extension of TEEN aiming to capture both time-critical events and periodic data collections. The network architecture is same as TEEN. After forming clusters the cluster heads broadcast attributes, the threshold values, and the transmission schedule to all nodes. Cluster heads are also responsible for data aggregation in order to decrease the size data transmitted so energy consumed. According to energy dissipation and network lifetime, TEEN gives better performance than LEACH and APTEEN because of the decreased number of transmissions. The main drawbacks of TEEN and APTEEN are overhead and complexity of forming clusters in multiple levels, implementing threshold-based functions and dealing with attribute based naming of queries.

Hybrid Energy Efficient Distributed clustering Protocol (HEED) [6]: In 2004, O. Younis and S. Fahmy proposed this protocol. It extends the basic scheme of LEACH by using residual energy as primary parameter and network topology features (e.g. node degree, distances to neighbours) are only used as secondary parameters to break tie between candidate cluster heads, as a metric for cluster selection to achieve power balancing. The clustering process is divided into a number of iterations, and in each iteration, nodes which are not covered by any cluster head double their probability of becoming a cluster head. Since these energy-efficient clustering protocols enable every node to independently and probabilistically decide on its role in the clustered network, they cannot guarantee optimal elected set of cluster heads.

Stable Election Protocol (SEP) [16]: In 2004, G. Smaragdakis, I. Matta and A. Bestavros proposed this protocol. This protocol is an extension to the LEACH protocol. It is a heterogeneous aware protocol, based on weighted election probabilities of each node to become cluster head according to their respective energy. This approach ensures that the cluster head election is randomly selected and distributed based on the fraction of energy of each node assuring a uniform use of the nodes energy. In this protocol, two types of nodes (two tier in-clustering) and two level hierarchies were considered.

Energy Efficient Clustering Scheme (EECS) [17]: In 2005, M. Ye, C. Li, G. Chen and J. Wu proposed this protocol. It is novel clustering scheme for periodical data gathering applications for wireless sensor networks. It elects cluster heads with more residual energy through local radio communication. In the cluster head election phase, a constant number of candidate nodes are elected and compete for cluster heads according to the node residual energy. The competition process is localized and without iteration. The method also produces a near uniform distribution of cluster heads. Further in the cluster formation phase, a novel approach is introduced to balance the load among cluster heads. But on the other hand, it increases the requirement of global knowledge about the distances between the cluster-heads and the base station.

Distributed Energy Efficient Clustering Protocol (DEEC) [18]: In 2006, Q. Li, Z. Qingxin and W. Mingwen proposed this protocol. This protocol is a cluster based scheme for multi level and two level energy heterogeneous wireless sensor networks. In this scheme, the cluster heads are selected using the probability based on the ratio between residual energy of each node and the average energy of the network. The epochs of being cluster-heads for nodes are different according to their initial and residual energy. The nodes with high initial and residual energy have more chances of the becoming cluster heads compared to nodes with low energy.

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