Routing in Sensor Networks

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Abstract. A wireless sensor network refers to a group of sensors, or nodes, linked by a wireless medium to perform distributed sensing tasks. The primary interest in wireless sensor networks is due to their ability to monitor the physical environment through ad hoc deployment of numerous tiny, intelligent, wireless networked sensor nodes. Traditional routing protocols developed for wireless ad hoc networks can not be used for sensor networks. This is because conventional protocols focus on avoiding congestion or maintaining connectivity when faced with mobility and not on the limited energy supply. This paper studies and compares Sensor Protocols for Information via Negotiation (SPIN), Directed Diffusion and Low-Energy Adaptive Clustering Hierarchy (LEACH), to bring out the significance of energy-efficiency for routing protocols deployed in sensor networks.

Keywords: sensor networks, routing, energy-efficient protocols, SPIN, LEACH, Directed Diffusion.

1. Introduction

Advances in wireless communications and electronics have fostered the development of relatively in-expensive and low-power wireless sensor nodes that are extremely small in size and communicate un-tethered in short distances. These small devices are incorporated with sensing, data processing and communicating components, to collect data, monitor equipment, and transmit information, which leverages the idea of sensor networks.

A sensor network is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it [1].The position of the nodes need not be engineered or predetermined and hence allows random deployment in inaccessible terrain or disaster relief operations. This implies that the nodes are expected to perform sensing and communication with no continual maintenance and battery replenishment which limits the amount of energy available to the nodes. Therefore, to prolong the network lifetime, the nodes in the network collaborate to perform high quality sensing and to behave as fault-tolerant systems.

Applications involving wireless sensor networks require long system lifetimes and robustness. Some such applications of sensor networks are emergency response information, energy management, medical monitoring, logistics and inventory management, battlefield management, home security, machine failure diagnosis, chemical or biological detection [1, 2].

Several obstacles arise for sensor networks that need to be addressed like energy, computation and communication resources [3].

- *Energy* – Because networked sensors can use up their limited supply of energy performing computations and transmitting information in a wireless environment, energy-conserving forms of communication and computation are essential.
- *Computation* – Sensors have limited computing power and therefore may not be able to run sophisticated network protocols.
- *Communication* – The bandwidth of the wireless links connecting sensor nodes is often limited constraining inter-sensor communication.

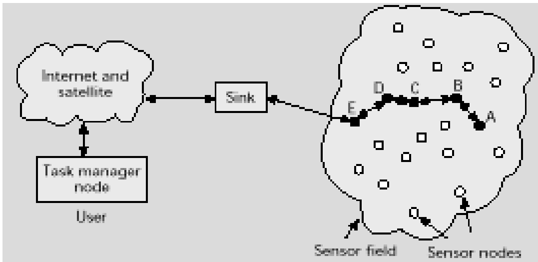

Figure 1. Sensor nodes scattered in a sensor field.

The communication architecture of the sensor networks is shown in Figure 1 [1]. The sensor nodes are usually scattered in a *sensor field*. Sensor field is an area where the sensor nodes are deployed. The nodes in these networks coordinate amongst themselves to produce easily accessible and high-quality information about the physical environment. Each sensor node in these networks operates autonomously with no central point of control in the network and communicates using infrared devices or radios. Each node bases its decisions on its mission, the information it currently has, and its knowledge of its computing, communication and energy resources.

Each of these scattered sensor nodes has the capabilities to collect data and route data back to the *sink.* A sink may be a long-range radio, capable of connecting the sensor network to existing long-haul communications infrastructure. The sink may also be a mobile node acting as an information sink, or any other entity required to extract information from the sensor network [4]. Data are routed back to the sink by a multi-hop infrastructure-less architecture through the sink as shown in Figure 1. The sink may communicate with the *task manager node*, the user, via internet or satellite. The design of the sensor network is influenced by many factors, including fault tolerance, scalability, production costs, hardware constraints, transmission media and power consumption. These design factors are important as they serve as a guideline to design a protocol or an algorithm for sensor networks [1].

- *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.
- *Scalability* – The number of sensor nodes deployed in studying a phenomenon may be in the order of hundreds or thousands. Depending on the application the number of nodes can be more. New schemes must be able to work with this many number of nodes.
- *Production costs* – Since sensor networks consist of a large number of sensor nodes, the cost of a single node is very important to justify the overall cost of the network. If the cost of the network is more expensive than deploying traditional sensors, the sensor network is not cost justified.
- *Hardware constraints* – A sensor node comprising of many hardware components should be smaller than a cubic centimeter, consume extremely low power, operate unattended, operate in high volumetric densities, have low production cost and adapt to the environment.
- *Transmission media* – In a multi-hop sensor network, communicating nodes are linked by a wireless medium. To enable global operation of these networks, the chosen transmission medium must be available worldwide.
- *Power consumption* – The wireless sensor node can be equipped with a limited power source. Sensor node lifetime therefore shows a strong dependence on battery lifetime. In a multi-hop ad hoc sensor network, each node plays the dual role of data originator and data router. The malfunctioning of a few nodes can cause significant topological changes and might require rerouting of packets and reorganization of the network.

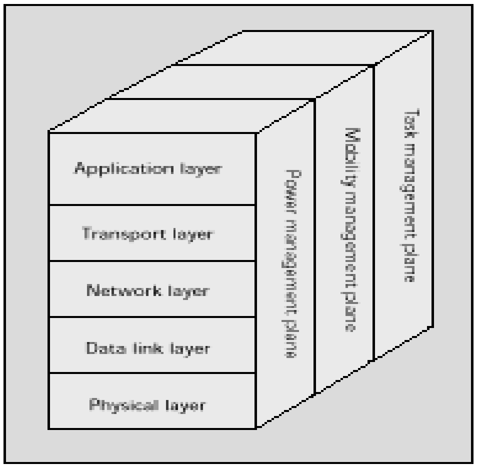

Figure 2. The sensor networks protocol stack.

The protocol stack used by the sink and the sensor nodes is as shown in Figure 2 [1]. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of the sensor nodes. The protocol stack consists of physical layer, data link layer, network layer, transport layer, application layer, power management plane, mobility management plane and task management plane. These management planes are needed so that sensor nodes can work together in a power-efficient way, route data in a mobile sensor network, and share resources between sensor nodes. The functionality of each layer is as described below:

- The physical layer addresses the needs of simple but robust modulation, transmission and receiving techniques.
- The medium access control (MAC) protocol must be power-aware and able to minimize collision with neighbors' broadcasts since the environment is noisy and sensor nodes can be mobile.
- The network layer takes care of routing the data supplied by the transport layer.
- The transport layer helps to maintain the flow of data if the sensor networks application requires it.
- Different types of application software can be built and used on the application layer, depending on the sensing tasks.
- The power management plane manages how a sensor node uses its power.
- The mobility management plane detects and registers the movement of sensor nodes, so a route back to the user is always maintained, and the sensor nodes can keep track of who its neighbors are.
- The task management plane balances and schedules the sensing tasks given to a specific region.

The focus of this paper is on the network layer where three routing protocols for sensor networks are studied and compared. These routing protocols must be designed to achieve fault tolerance in the presence of individual node failure while minimizing energy consumption. In addition, since the limited wireless channel bandwidth must be shared among all the sensors in the network, routing protocols for these networks should be able to perform local collaboration to reduce bandwidth requirements. SPIN, LEACH and Directed Diffusion are three such routing protocols that are analyzed here. Many protocols being developed in this area are based on the three chosen protocols which is the reason why they are the focus of this paper.

The remainder of the paper is organized as follows. In Section 2 the prior and ongoing research in this area is discussed. Section 3 presents the three network layer protocols. Section 4 compares these protocols followed by conclusions in Section 5.

2. Related Work

Wireless sensor networks have spurred a lot of interest in the networking research community recently. These sensor networks are a specific instance of ubiquitous computing as envisioned by Weiser [5]. A number of proposals have addressed various aspects in sensor node design [6, 7, 8]. Likewise, aspects like security [9] and quality of service [10] for sensor networks have also been addressed. A number of high profile applications for wireless sensor networks have been proposed in [11, 12]. Different MAC layer protocols for sensor networks are proposed in [2, 13].

Routing has been an active research area in the context of sensor networks. SPIN [14, 15], Directed Diffusion [16, 17] and LEACH [18, 19] are three recent routing protocols discussed in this paper. SPIN is designed to address the deficiencies of classic flooding by negotiation and resource adaptation. These protocols are designed based on two basic ideas: sensor nodes operate more efficiently and conserve energy by sending data that describe the sensor data, called meta-data, instead of sending all the data. Directed Diffusion is a data-centric paradigm and is applied to query dissemination and processing. LEACH is a clustering based energy-efficient communication protocol where the cluster membership as well as cluster-head is changed randomly. The cluster-head collects and aggregates information from sensors in its own cluster ad passes in information to the sink. Several other routing protocol proposals have been proposed in the literature [4, 6, 20, 21, 22].

3. Sensor Network Routing Protocols

The main goal in conventional wireless networks is providing high quality of service and high bandwidth efficiency when mobility exists. In contrast, in a sensor network conservation of energy is considered to be important than the performance of the network. Therefore, the current routing protocols designed for traditional networks cannot be used directly in a sensor network due to the following reasons [20].

- Sensor networks are data centric, that it unlike traditional networks where data is requested from a specific node, data is requested based on certain attributes.
- The requirements of the network change with the application and so, it is application-specific.
- Adjacent nodes may have similar data. So rather than sending data separately from each node to the requesting node, similar data is aggregated and then sent.
- Each node is given a unique id which is used for routing in traditional networks. This cannot be effectively used in sensor networks because they are data centric. Also, the large number of nodes in the network implies large ids which might be substantially larger than the actual data being transmitted.

To achieve the above, new routing schemes have been proposed. Routing protocols must select the best path to minimize the total power needed to route packets on the network and to maximize the lifetime of all nodes. That is, these protocols should be scalable to obtain different energy and quality operating points as the relative importance of different resources as requirements might change over the system lifetime. Also, wireless sensor networks need protocols which are data centric, capable of effective data aggregation, distribute energy dissipation evenly, efficiently use their limited energy to increase the longevity of the network and avoid any single point bottleneck (except the sink). As the energy gets depleted, the network may be required to reduce the quality of the results in order to reduce the energy dissipation in the nodes and hence lengthen the total system lifetime. In addition, sensor network protocols should be scalable to respond to events in the environment. Until an event occurs, most of the sensors can remain in the sleep state, with the data from the few remaining sensors providing a coarse quality. Once an event of interest is detected, the system should be able to configure itself so as to obtain very high quality results. Several energy-aware routing protocols like SPIN, LEACH and Directed Diffusion were proposed to cater to this requirement.

3.1 SPIN

Conventional protocols like flooding, on receiving data stores a copy and sends a copy to all its neighbors, have many limitations like implosion, overlap and resource blindness. Implosion is caused when a node always sends data to its neighbors, regardless of whether or not the neighbor has already received the data from another source. Overlap occurs when sensor nodes often cover overlapping geographic areas and gather overlapping pieces of data. Instead of processing the common area and sending it once to their common neighbor, the sensor nodes send two separate copies wasting energy and bandwidth. Resource blindness happens when nodes do not modify their activities based on the amount of energy available to them at a given time.

The SPIN family of protocols, SPIN-1 and SPIN-2, incorporates negotiation and resource-adaptation to overcome the deficiencies of classic flooding. Nodes negotiate with each other before transmitting data to ensure that only useful information will be transferred to eliminate implosion and overlap. This is done by naming the data descriptors referred to as meta-data; the format of which is application-specific. Also, each node has its own resource manager that keeps track of resource consumption which the nodes poll before data transmission.

SPIN-1 protocol is a 3-stage protocol. Nodes use three types of messages ADV, REQ and DATA to communicate. ADV is used to advertise new data, REQ to request for data and DATA is the actual message itself. The protocol starts when a SPIN node obtains new data that it is willing to share. It does so by broadcasting an ADV message containing meta-data. If a neighbor is interested in the data, it sends an REQ message for the DATA and the DATA is sent to this neighbor node. The neighbor sensor node then repeats this process to its neighbors as a result of which the entire sensor area will get a copy.

Figure 3[14], shows an example on how this protocol works. Upon receiving an ADV packet from node A, node B checks to see if it possesses all of the advertised data (a). If not, it sends an REQ message back to node A, asking for all the data it would like to acquire (b). When node A receives this REQ packet, it retrieves the requested data and sends it back to node B as a DATA message (c). Node B, in turn, sends ADV messages to all its neighbors advertising the new data it received from node A (d). Note that it does not send an advertisement back to A, because it knows that node A already has the data. If any of the nodes send back an REQ it forwards the data to them (f). The neighboring nodes of node B then send advertisements of the new data to all of their neighbors and the protocol continues. Node B can aggregate data with the data of node A when sending an advertisement to all its neighbors. Nodes that are not interested are not required to send an REQ message back (e).

The strength of this protocol lies in its simplicity. Each node in the network performs little decision making when it receives new data, and therefore wastes little energy in computation. Furthermore, each node only needs to know about its single-hop network neighbors.

An extension to SPIN-1 is SPIN-2, incorporates threshold-based resource-awareness mechanism in addition to negotiation. When energy in the nodes is plenty, SPIN-2 communicated using the 3-stage protocol as SPIN-1 nodes. But when the energy in a node starts approaching a low-energy threshold, it reduces its participation in the protocol, that is it participates only when it believes that it can complete all the other stages of the protocol without going below the low-energy threshold. This approach does not prevent a node from receiving, and therefore spending energy on ADV, or REQ messages below its low-energy threshold. It does, however, prevent the node from ever handling a DATA message below this threshold.

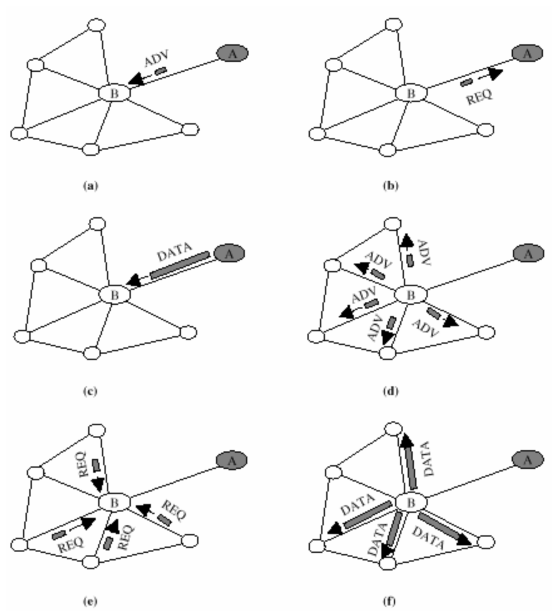

Figure 3. The SPIN-1 Protocol. Node A starts by advertising its data to node B (a). Node B responds by sending a request to node A (b). After receiving the requested data (c), node B then sends out advertisements to its neighbors (d), who in turn send requests back to B (e,f).

3.2 Directed Diffusion

Networks of sensor nodes coordinate to perform distributed sensing of environmental phenomena. The directed diffusion data dissemination paradigm is used for such coordination. Directed Diffusion is data-centric and application-aware. It is data-centric in the sense that all the data generated by sensor nodes is named by attribute-value pairs. All nodes in a directed diffusion-based network are application-aware, which enables diffusion to achieve energy savings by selecting empirically good paths and by caching and processing data in the network.

A sensor network based on directed diffusion exhibits the following properties. Each sensor node names data that it generates with one or more attributes. The sink broadcasts the *interest*, which is a named task descriptor, to all sensors. The task descriptors are named by assigning attribute-value pairs that describe the task. Each sensor node then stores the interest entry in its cache. Caching can increase the efficiency, robustness and scalability of coordination. Locally cached data may be accessed by other users with lower energy consumption than if the data were to be resent end to end. Intermediate node storage increases availability of the data, thereby improving robustness. Finally, intermediate nodes can increase the scalability of coordination by using cached information to carefully direct interest propagation. The interest entry contains a timestamp field and several gradient fields. As the interest is propagated throughout the network, the gradients from the source back to the sink are setup. When the source has data for the interest, the source sends the data along the interest's gradient path. As the data propagates, data may be transformed locally at each node. The sink periodically refreshes and resends the interest when it starts to receive data from the source. This is necessary because interests are not reliably transmitted through out the network.

The above protocol is explained with an example. Figure 4[16], shows a sensor network in which each node can detect motion within some vicinity. One or more sink nodes may query the sensor network for motion information from a particular section of the terrain (e.g., from the southeast quadrant). One goal of this protocol is to robustly compute path from source to sink.

Attribute-based naming is the first characteristic of directed diffusion systems. In this example, each sensor names data that it generates using a single attribute motion, which has a geographic location (e.g., latitude/ longitude, or relative location with respect to some landmark) as its value. In general, motion data may be described using several attributes: (type=seismic, id=12, timestamp=99.01.22/21:08:15,location=75N/120E, footprint= vehicle/wheeled/over-40-ton).

Node a, which is a sink (a) may query for motion information by disseminating an interest, which is a range of values for one or more attributes. Node a in the example, specifies south-east quadrant as the value of the motion attribute in its interest.

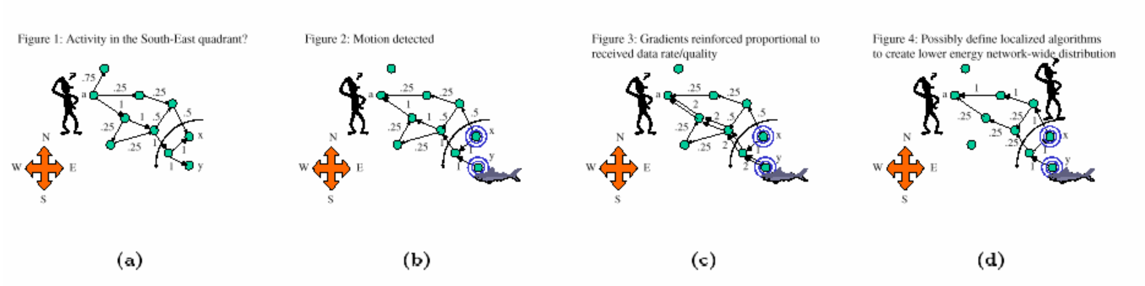

Figure 4. Diffusion for path finding: This illustrates the basic diffusion constructs: data naming, interests that set up gradients, data diffusing along gradients

Each node disseminates interests based on the contents of the interest. That is in this example intermediate nodes send the interest towards the neighbor in the direction of the south-east quadrant. Conceptually, the path of interest propagation sets up a reverse data path for data that matches the interest. Then, when nodes x and y in the southeast quadrant detect motion, the motion signature travels towards node a along data propagation path.
In the diffusion model the data propagation path has an associated gradient. The notion of gradient is useful for robustness. Each intermediate node propagates the interest towards multiple neighbors (b). The strength of the interest is different towards different neighbors, resulting in source-to-sink paths with different gradients. In its simplest form, a gradient is a scalar quantity. Negative gradients inhibit the distribution of data along a particular path, and positive gradients encourage the transmission of data along the path.

In this motion sensing scenario, for instance, if a node has two outgoing paths, one with a gradient of 0.8 and another with a gradient of 0.4, then the node may send twice as much detail along the higher gradient path than along the lower.

An important feature of directed diffusion is that interest, data propagation and aggregation are determined by localized interactions, that is through messages exchanged between neighbors or nodes within some vicinity.

3.3 LEACH

Conventional protocol for wireless networks, clustering, is where nodes are organized into clusters that communicate with a local base station. These local base stations transmit the data to the global base station where the data is accessed by the end-user. This scheme greatly reduces the energy needed by the nodes in a cluster to transmit their data, as typically the local base station is close to all the nodes in the cluster. However, the local base station is assumed to be a high energy node, if not it would die quickly as it is being heavily utilized. To overcome this LEACH has been proposed.

LEACH is a clustering-based protocol that utilizes randomized rotation of local cluster base stations to evenly distribute the energy load among the sensors in the network. It uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station. The purpose of LEACH is to randomly select sensor nodes as cluster-heads, so the high energy dissipation in communicating with the base station is spread to all the sensor nodes in the sensor network. The dark spots in figure 5 [18] represent a set of C nodes that have elected themselves as cluster-heads at time t1. The operation of LEACH is separated into two phases, the setup phase and the steady state phase. In the setup phase the clusters are organized followed by the steady state phase when data transfer occurs to the base station. The duration of the steady state phase is longer than the duration of the setup phase in order to minimize overhead.

During the setup phase, a sensor node chooses a random number between 0 and 1. If this random number is less than a threshold T (n), the node becomes a cluster-head for the current round. The threshold T (n) is calculated from the equation below

$$T(n) = \begin{cases} \dfrac{P}{1 - P * [r \bmod (1/P)]} & \text{if } n \in G \\ 0 & \text{otherwise,} \end{cases}$$

where P is the desired percentage to become a cluster-head, r is the current round, and G is the set of nodes that have not being selected as a cluster-head in the last 1/P rounds. Once the cluster-head has been elected, these nodes broadcast an advertisement message to the rest of the nodes in the network that they are the new cluster-heads. All the non-cluster-head nodes after receiving this advertisement, decide on the cluster to which they want to belong to. This decision is based on the signal strength of the advertisement. The non-cluster-head nodes inform the appropriate cluster-heads that they will be a member of the cluster. After receiving all the messages from the nodes that would like to be included in the cluster and based on the number of nodes in the cluster, the cluster-head node creates a TDMA schedule and assigns each node a time slot when it can transmit. This schedule is broadcast to all the nodes in the cluster. During the steady state phase, the sensor nodes can begin sensing and transmitting data to the cluster-heads. The cluster-head node after receiving all the data aggregates it before sending it to the base station. After a certain time which is determined a priori, the network goes back into the setup phase again and enters another round of selecting cluster-heads. Each cluster communicates using different CDMA codes to reduce interference from nodes belonging to other clusters.

An extension to LEACH, LEACH with negotiation [18], is to precede data transfers with high-level negotiation using meta-data descriptors as in the SPIN protocol. This ensures that only data that provides new information is transmitted to the cluster-head.

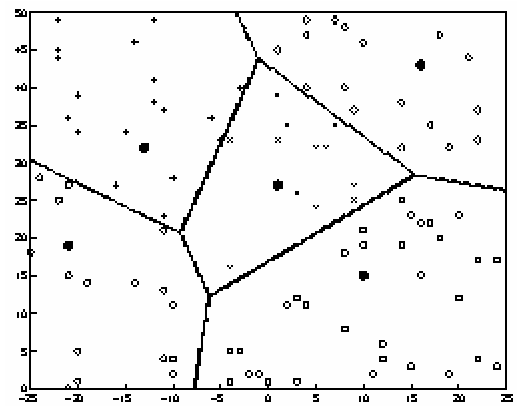

Figure 5. Dynamic Clusters: cluster-head nodes = C at time t1.

4. Observations and Comparison

No simulations results are available to carryout a performance comparison of the three protocols chosen because all the papers referred to compare the performance of the individual protocols with very basic protocols. Therefore, the protocols under consideration are shown to fare better than the basic routing protocols because of their enhanced capabilities. Comparison with peer protocols has not been studied in the related work referred. As a result of which, it cannot be said which protocol is considered to be the best. However, a comparison can be made based on information gathered from the referred literature about the working of the protocols. The SPIN protocol mentioned in table 1 is a generalization of both SPIN-1 and SPIN-2 protocols. A consolidated view of these two protocols is presented.

Based on the information available, it can be inferred that all the three algorithms base their routing decisions on battery power alone and do not consider the fact that different links require different transmission powers. Many new hybrid algorithms are being proposed which are combinations of two or more protocols mentioned. There algorithms good characteristics features available from the original protocols. Therefore, there is a possibility of these algorithms being able to server the purpose of routing in sensor networks more efficiently.

A summary of the comparison of the three protocols discussed has been tabulated in Table 1.

Table 1. Comparison of SPIN, LEACH and Directed Diffusion.

Parameter	SPIN	LEACH	Directed Diffusion
Optimal Route	No	No	Yes
Network Lifetime	Good	Good	Good
Robust Routing	No	Good	Good
Resource Awareness	Yes	Yes	Yes
Data aggregation	Yes	Yes	Yes
Caching	No	Yes	Yes
Use of Meta-data descriptors	Yes	No	Yes

5. Conclusions

In power-controlled wireless sensor networks, battery energy at network nodes is a very limited resource that needs to be utilized efficiently. One of the conventional routing objectives was to minimize the total consumed energy in reaching the destination. The drawback with this approach is that the battery may drain out in certain nodes which might hinder the delivery of information in future even tough there might be nodes with plenty of energy for carrying out data dissemination.

With this in mind three protocols with energy efficiency as their focus were studied from which the following can be inferred:

SPIN uses meta-data negotiation and resource-adaptation to overcome several deficiencies in traditional dissemination approaches. Using meta-data names, nodes negotiate with each other about the data they possess. These negotiations ensure that nodes only transmit data when necessary and never waste energy on useless transmissions. Being resource-aware, nodes are able to cut back on their activities whenever their resources are low to increase their longevity. Naming data using meta-data descriptors and negotiating data transmissions using meta-data successfully solve the implosion and overlap problems. SPIN-l and SPIN-2 are simple protocols that efficiently disseminate data, while maintaining no per-neighbor state. These protocols are well-suited for an environment where the sensors are mobile because they base their forwarding decisions on local neighborhood information.

Directed diffusion has the potential for significant energy efficiency. Diffusion mechanisms are stable under different application interests. Directed diffusion has some novel features like data-centric dissemination and in-network data aggregation and caching.

LEACH outperforms static clustering algorithms by requiring nodes to volunteer to be high-energy cluster-heads and adapting the corresponding clusters based on the nodes that choose to be cluster-heads at a given time. LEACH is completely distributed, requiring no control information from the base station, and the nodes do not require knowledge of the global network in order for LEACH to operate. Distributing the energy among the nodes in the network is effective in reducing energy dissipation from a global perspective and enhancing system lifetime.

As far as the three protocols are concerned, there is no absolute choice it depends on which kind of application you are going to use. To summarize, Leach and Directed Diffusion provide more reliable communication at the cost of computing and caching power. Spin is lighter than LEACH and Directed Diffusion in terms of computing and caching.

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