Analysis of Routing Protocols for Wireless Sensor Networks: A Survey

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Abstract: ***Recent advances in wireless sensor networks have led to many new protocols specifically designed for sensor networks where energy awareness is an essential consideration. Most of the attention, however, has been given to the routing protocols since they might differ depending on the application and network architecture. This paper surveys recent routing protocols for sensor networks and presents a classification for the various approaches pursued. The three main categories explained in this paper are flat, hierarchical and location based. Each routing protocol is described and discussed under the appropriate category. Moreover, advantages and performance issues of each routing techniques are also described.***

Keywords: Wireless Sensor Networks, Energy Awareness, Routing Protocols, Classification of Protocols

1. Introduction

The demand for real-time data has exploded as technological advancements produce devices that are physically smaller, faster, and cheaper. Among such devices are autonomous sensors that provide data in a simple and cost-effective manner. As the uses for these sensors grow, so does the need for them to communicate with each other in ever-increasing numbers. That, coupled with applications requiring mobile sensors, led to the development of wireless sensor networks (WSN). Today, WSNs are embedded in structures, machinery and environments, aiding in such tasks as averting disastrous structural failures, conserving natural resources, providing improved emergency response, and enhanced homeland security.

A wireless sensor network is a collection of small randomly dispersed devices that provide three essential functions; the ability to monitor physical and environmental conditions, often in real time, such as temperature, pressure, light and humidity; the ability to operate devices such as switches, motors or actuators that control those conditions; and the ability to provide efficient, reliable communications via a wireless network.

Once nodes are identified, routing protocols are in charge of constructing and maintaining routes between distant nodes. The different ways in which routing protocols operate make them appropriate for certain applications. In the related literature, there are plenty of proposals concerning routing algorithms in wireless sensor networks. This paper aims at describing the most relevant ones in order to facilitate the understanding of the different routing techniques that could be applied into wireless sensor networks .The paper is organized as follows: In section 3 Network Structure based protocols are covered; Section 4 Operational based protocols are described; Section 5 concludes the paper with a comparative summary of the surveyed approaches.

2. Routing Protocols in WSNs

Wireless sensor networks require specialized protocols that conserve power and minimize network traffic. Therefore, it is vitally important to analyze how the parameters of a protocol affect these metrics. In general, routing in WSNs can be divided into flat-based routing, hierarchical-based routing, and location-based routing depending on the network structure. In flat-based routing, all nodes are typically assigned equal roles or functionality. In hierarchical-based routing, however, nodes will play different roles in the network. In location-based routing, sensor nodes' positions are exploited to route data in the network. In addition to the above, routing protocols can be classified into three categories, namely, proactive, reactive, and hybrid protocols depending on how the source finds a route to the destination. In proactive protocols, all routes are computed before they are really needed, while in reactive protocols, routes are computed on demand. Hybrid protocols use a combination of these two ideas. Another class of routing protocols is called the cooperative routing protocols. In cooperative routing, nodes send data to a central node where data can be aggregated and may be subject to further processing, hence reducing route cost in terms of energy use. Many other protocols rely on timing and position information [24].

3. Network Structure Based Protocols

The underlying network structure can play significant role in the operation of the routing protocol in WSNs.

3.1 Flat Routing

In flat networks, each node typically plays the same role and sensor nodes collaborate together to perform the sensing task. Due to the large number of such nodes, it is not feasible to assign a global identifier to each node.

3.1.1 Sensor Protocols for Information via Negotiation (SPIN)

SPIN disseminate all the information at each node to every node in the network assuming that all nodes in the network are potential base-stations [1]. This enables a user to query any node and get the required information immediately. These protocols make use of the property that nodes in close proximity have similar data, and hence there is a need to only distribute the data that other nodes do not posses. The SPIN family of protocols uses data negotiation and resource-adaptive algorithms. Nodes running SPIN assign a high-level name to completely describe their collected data (called meta-data) and perform meta-data negotiations before any data is transmitted. This assures that there is no redundant data sent throughout the network. These protocols work in a time-driven fashion and distribute the information all over the network, even when a user does not request any data.

3.1.2 Directed Diffusion

As a data-centric protocol, applications in sensors label the data using attribute-value pairs. A node that demands the data generates a request where an interest is specified according to the attribute-value based scheme defined by the application. The sink usually injects an interest in the network for each application task [2]. The nodes update an internal interest cache with the interest messages received. The nodes also keep a data cache where the recent data messages are stored. This structure helps on determining the data rate. On receiving this message, the nodes establish a reply link to the originator of the interest. This link is called gradient and it is characterized by the data rate, duration and expiration time. Additionally, the node activates its sensors to collect the intended data. The reception of an interest message makes the node establish multiple gradients (or first hop in a route) to the sink. In order to identify the optimum gradient, positive and negative reinforcements are used. There algorithm works with two types of gradients: exploratory and data gradients. Exploratory gradients are intended for route set-up and repair whereas data gradients are used for sending real data.

3.1.3 Rumor routing

The Rumor Routing protocol improves a nodes ability to transmit queries and event information throughout a wireless sensor network. The most expedient way to guarantee every query is successful is to flood the WSN with both query and event information [3] [4]. Each node within a WSN with Rumor Routing initializes using an active broadcast to locate neighboring nodes. These neighbors are added to a list within the nodes memory, which is maintained through subsequent active broadcasts, or by passively listening to other nodes' broadcasts. Additionally, each node maintains an event table containing forwarding information for each event it has been informed of. If a node witnesses an event, it adds it to its event table and generates an agent. The agent traverses the network, "informing" other nodes of events it has witnessed. The agent uses a straightening algorithm to maintain a straight path, thereby transmitting information as far across the network as possible. The agent contains a list of witnessed events as well as the number of hops to each event. When received by a node, the agent synchronizes its list with the node's list so both of their tables contain routes to every event. In addition, since agents are broadcast in the WSN, every neighboring node within receiving distance of the agent receives the updated information and updates their event tables as well. This behaviour continues until the agent's lifetime expires.

To receive event information, a node within the WSN generates a query. The query is sent in a random direction to a neighboring node. That node, if aware of a route to the event, forwards the query accordingly. Otherwise, it forwards the query in a random direction to one of its neighboring nodes. The query uses the same algorithm as the agent to determine the direction to send the query, thus avoiding the same nodes. Should a node within the network fail, however, it is possible the query could be caught in a loop. To avoid this, each query is assigned a limited lifetime, as well as a random identification number. If a query arrives at a node which has already forwarded it, the node instead sends the query to a random neighbor, thus breaking the loop. This process continues until the query has reached a node that has information about the event, or until the query's lifetime expires. If the originating node of a query determines it did not reach the event, it can retransmit the query, quit the query, or flood the network with the query.

The Rumor Routing protocol has several drawbacks. First, its straightening algorithm is not always effective in ensuring agents and queries are spread across the network. Although it prevents revisiting nodes and loops, it is susceptible to following a spiral pattern. Thus, the agent or query could stay within a relatively small area within the WSN, reducing the probability of a successful query. Furthermore, when dealing with a large WSN, the agent's and query's list of visited nodes grows each time they are forwarded. Eventually, this information constitutes an enormous amount of data, requiring each node to expend a greater amount of energy with each subsequent transmission, resulting in earlier network failure.

3.1.4 Minimum Cost Forwarding (MCF)

Minimum Cost Forwarding is an efficient protocol appropriate for simple WSN with limited resources. The aim of MCF is to establish a means of delivering messages from any sensor in a field of sensor nodes along a minimum cost path to an interested client node or base station [5]. MCF exploits the fact that the direction of routing is always known, i.e. data always flows from sensor nodes towards a base station. A sensor node need not possess a unique ID nor store a routing table. In fact, the cost of sending a message to the base station is the sole information required by a node to implement the MCF protocol. The simplicity of the MCF is an advantage for sensor nodes with limited processing capability and/or memory. MCF is uncomplicated in operation; nodes may be in one of two states, that is initialization or operational. In the initial state, initialization, the minimum cost field is established over the network. This is followed by the The minimum cost for a particular node is the optimal path to the destination node. The cost of a link may simply be the hop count, a measure of consumed wireless energy, the delay between the source and sink, a function of the received signal strength, number of retransmissions or some composite. Messages are broadcast to neighboring nodes either when information is sensed or when forwarding other messages.

3.1.5 Gradient-Based Routing

The key idea in GBR is to memorize the number of hops when the interest is diffused through the whole network. As such, each node can calculate a parameter called the height of the node, which is the minimum number of hops to reach the BS. The difference between a node's height and that of its neighbor is considered the gradient on that link. A packet is forwarded on a link with the largest gradient. GBR uses some auxiliary techniques such as data aggregation and traffic spreading in order to uniformly divide the traffic over the network. When multiple paths pass through a node, which acts as a relay node, that relay node may combine data according to a certain function. In GBR, three different data dissemination techniques have been discussed (1) Stochastic Scheme, where a node picks one gradient at random when there are two or more next hops that have the same gradient, (2) Energy-based scheme, where a node increases its height when its energy drops below a certain threshold, so that other sensors are discouraged from sending data to that node, and (3) Stream-based scheme, where new streams are not routed through nodes that are currently part of the path of other streams. The main objective of these schemes is to obtain a balanced distribution of the traffic in the network, thus increasing the network lifetime.

3.1.6 Information-driven sensor querying (IDSQ)

The main idea of the information-driven approach is to base the decision for sensor collaboration on information constraints as well as constraints on cost and resource consumption. Using measures of information utility, the sensors in a network can exploit the information content of data already received to optimize the utility of future sensing actions, thereby efficiently managing the scarce communication and processing resources. In IDSQ, the querying node can determine which node can provide the most useful information with the additional advantage of balancing the energy cost. However, IDSQ does not specifically define how the query and the information are routed between sensors and the BS. Therefore, IDSQ can be seen as a complementary optimization procedure [6].

operational state during which nodes generate and forward messages to the base station using the minimum cost paths established during initialization. After initialization, the node remains in operational mode.

3.1.9 COUGAR

COUGAR utilizes in-network data aggregation to obtain more energy savings. The abstraction is supported through an additional query layer that lies between the network and application layers. COUGAR incorporates architecture for the sensor database system where sensor nodes select a leader node to perform aggregation and transmit the data to the BS [7]. The BS is responsible for generating a query plan, which specifies the necessary information about the data flow and in-network computation for the incoming query and send it to the relevant nodes. The query plan also describes how to select a leader for the query. The architecture provides in-network computation ability that can provide energy efficiency in situations when the generated data is huge. COUGAR has some drawbacks. First, the addition of query layer on each sensor node may add an extra overhead in terms of energy consumption and memory storage. Second, to obtain successful in-network data computation, synchronization among nodes is required before sending the data to the leader node. Third, the leader nodes should be dynamically maintained to prevent them from being hot-spots (failure prone) [25].

3.1.7 ACQUIRE

The operation of ACQUIRE can be described as follows. The BS node sends a query, which is then forwarded by each node receiving the query. During this, each node tries to respond to the query partially by using its pre-cached information and then forward it to another sensor node. Once the query is being resolved completely, it is sent back through either the reverse or shortest-path to the BS. Hence, ACQUIRE can deal with complex queries by allowing many nodes to send responses [8].

3.1.8 Energy Aware Routing

The objective of energy-aware routing protocol is to increase the network lifetime. Although this protocol is similar to directed diffusion, it differs in the sense that it maintains a set of paths instead of maintaining or enforcing one optimal path at higher rates. These paths are maintained and chosen by means of a certain probability. The value of this probability depends on how low the energy consumption of each path can be achieved. By having paths chosen at different times, the energy of any single path will not deplete quickly. This can achieve longer network lifetime as energy is dissipated more equally among all nodes. Network survivability is the main metric of this protocol. The protocol assumes that each node is addressable through a class-based addressing which includes the location and types of the nodes. The protocol initiates a connection through localized flooding, which is used to discover all routes between source/destination pair and their costs; thus building up the routing tables. The high-cost paths are discarded and a forwarding table is built by choosing neighboring nodes in a manner that is proportional to their cost. Then, forwarding tables are used to send data to the destination with a probability that is inversely proportional to the node cost. Localized flooding is performed by the destination node to keep the paths alive [9].

3.1.10 Routing Protocols with Random Walks

The objective of random walks based routing technique is to achieve load balancing in a statistical sense and by making use of multi-path routing in WSNs. This technique considers only large scale networks where nodes have very limited mobility. In this protocol, it is assumed that sensor nodes can be turned on or off at random times. Further, each node has a unique identifier but no location information is needed. Nodes were arranged such that each node falls exactly on one crossing point of a regular grid on a plane, but the topology can be irregular. To find a route from a source to its destination, the location information or lattice coordination is obtained by computing distances between nodes [10].

3.2 Hierarchical Routing

Hierarchical or cluster-based routing, originally proposed in wire line networks, are well-known techniques with special advantages related to scalability and efficient communication. As such, the concept of hierarchical routing is also utilized to perform energy-efficient routing in WSNs. In a hierarchical architecture, higher energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing in the proximity of the target. This means that 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 and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS.Hierarchical routing is mainly two-layer routing where one layer is used to select cluster heads and the other layer is used for routing.

3.2.1 LEACH protocol

The goal of LEACH is to find the way to low consumption of energy in the cluster and to improve the life time of the wireless sensor network. LEACH is a hierarchical protocol in which most nodes transmit to cluster heads, and the cluster heads aggregate and compress the data and forward it to the base station. Each node uses a stochastic algorithm at each round to determine whether it will become a cluster head in this round. LEACH assumes that each node has a radio powerful enough to directly reach the base station or the nearest cluster head, but that using this radio at full power all the time would waste energy. Nodes that have been cluster heads cannot become cluster heads again for P rounds, where P is the desired percentage of cluster heads. Thereafter, each node has a 1/P probability of becoming a cluster head in each round. At the end of each round, each node that is not a cluster head selects the closest cluster head and joins that cluster. The cluster head then creates a schedule for each node in its cluster to transmit its data. All nodes that are not cluster heads only communicate with the cluster head in a TDMA fashion, according to the schedule created by the cluster head. They do so using the minimum energy needed to reach the cluster head, and only need to keep their radios on during their time slot. LEACH also uses CDMA so that each cluster uses a different set of CDMA codes, to minimize interference between clusters.

LEACH is a cluster-based protocol, which includes distributed cluster formation. LEACH randomly selects a few sensor nodes as cluster heads (CHs) and rotates this role to evenly distribute the energy load among the sensors in the network. In LEACH, the cluster head (CH) nodes compress data arriving from nodes that belong to the respective cluster, and send an aggregated packet to the base station in order to reduce the amount of information that must be transmitted to the base station. LEACH uses a TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions. However, data collection is centralized and is performed periodically. Therefore, this protocol is most appropriate when there is a need for constant monitoring by the sensor network. A user may not need all the data immediately. Hence, periodic data transmissions are unnecessary which may drain the limited energy of the sensor nodes. After a given interval of time, a randomized rotation of the role of the CH is conducted so that uniform energy dissipation in the sensor network is obtained. 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 and CHs are selected. In the steady state phase, the actual data transfer to the base station takes place. The duration of the steady state phase is longer than the duration of the setup phase in order to minimize overhead [11].

3.2.2 Power-Efficient Gathering in Sensor Information Systems (PEGASIS)

PEGASIS (Power-Efficient Gathering in Sensor Information Systems), which is near optimal for this data gathering application in sensor networks. The key idea in PEGASIS is to form a chain among the sensor nodes so that each node will receive from and transmit to a close neighbor. Gathered data moves from node to node, get fused, and eventually a designated node transmits to the BS. Nodes take turns transmitting to the BS so that the average energy spent by each node per round is reduced. Building a chain to minimize the total length is similar to the travelling salesman problem, which is known to be intractable. However, with the radio communication energy parameters, a simple chain built with a greedy approach performs quite well. PEGASIS has two main objectives. First, increase the lifetime of each node by using collaborative techniques and as a result the network lifetime will be increased. Second, allow only local coordination between nodes that are close together so that the bandwidth consumed in communication is reduced [12].

3.2.3 Threshold-sensitive Energy Efficient Protocols (TEEN and APTEEN)

TEEN is a energy efficient hierarchical clustering protocol which is suitable for time critical applications.. The CH sends aggregated data to the next higher level CH until data reaches the sink. TEEN is designed for reactive networks, where the sensor nodes react immediately to sudden changes in the value of the sensed attribute. Sensor nodes sense the environment continuously, but data transmission is done occasionally and this helps in energy efficiency. This protocol sends data if the attribute of the sensor reaches a Hard Threshold and a small change the Soft Threshold. The drawback of this protocol is that if the threshold is not reached, the nodes may not communicate and. we do not know if a node is dead [13].

APTEEN is an improvement to TEEN and aims at periodic data collection and reacting to time critical events. It is a hybrid clustering based protocol and supports different types of queries like (i) historical query, to get results on past data (ii) one-time query that gives a snapshot of the environment and (iii) persistent queries, to monitor an event for a time period. The cluster exists for an interval called the cluster period, and then the BS re-groups clusters, at the cluster change time. For query responses it uses node pairs. If adjacent nodes sense similar data, only one of them responds to a query, the other one goes to sleep mode and thereby saves energy [14].

3.2.4 Minimum Energy Communication Network (MECN)

MECN is a location-based protocol for achieving minimum energy for randomly deployed networks, which uses mobile sensors to maintain a minimum energy network. It computes an optimal spanning tree with sink as root that contains only the minimum power paths from each sensor to the sink. This tree is called minimum power topology. It has two phases:

Enclosure Graph Construction: MECN constructs sparse graph, called a enclosure graph, based on the immediate locality of the sensors. An enclosure graph is a directed graph that includes all the sensors as its vertex set and edge set is the union of all edges between the sensors and its neighbours located in their enclosure regions.

Cost distribution: In this phase non-optimal links of the enclosure graphs are simply eliminated and the resulting graph is a minimum power topology. This graph has a directed path from each sensor to the sink and consumes the least total power among all graphs having directed paths from each sensor to the sink. Every sensor broadcasts its cost to its neighbours, where the cost of a node is the minimum power required for this sensor to establish a directed path to the sink [15].

3.2.5 Hierarchical Power-aware Routing (HPAR)

The protocol divides the network into groups of sensors. Each group of sensors in geo-graphic proximity is clustered together as a zone and each zone is treated as an entity. To perform routing, each zone is allowed to decide how it will route a message hierarchically across the other zones such that the battery lives of the nodes in the system are maximized. Messages are routed along the path which has the maximum over all the minimum of the remaining power, called the max-min path. The motivation is that using nodes with high residual power may be expensive as compared to the path with the minimal power consumption [16].

3.3 Location based routing protocols

In this kind of routing, sensor nodes are addressed by means of their locations. The distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors.

3.3.1 Geographic and Energy Aware Routing (GEAR)

The protocol, called Geographic and Energy Aware Routing (GEAR), uses energy aware and geographically-informed neighbor selection heuristics to route a packet towards the destination region. The key idea is to restrict the number of interests in directed diffusion by only considering a certain region rather than sending the interests to the whole network. By doing this, GEAR can conserve more energy than directed diffusion [17]. There are two cases to consider:

(a) When a closer neighbor to the destination exists:
GEAR picks a next-hop node among all neighbours that are closer to the destination.
(b) When all neighbors are further away:

In this case, there is a hole. GEAR picks a next-hop node that minimizes some cost value of this neighbor.

3.3.2 The Greedy Other Adaptive Face Routing (GOAFR)

GOAFR is a combination of greedy routing and face routing in the following sense: Whenever possible, the algorithm tries to route in a greedy manner; in order to overcome local minima with respect to the distance from the destination. GOAFR Algorithm is used in both average case and Worst case environments. This Algorithm provides good enough result for routing and it outperforms other routing algorithm such as AFR. GOAFR does guarantee the source to destination delivery of data [18].

3.3.3 SPAN

SPAN is a power saving technique for multi hop ad-hoc wireless networks that reduces energy consumption without significantly diminishing the capacity or connectivity of the network. It is a distributed, randomized algorithm where nodes make local decisions on whether to sleep, or to join forwarding backbones as a coordinator. Each node bases its decisions on an estimate of how many of its neighbors will benefit from it being awake and the amount of energy available to it.

To preserve capacity, a node decides to volunteer be a coordinator if it discovers that two of its neighbors cannot communicate with each other directly or through an existing coordinators low and rotate this role amongst all nodes, each node delays announcing its willingness with a random delay that takes two factors into account: the amount of remaining battery energy, and the number of pairs of neighbors it can connect together. This combination ensures with high probability, a capacity preserving connected backbone at any point in time, where nodes tend to consume energy at about the same rate. SPAN does all this using only local information consequently sending well with the number of nodes [19].

4. Routing Protocols based on Protocol Operation

In this section, routing protocols are described based on their routing functionalities. It should be noted that some of these protocols may fall below one or more of the above routing categories.

4.1 Multi path routing protocols

The fault tolerance (resilience) of a protocol is measured by the likelihood that an alternate path exists between a source and a destination when the primary path fails. This can be increased by maintaining multiple paths between the source and the destination at the expense of an increased energy consumption and traffic generation. These alternate paths are kept alive by sending periodic messages. Hence, network reliability can be increased at the expense of increased overhead of maintaining the alternate paths [20].

4.2 Query based routing

In this kind of routing, the destination nodes propagate a query for data (sensing task) from a node through the network and a node having this data sends the data which matches the query back to the node, which initiates the query [21].

4.3 Negotiation based routing protocols

These protocols use high level data descriptors in order to eliminate redundant data transmissions through negotiation. Communication decisions are also taken based on the resources that are available to them [22].

4.4 QoS-based routing

In sensor networks, nodes, as well as sink nodes, frequently change their position and due to the use of power management and energy efficient schemes a node state transition occurs, which leads to node failure, which makes QoS provisioning complex. In order to increase the lifetime of a network, the energy load must be evenly distributed among all sensor nodes so that the energy in a single sensor node or a small set of sensor nodes will not be drained too quickly. QoS support should take this factor into account [23]. In QoS-based routing protocols, the network has to balance between energy consumption and data quality. In particular, the network has to satisfy certain QoS metrics, e.g., delay, energy, bandwidth, etc. when delivering data to the BS.

5. Conclusion

Routing in sensor networks is a new area of research, with a limited, but rapidly growing set of research results. In this paper, comprehensive surveys of routing techniques in wireless sensor networks which have been presented in the literature were described. They have the common objective of trying to extend the lifetime of the sensor network, while not compromising data delivery. Overall, the routing techniques are classified based on the network structure into three categories: flat, hierarchical, and location based routing protocols. Furthermore, these protocols are classified into multipath-based, query-based, negotiation-based, or QoS-based routing techniques depending on the protocol operation. We also highlighted the design tradeoffs between energy and communication overhead savings in some of the routing paradigm, as well as the advantages and disadvantages of each routing technique.

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