Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2015, 2(6):62-69

Review Article ISSN: 2394 - 658X

Data Centric Routing Protocols in Wireless Sensor Networks: A Survey

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of small nodes with sensing, computation, and wireless communications capabilities. Many routing, power management, and data dissemination protocols have been specifically designed for Wireless Sensor Networks, where energy awareness is an essential design issue. The focus has been given to the routing protocols which might differ depending on the application and network architecture. In this paper, we present a survey of the state – of – the – art routing techniques in Wireless Sensor Networks. We first outline the design challenges for routing protocols in Wireless Sensor Networks followed by a comprehensive survey of different routing techniques. Overall, the routing techniques are classified into three categories based on the underlying network structure: Flat, Hierarchical, and Location – based routing. Furthermore, these protocols can be classified into multipath – based, query – based, negotiation – based, QoS – based, and coherent – based depending on the protocol operation. We study the design tradeoffs between energy and communication overhead savings in every routing paradigm. We also highlight the advantages and performance issues of each routing technique. The paper concludes with possible future research areas.

Key words: Sensor Network, Data centric protocols, Flooding, Gossiping, SPIN

INTRODUCTION

The emerging field of Wireless Sensor Networks combines sensing, computation and communication into a single tiny device. By the use of advanced mesh networking protocols, these devices form a sea of connectivity that extends the reach of the physical world. Wireless Sensor Networks refer to a group of spatially dispersed and dedicated sensors for monitoring and recording the physical conditions of the environment. They are also responsible for organizing the collected data at a central location. Wireless Sensor Networks measure environmental conditions like temperature, sound, pollution levels, humidity, wind speed and direction etc. A Wireless Sensor Network consists of hundreds to thousands of sensor nodes. The sensor node equipment includes a radio transceiver along with an antenna, a microcontroller, an interfacing electronic circuit, and an energy source, usually a battery.

The routing in a sensor network is very challenging due to several characteristics that distinguish them from Wireless Ad Hoc Networks. Number of sensor network can be several orders of magnitude higher than the node in adhoc network. Sensor networks are densely deployed as well as prone to failure. The topology of the sensor network changes frequently and it uses broadcast communication whereasadhoc networks use point – to – point communication. Sensor networks are limited in power computational capacities and memory as well as it does not have global identification (ID) because of the large amount of overhead and large number of sensors [1].The various areas in which sensor networks can be used as an application include -

- **Military Application:** Some examples of the possible utilizations of Wireless Sensor Networks for military application are position and movement control of troops and vehicles, target detection, non – human combat – area monitoring as well as landmine removal or building exploration.
- **Intelligent Housing:** Some examples of the possible usage of Wireless Sensor Networks include permitting houses to be equipped with movement, light and temperature sensors, microphones can be used for voice activation, pressure sensors can be incorporated in chairs for building automation. Others also include such as air temperatures, natural and artificial lighting can be tuned according to specific needs.

- **Machine Surveillance and Preventive Maintenance:** This can be performed by Embedded Sensing / Control functions into places where no cable has gone before. Example – tire pressure monitoring.
- **Precision Agriculture:** With the help of Wireless Sensor Networks, irrigation control and precise pesticide applications are possible on farmlands.
- **Medicine and Health Care:** It can be utilized in Post – operative / Intensive care or for long – term surveillance of chronically ill patients or the elderly [15].

ARCHITECTURE OF A WIRELESS SENSOR NETWORK

The architecture of a Wireless Sensor Network is shown in Fig. 1 [2].In a sensor field, the sensor nodes are scattered and deployed. The nodes in these networks manage amongst themselves to produce simply accessible and high – quality information about the physical environment. Every sensor node in these networks operates alone without any central point and communicates using infrared devices or radios. Each of these scattered sensor nodes has the capabilities to accumulate data and route the data back to the destination or sink. A destination or 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 take out information from the sensor network [3]. The data is routed back to the sink by a multi – hop infrastructure-less architecture through the sink as shown in Fig. 1. The sink may communicate with the satellite. The design of the senor network is influenced by many factors which include fault tolerance, scalability, production costs, hardware constraints, transmission media and power consumption [2-3].

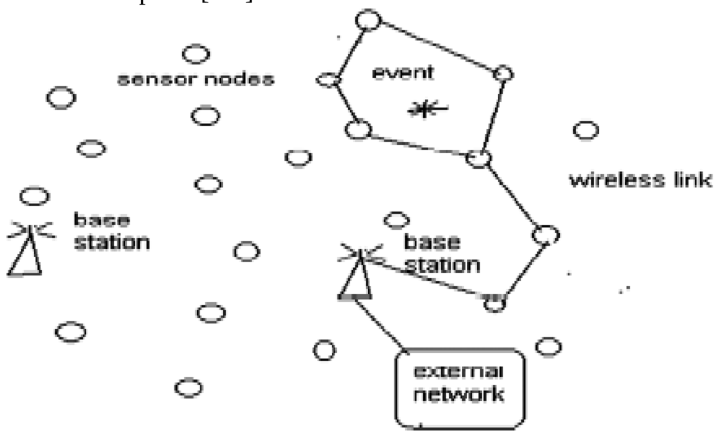

Fig. 1 Wireless Sensor Network

ROUTING CHALLENGES AND DESIGN ISSUES IN WIRELESS SENSOR NETWORKS

Despite the innumerable applications of Wireless Sensor Networks, these networks have several restrictions, e.g., limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. The main design goal of Wireless Sensor Networks is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. The design of the routing protocols in Wireless Sensor Networks is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved in Wireless Sensor Networks. Here, we summarize some of the routing challenges and design issues that affect the routing process in Wireless Sensor Networks.

Node Deployment

Node deployment in Wireless Sensor Networks is application dependent and affects the performance of the routing protocol. The deployment can be either deterministic or randomized. In deterministic deployment, the sensors are manually placed and data is routed through pre – determined paths. In random node deployment, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner. If the resultant distribution of nodes is not uniform, optimal clustering becomes necessary to allow connectivity and enable energy efficient network operation. The 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 can use their limited supply of energy performing computations and transmitting information in a wireless environment. As such, energy – conserving forms of communications and computations are essential. A Sensor Nodes lifetime shows a strong dependence on the battery lifetime [1]. In a multi – hop Wireless Sensor Networks, each node plays a dual role as data sender and data router. 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 Model

Data sensing and reporting in Wireless Sensor Networks is dependent on the application and the time criticality of the data reporting. Data reporting can be classified into time – driven (continuous), event – driven, query – driven, and hybrid [13]. The time – driven delivery model is suitable for applications that require periodic data monitoring. As such, sensor nodes will periodically switch on their sensors and transmitters, sense the environment and transmit the data of interest at constant periodic time intervals. In event – driven and query – driven models, the sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute due to the occurrence of a certain event or a query is generated by the Base Station. As such, these are well suited for time critical applications. A combination of the previous models is also possible. The routing protocol is highly influenced by the data reporting model with regard to energy consumption and route stability.

Node / Link Heterogeneity

It is assumed that all sensor nodes are homogeneous, i.e., having equal capacity in terms of computation, communication, and power. Depending on an application, a sensor node can have different role or capability. The existence of heterogeneous set of sensors raises many technical issues related to data routing. There are special sensors that can be either deployed independently or different functionalities can be included in the same sensor node. Even data reading and reporting can be generated from these sensors at different rates, subject to diverse quality of service constraints, and can follow multiple data reporting models.

Fault Tolerance

Some sensor nodes may fail or can be blocked due to the lack of power, physical damage, or environmental interference. The failure of the sensor nodes should not affect the overall task of the sensor network. If many nodes fail, Medium Access Control and the routing protocols must accommodate for the formation of new links and routes to the data collection base stations. This may require actively adjusting transmission powers and signalling rates on the existing links to reduce energy consumption, or re – routing packets through regions of the network where more energy is available. Hence, multiple levels of redundancy may be needed in a fault – tolerant sensor network.

Scalability

The number of sensor nodes deployed in the sensing area may be in the order of hundreds or thousands, or more. Any routing scheme must be able to work with this huge number of sensor nodes. In addition to this, sensor network routing protocols should be scalable enough to respond to events in the environment. Until an event occurs, most of the sensors remain in the sleep state, with data from the few remaining sensors providing a coarse quality.

Network Dynamics

Most of the network architectures assume that the sensor nodes are stationary. However, the mobility of either Base Station or sensor nodes is sometimes necessary in many applications [19]. Routing messages from or to a moving node is more challenging, since route stability becomes an important issue in addition to energy, bandwidth etc. The sensed phenomenon can be either dynamic or static depending on the application. It is dynamic in target detection / tracking application, while it is static in forest monitoring for early fire prevention. Monitoring static events allows the network to work in a reactive mode, simply generating traffic when reporting. Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the Base Station.

Transmission Media

In a multi – hop sensor network, the communicating nodes are linked by a wireless medium. The problems associated with a wireless channel such as fading, high error rate, may also affect the operation of the sensor network. The required bandwidth of sensor data will be low, in the order 1 – 100 Kbit/s, related to the transmission media is the design of Medium Access Control. One approach of MAC design for sensor networks is to use TDMA based protocols that conserve more energy as compared to contention based protocols like CSMA. Bluetooth technology can also be used.

Connectivity

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

Coverage

In Wireless Sensor Networks, each sensor node obtains certain view of the environment. A given sensor's view of the environment is limited both in range and in accuracy. It can only cover a limited physical area of the environment. Hence, area coverage is also an important design parameter in Wireless Sensor Networks.

Data Aggregation

Since the sensor nodes may generate significant redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions is reduced. 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. 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 beam forming to combine the incoming signals and reducing the noise in these signals.

Quality of Service

In some of the applications, data should be delivered within a certain period of time from the moment it is sensed; otherwise the data will be useless. Therefore, a bounded latency for data delivery is another condition for time – constrained applications. In many applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of data sent. 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 network lifetime. Hence, energy – aware routing protocols are required to capture this requirement.

ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS- DATA CENTRIC PROTOCOLS

In this section, a survey is done on the state – of – the – art routing protocols for Wireless Sensor Networks. The routing protocols in Wireless Sensor Networks can be classified into flat – based routing, hierarchical – based routing, and location – based routing, depending on the network structure.

- In flat – based routing, all nodes are assigned with equal roles or functionality.
- In hierarchical – based routing, nodes play different roles in the network.
- In location – based routing, sensor nodes' positions are exploited to route data in the network.

A routing protocol is adaptive, if certain system parameters can be controlled in order to adapt to the current network conditions and available energy levels. These protocols can be classified into multipath – based, query – based, negotiation – based, QoS – based, or coherent – based routing techniques depending on the protocol operation. In addition, the 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 routing protocols, all routes are computed before they are really needed. In reactive protocols, routes are computed on demand.

Hybrid protocols use the combination of two ideas. When sensor nodes are static, it is preferable to have table driven routing protocols rather than using reactive protocols. A significant amount of energy is used in route discovery and setup of reactive protocols. Another class of routing protocols is called cooperative routing protocols. In cooperative routing, the 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.

In Wireless Sensor Networks, data centric routing is used to control the redundancy of data. This is because the sensors nodes don not have global identification number which specifies them uniquely; hence data is transmitted to each node with significant redundancy. In data centric routing, the sink requests for data by sending the query, so that the nearest sensor node transmits the data selected and that is understood in the query. The property of data is specified by attribute based manning. The protocols used in data centric routing include: Flooding and Gossiping, Sensor Protocols for Information via Negotiation (SPIN), Directed Diffusion, Energy – aware routing, Rumor routing, Constrained Anisotropic Diffusion Routing (CADR), COUGAR, ACtiveQUery forwarding In sensoRnEtworks (ACQUIRE).

Flooding and Gossiping

These are the two mechanisms to transmit the data without using routing algorithms and topology maintenance. In Flooding Sensor node transmits the data to its entire neighbours till the packet reaches the destination [14]. Its advantage is easy to implement. Some of the limitations associated with flooding include Implosion Problem, Overlap Problem and Resource Blindness.

Implosion Problem

It is caused by duplicated messages being sent to its neighbour node as shown in Fig. 2 [1], [8]. Node A, starts by flooding its data to all of its neighbours. Node D gets two same copies of data eventually from Node B and Node C, which is not necessary.

Overlap Problem

The same event may be sensed by more than one node due to overlapping regions of coverage. This results in their neighbours receiving duplicate reports of the same event as shown in Fig. 3 [1], [8]. Two sensor nodes cover an overlapping geographic region and C gets the same copy of data from the nodes.

Resource Blindness

The flooding protocol does not consider the available energy at the nodes and results in many redundant transmissions. Hence, it reduces network lifetime.

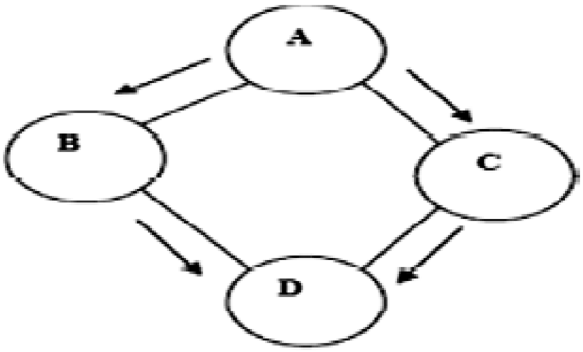

Fig. 2 Implosion problem

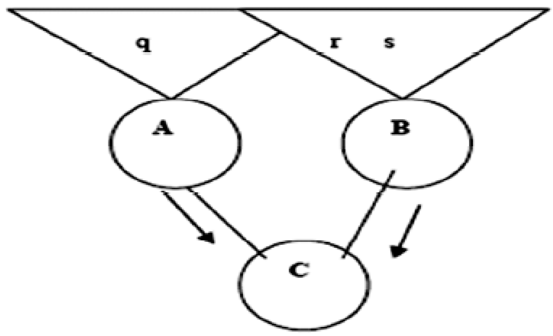

Fig. 3 Overlap problem

Gossiping

In this mechanism, a packet is sent to a randomly selected neighbour which then selects another random neighbour to forward the packet and so on. Its advantage is that it avoids the problem of implosion. However, this mechanism causes the problem of delay in propagation of data among the nodes.

Sensor Protocols for Information via Negotiation (SPIN)

The key feature of SPIN is that it uses advertisement mechanism. In this, the Meta data is exchanged among sensors. Each node on receiving new data advertises to its neighbours. The interested neighbours retrieve the data by sending request messages. The advantages of the SPIN include the nodes need to know only its single hop neighbours. It overcomes the problem of Resource Blindness and no redundant information passes thus achieving a lot of energy efficiency. The disadvantage of SPIN is that it does not guarantee the delivery of data i.e., if the destination node is far away from source node and intermediate nodes are not interested in data delivery to the destination node.

Directed Diffusion

The key features are named attribute value pairs and path reinforcement [4-5]. In this, the data is transmitted by using naming scheme for data. Direct diffusion uses the attribute value pairs for the data and on demand basis, queries the sensor using those pairs. The query is created using list of attribute value pairs such as name of objects, interval, duration, geographical area etc. Fig. 5 summarizes the data diffusion protocols. When a node known as the sink node wants information about a particular attribute, it broadcasts interest messages to all of its neighbours. These interest messages are flooding through the network and are added to each node's interest cache. Each interest record in this cache has one or more gradients which correspond to the neighbouring nodes that transmitted the interest. The gradient also stores the rate at which data is desired, the duration of the interest, and a timestamp. When a node generates data that matches an interest in its cache, it sends the data back to the source along the gradients. Intuitively, the data is drawn to the sink through the gradients. The sink node may reinforce the shortest path i.e., the one with the fastest response, by sending an interest with a higher data rate along that path. Intermediate nodes propagate the reinforcement by examining a local cache of recently sent data messages. The data cache also prevents loops in data delivery. Slower data paths may be sent negative reinforcement, i.e. interest messages with a slow data rate to save network bandwidth. If a sink wants to continue receiving data it must periodically reinforce the path to update the timestamp and duration in the gradients [6].

Energy – Aware Routing

Shah and Rabaey [12] proposed to use a set of sub – optimal paths to enhance the lifetime of the network. These paths are selected by means of a probability function, which depends on the energy consumption of each point. Multiple paths are used with a certain probability so that the whole network lifetime gets a chance and energy of the nodes doesn’t get depleted. There are three phases in this protocol namely setup phase, data communication phase and route maintenance phase.

Setup Phase

Localized flooding occurs to find the routes and to create the routing tables. This helps in calculating total energy cost of the node.

Data Communication Phase

Each node forwards the packet by randomly choosing a node from its forwarding table using the possibilities.

Route Maintenance Phase

Local flooding is performed uncommonly to keep all the paths active. The approach is similar to Directed Diffusion in the way that potential paths from data sources to the sink are discovered. In Directed Diffusion, data is sent through multiple paths, one of them being reinforced to send at higher rates. On the other hand, Shah and Rabaey, selects a single path haphazardly from the multiple alternatives in order to save energy. Therefore, when compared to Directed Diffusion, it provides an overall improvement of 21.5% energy saving and a 44% increase in network lifetime. This complicates the route setup as compared to Directed Diffusion.

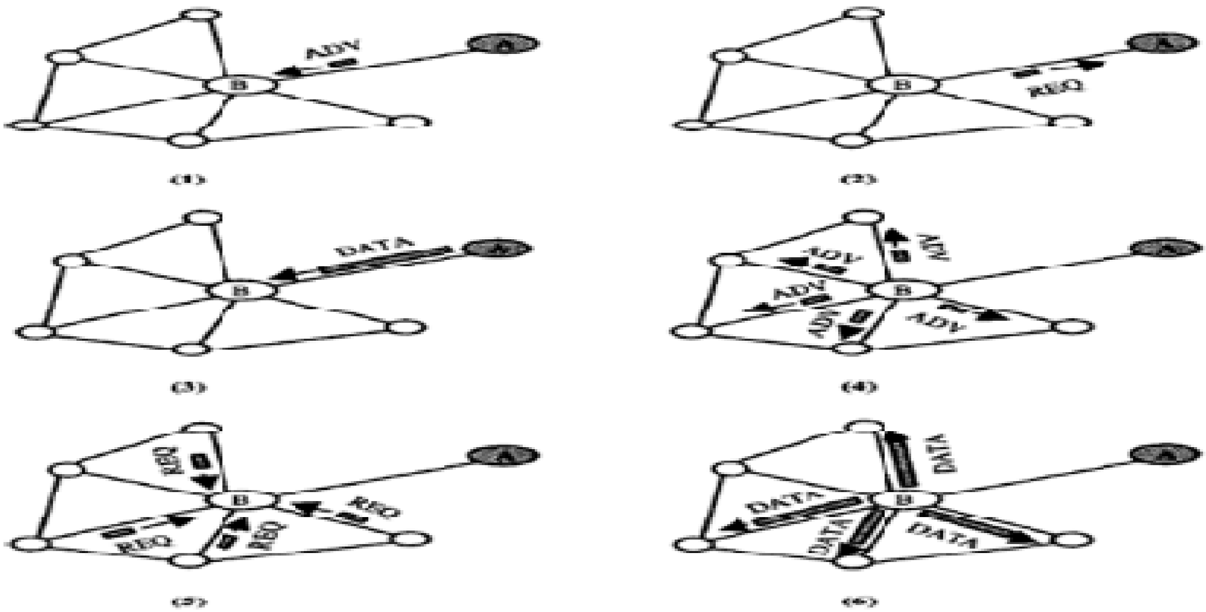

Fig.4 SPIN protocol (1) Node A starts advertising to node B by sending ADV message. (2) Node B responds to the ADV message by sending a REQ message to Node A. (3) Node B receives the requested data from Node A through the DATA message. (4) Node B then sends out ADV message to all its neighbours. (5) All the neighbouring nodes send REQ message to Node B. (6) Node B responds to the REQ message by sending data through DATA message

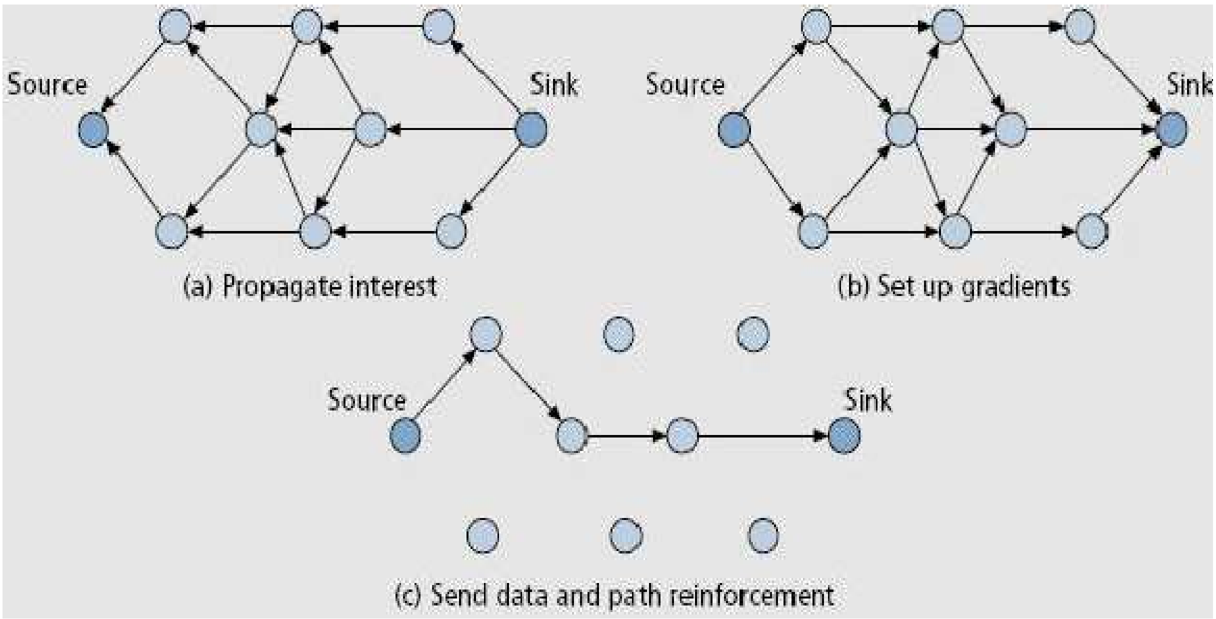

Fig. 5 Directed Diffusion protocols phases

Rumor Routing

It is an agent – based path creation algorithm. It is another variation of Directed Diffusion and is mainly intended for applications where geographic routing is not feasible. Directed Diffusion uses flooding to inject the query to the entire network when there is no geographic criterion to diffuse tasks. In some cases, there is only a little amount of data requested from the nodes and thus the use of flooding is unnecessary. An alternative approach is to flood the events if the number of events is small and the number of queries is large. The key idea is to route the queries to the nodes that have observed a particular event rather than flooding the entire network to retrieve information about the occurring events. In order to flood events through the network, the rumor routing algorithm employs long – lived packets, called agents. When a node detects an event, it adds such event to its local table, called events table, and generates an agent. The agents travel the network in order to propagate information about local events to distant nodes. When a node generates a query for an event, the nodes that know the route, may respond to the query by inspecting its event table. Thus, there is no need to flood the whole network, which reduces the communication cost. On the other hand, rumor routing maintains only one path between source and destination as opposed to Directed Diffusion, where data can be routed through multiple paths at low rates. Rumor routing achieves significant energy savings when compared to event flooding and can also handle node's failure. However, rumor routing performs well only when the number of events is small. For a large number of events, the cost of maintaining agents and event – tables in each node becomes infeasible if there is not enough interest in these events from the Base Station. Moreover, the overhead associated with rumor routing is controlled by different parameters used in the algorithm such as time – to – live (TTL) pertaining to queries and agents. Since the nodes become aware of events through the event agents, the heuristic for defining the route of an event agent highly affects the performance of next hop selection in rumor routing.

Constrained Anisotropic Diffusion Routing (CADR)

It aims to be a general form of Directed Diffusion. The key idea is to query sensors and route data in the network such that the information gain is maximized while latency and bandwidth are minimized. CADR dif- fuses queries by using a set of information criteria to select which sensors can get the data. This is achieved by activating only the sensors that are close to a particular event and dynamically adjusting the data routes. The main difference from Directed Diffusion is the consideration of information gain in addition to the communication cost. In CADR, each node evaluates an information / cost objective and routes data based on the local information / cost gradient and end – user requirements. Estimation theory is used to model information utility measure. These approaches are more energy – efficient than Directed Diffusion where the queries are diffused in an isotropic fashion and reaching nearest neighbours first.

COUGAR

Another data – centric protocol called COUGAR [13] which views the network as a huge distributed database system. The key idea is to use declarative queries in order to abstract query processing from the network layer functions such as selection of relevant sensors and so on. 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 Base Station. The Base Station 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 provided a network – layer independent method for data query. COUGAR has some drawbacks.

The addition of query layer on each sensor node may add an extra overhead in terms of energy consumption and memory storage. To obtain successful in – network data computation, synchronization among nodes is required (not all data are received at the same time from incoming sources) before sending the data to the leader node. The leader nodes should be dynamically maintained to prevent them from being hot – spots (failureprone).

ACtiveQUery forwarding InsensoR nEtworks(ACQUIRE)

Similar to COUGAR, ACQUIRE views the network as a distributed database where complex queries can be further divided into several sub queries. The operation of ACQUIRE can be described as follows. The Base Station 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. If the pre – cached information is not up – to – date, the nodes gather information from their neighbours within a look – ahead of d hops. Once the query is being resolved completely, it is sent back through either the reverse or shortest – path to the Base Station. Thus, ACQUIRE can deal with complex queries by allowing many nodes to send responses. Directed Diffusion may not be used for complex queries due to energy considerations as Directed Diffusion also uses flooding – based query mechanism for continuous and aggregate queries. On the other hand, ACQUIRE can provide efficient querying by adjusting the value of the look – ahead parameter d. When d is equal to network diameter, ACQUIRE mechanism behaves similar to flooding. However, the query has to travel more hops, if d is too small. To select the next node for forwarding the query, ACQUIRE either picks it randomly or the selection is based on maximum potential of query satisfaction. The selection of next node is based on either information gain (CADR and IDSQ) or query is forwarded to a node, which knows the path to the searched event (Rumor routing).

CONCLUSION

Routing in sensor networks is a new area of research, with a limited, but rapidly growing set of research results. In this paper, we presented a comprehensive survey of routing techniques in Wireless Sensor Networks which have been presented in the literature. 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 highlight 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. Although many of these routing techniques look promising, there are still many challenges that need to be solved in the sensor networks. We highlighted those challenges and pin – pointed future research directions in this regard.

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