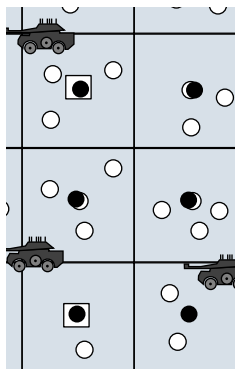


ROUTING TECHNIQUES IN WIRELESS SENSOR NETWORKS: A SURVEY

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WSNs consist of small nodes with sensing, computation, and wireless communications capabilities. Many protocols have been specifically designed for WSNs where energy awareness is an essential design issue.

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¹ In this article, we consider routing toward a BS only.

ABSTRACT

Wireless sensor networks consist of small nodes with sensing, computation, and wireless communications capabilities. Many routing, power management, and data dissemination protocols have been specifically designed for WSNs where energy awareness is an essential design issue. Routing protocols in WSNs might differ depending on the application and network architecture. In this article we present a survey of state-of-the-art routing techniques in WSNs. We first outline the design challenges for routing protocols in WSNs followed by a comprehensive survey of 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 trade-offs between energy and communication overhead savings in every routing paradigm. We also highlight the advantages and performance issues of each routing technique. The article concludes with possible future research areas.

INTRODUCTION

Due to recent technological advances, the manufacturing of small and low-cost sensors has become technically and economically feasible. These sensors measure ambient conditions in the environment surrounding them and then transform these measurements into signals that can be processed to reveal some characteristics about phenomena located in the area around these sensors. A large number of these sensors can be networked in many applications that require unattended operations, hence producing a wireless sensor network (WSN). In fact, the applications of WSNs are quite numerous. For example, WSNs have profound effects on military and civil applications such as target field imaging, intrusion detection, weather monitoring, security and tactical surveillance, distributed computing, detecting ambient conditions such as temperature, movement, sound, light, or the

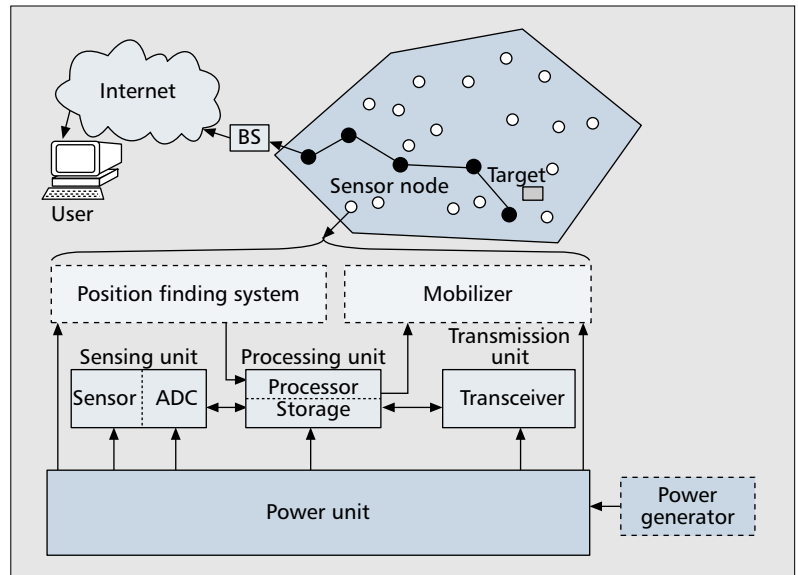
presence of certain objects, inventory control, and disaster management. Deployment of a sensor network in these applications can be in random fashion (e.g., dropped from an airplane in a disaster management application) or manual (e.g., fire alarm sensors in a facility or sensors planted underground for precision agriculture). Creating a network of these sensors can assist rescue operations by locating survivors, identifying risky areas, and making the rescue team more aware of the overall situation in a disaster area.

Typically, WSNs contain hundreds or thousands of these sensor nodes, and these sensors have the ability to communicate either among each other or directly to an external base station (BS). A greater number of sensors allows for sensing over larger geographical regions with greater accuracy. Figure 1 shows a schematic diagram of sensor node components. Basically, each sensor node comprises sensing, processing, transmission, mobilizer, position finding system, and power units (some of these components are optional, like the mobilizer). The same figure shows the communication architecture of a WSN. Sensor nodes are usually scattered in a sensor field, which is an area where the sensor nodes are deployed. Sensor nodes coordinate among themselves to produce high-quality information about the physical environment. Each sensor node bases its decisions on its mission, the information it currently has, and its knowledge of its computing, communication, and energy resources. Each of these scattered sensor nodes has the capability to collect and route data either to other sensors or back to an external BS(s).¹ A BS may be a fixed or mobile node capable of connecting the sensor network to an existing communications infrastructure or to the Internet where a user can have access to the reported data.

In the past few years, intensive research that addresses the potential of collaboration among sensors in data gathering and processing, and coordination and management of the sensing activity was conducted. In most applications, sensor nodes are constrained in energy supply and communication bandwidth. Thus, innovative techniques to eliminate energy inefficiencies that shorten the lifetime of the network and efficient

use of the limited bandwidth are highly required. Such constraints combined with a typical deployment of large number of sensor nodes pose many challenges to the design and management of WSNs and necessitate energy-awareness at all layers of the networking protocol stack. For example, at the network layer, it is highly desirable to find methods for energy-efficient route discovery and relaying of data from the sensor nodes to the BS so that the lifetime of the network is maximized.

Routing in WSNs is very challenging due to the inherent characteristics that distinguish these networks from other wireless networks like mobile ad hoc networks or cellular networks. First, due to the relatively large number of sensor nodes, it is not possible to build a global addressing scheme for the deployment of a large number of sensor nodes as the overhead of ID maintenance is high. Thus, traditional IP-based protocols may not be applied to WSNs. Furthermore, sensor nodes that are deployed in an ad hoc manner need to be self-organizing as the ad hoc deployment of these nodes requires the system to form connections and cope with the resultant nodal distribution, especially as the operation of sensor networks is unattended. In WSNs, sometimes getting the data is more important than knowing the IDs of which nodes sent the data. Second, in contrast to typical communication networks, almost all applications of sensor networks require the flow of sensed data from multiple sources to a particular BS. This, however, does not prevent the flow of data to be in other forms (e.g., multicast or peer to peer). Third, sensor nodes are tightly constrained in terms of energy, processing, and storage capacities. Thus, they require careful resource management. Fourth, in most application scenarios, nodes in WSNs are generally stationary after deployment except for maybe a few mobile nodes. Nodes in other traditional wireless networks are free to move, which results in unpredictable and frequent topological changes. However, in some applications, some sensor nodes may be allowed to move and change their location (although with very low mobility). Fifth, sensor networks are application-specific (i.e., design requirements of a sensor network change with application). For example, the challenging problem of low-latency precision tactical surveillance is different from that of a periodic weather monitoring task. Sixth, position awareness of sensor nodes is important since data collection is normally based on the location. Currently, it is not feasible to use Global Positioning System (GPS) hardware for this purpose. Methods based on triangulation [1], for example, allow sensor nodes to approximate their position using radio strength from a few known points. It is found in [1] that algorithms based on triangulation or multilateration can work quite well under conditions where only very few nodes know their positions a priori (e.g., using GPS hardware). Still, it is favorable to have GPS-free solutions [2] for the location problem in WSNs. Finally, data collected by many sensors in WSNs is typically based on common phenomena, so there is a high probability that this data has some redundancy. Such redundancy needs to be exploited by the



■ Figure 1. The components of a sensor node.

routing protocols to improve energy and bandwidth utilization. Usually, WSNs are *data-centric* networks in the sense that data is requested based on certain attributes (i.e., attribute-based addressing). An attribute-based address is composed of a set of attribute-value pair query. For example, if the query is something like [temperature > 60°F], sensor nodes that sense temperature > 60°F only need to respond and report their readings.

Due to such differences, many new algorithms have been proposed for the routing problem in WSNs. These routing mechanisms have taken into consideration the inherent features of WSNs along with the application and architecture requirements. The task of finding and maintaining routes in WSNs is nontrivial since energy restrictions and sudden changes in node status (e.g., failure) cause frequent and unpredictable topological changes. To minimize energy consumption, routing techniques proposed in the literature for WSNs employ some well-known routing tactics as well as tactics special to WSNs, such as data aggregation and in-network processing, clustering, different node role assignment, and data-centric methods. Almost all of the routing protocols can be classified according to the *network structure* as flat, hierarchical, or location-based. Furthermore, these protocols can be classified into multipath-based, query-based, negotiation-based, quality of service (QoS)-based, and coherent-based depending on the *protocol operation*. In flat networks all nodes play the same role, while hierarchical protocols aim to cluster the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy. Location-based protocols utilize position information to relay the data to the desired regions rather than the whole network. The last category includes routing approaches based on protocol operation, which vary according to the approach used in the protocol. In this article we explore these routing techniques in WSNs that have been developed in recent years and develop a classification for these protocols.

One of the main design goals of WSNs 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.

Then we discuss each of the routing protocols under this classification. Our objective is to provide deeper understanding of the current routing protocols in WSNs and identify some open research issues that can be further pursued.

Although there are some previous efforts on surveying the characteristics, applications, and communication protocols in WSNs [3, 4], the scope of the survey presented in this article is distinguished from these surveys in many aspects. The surveys in [3, 4] addressed several design issues and techniques for WSNs describing the physical constraints on sensor nodes, applications, architectural attributes, and the protocols proposed in all layers of the network stack. However, these surveys were not devoted to routing only. Due to the importance of routing in WSNs and the availability of a significant body of literature on this topic, a detailed survey becomes necessary and useful at this stage. Our work is a dedicated study of the network layer, describing and categorizing the different approaches to data routing. In addition, we summarize routing challenges and design issues that may affect the performance of routing protocols in WSNs. The rest of this article is organized as follows. We discuss routing challenges and design issues in WSNs. A classification and comprehensive survey of routing techniques in WSNs is presented. A summary of future research directions on routing in WSNs is discussed. We then conclude with final remarks.

ROUTING CHALLENGES AND DESIGN ISSUES IN WSNs

Despite the innumerable applications of WSNs, these networks have several restrictions, such as limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. One of the main design goals of WSNs 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 routing protocols in WSNs is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved in WSNs. In the following, we summarize some of the routing challenges and design issues that affect the routing process in WSNs.

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

Energy consumption without losing accuracy: Sensor nodes can use up their limited supply of

energy performing computations and transmitting information in a wireless environment. As such, energy-conserving forms of communication and computation are essential. Sensor node lifetime shows a strong dependence on battery lifetime [5]. In a multihop WSN, 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 method: Data reporting in WSNs is application-dependent and also depends on the time criticality of the data. Data reporting can be categorized as either time-driven, event-driven, query-driven, or a hybrid of all these methods. The time-driven delivery method 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 methods, sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute due to the occurrence of a certain event, or respond to a query generated by the BS or another node in the network. As such, these are well suited to time-critical applications. A combination of the previous methods is also possible. The routing protocol is highly influenced by the data reporting method in terms of energy consumption and route calculations.

Node/link heterogeneity: In many studies, all sensor nodes were assumed to be homogeneous (i.e., have equal capacity in terms of computation, communication, and power). However, depending on the application a sensor node can have a different role or capability. The existence of a heterogeneous set of sensors raises many technical issues related to data routing. For example, some applications might require a diverse mixture of sensors for monitoring temperature, pressure, and humidity of the surrounding environment, detecting motion via acoustic signatures, and capturing images or video tracking of moving objects. Either these special sensors can be deployed independently or the different functionalities can be included in the same sensor nodes. Even data reading and reporting can be generated from these sensors at different rates, subject to diverse QoS constraints, and can follow multiple data reporting models. For example, hierarchical protocols designate a cluster head node different from the normal sensors. These cluster heads can be chosen from the deployed sensors or be more powerful than other sensor nodes in terms of energy, bandwidth, and memory. Hence, the burden of transmission to the BS is handled by the set of cluster heads.

Fault tolerance: Some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, medium access control (MAC) and routing protocols must accommodate formation of new links and routes to the data collection BSs. This may require actively adjusting transmit powers

and signaling rates on the existing links to reduce energy consumption, or rerouting packets through regions of the network where more energy is available. Therefore, multiple levels of redundancy may be needed in a fault-tolerant sensor network.

Scalability: The number of sensor nodes deployed in the sensing area may be on 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, sensor network routing protocols should be scalable enough to respond to events in the environment. Until an event occurs, most sensors can remain in the sleep state, with data from the few remaining sensors providing coarse quality.

Network dynamics: In many studies, sensor nodes are assumed fixed. However, in many applications both the BS or sensor nodes can be mobile [6]. As such, routing messages from or to moving nodes is more challenging since route and topology stability become important issues, in addition to energy, bandwidth, and so forth. Moreover, the phenomenon can be mobile (e.g., a target detection/ tracking application). On the other hand, sensing fixed events allows the network to work in a reactive mode (i.e., generating traffic when reporting), while dynamic events in most applications require periodic reporting to the BS.

Transmission media: In a multihop sensor network, communicating nodes are linked by a wireless medium. The traditional problems associated with a wireless channel (e.g., fading, high error rate) may also affect the operation of the sensor network. In general, the required bandwidth of sensor data will be low, on the order of 1–100 kb/s. Related to the transmission media is the design of MAC. One approach to MAC design for sensor networks is to use time-division multiple access (TDMA)-based protocols that conserve more energy than contention-based protocols like carrier sense multiple access (CSMA) (e.g., IEEE 802.11). Bluetooth technology [7] 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, however, may not prevent the network topology from being variable and the network size from shrinking due to sensor node failures. In addition, connectivity depends on the possibly random distribution of nodes.

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

Data aggregation: Since sensor nodes may generate significant redundant data, similar packets from multiple nodes can be aggregated to reduce the number of transmissions. 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 trans-

fer optimization in a number of routing protocols. Signal processing methods can also be used for data aggregation. In this case, it is referred to as *data fusion* where a node is capable of producing a more accurate output signal by using some techniques such as beamforming to combine the incoming signals and reducing the noise in these signals.

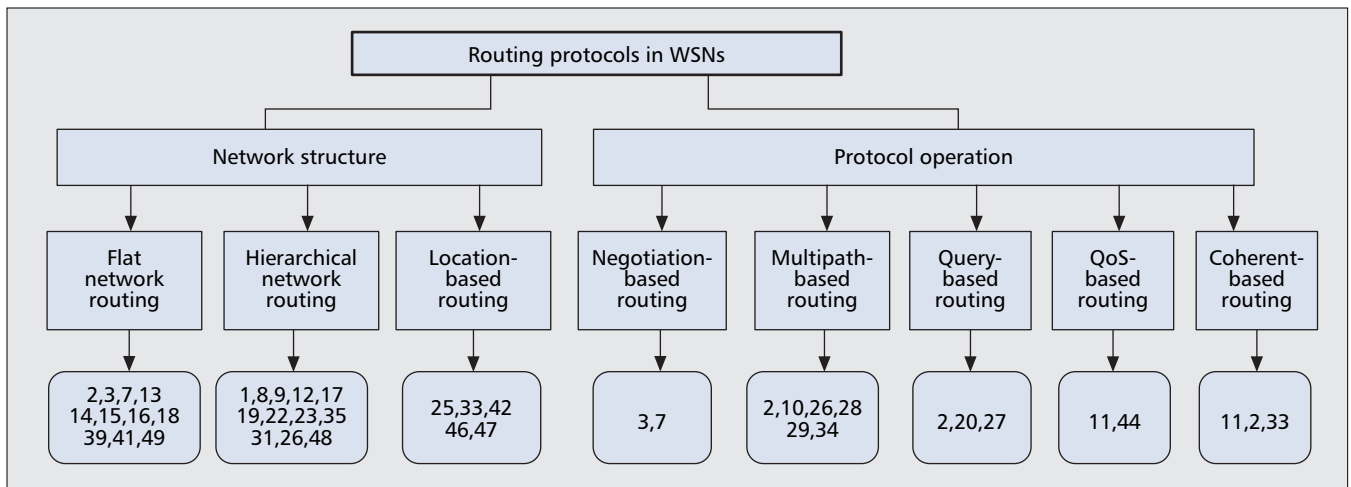
Quality of service: In some applications, data should be delivered within a certain period of time from the moment it is sensed, or it will be useless. Therefore, bounded latency for data delivery is another condition for time-constrained applications. However, in many applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of data sent. As energy is depleted, the network may be required to reduce the quality of results in order to reduce 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 WSNs

In this section we survey the state-of-the-art routing protocols for WSNs. 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, nodes will 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 considered adaptive if certain system parameters can be controlled in order to adapt to current network conditions and available energy levels. Furthermore, these protocols can be classified into *multipath-based*, *query-based*, and *negotiation-based*, *QoS-based*, or *coherent-based* routing techniques depending on the protocol operation. In addition to the above, routing protocols can be classified into three categories, proactive, reactive, and hybrid, 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. When sensor nodes are static, it is preferable to have table-driven routing protocols rather than 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*. 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. We also shed some light on these types of protocols in this article. In order to streamline this survey, we use a classification according to the network structure and protocol operation (routing criteria). The classification is shown in Fig. 2 where numbers in the future indicate the references.

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■ **Figure 2.** Routing protocols in WSNs: a taxonomy.

detailed overview of the main routing paradigms in WSNs. We start with network-structure-based protocols.

NETWORK-STRUCTURE-BASED PROTOCOLS

The underlying network structure can play a significant role in the operation of the routing protocol in WSNs. In this section we survey in detail most of the protocols that fall into this category.

Flat Routing — The first category of routing protocols are the multihop flat routing protocols. In flat networks, each node typically plays the same role and sensor nodes collaborate 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. This consideration has led to data-centric routing, where the BS sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data. Early work on data centric routing (e.g., SPIN and directed diffusion [8]) were shown to save energy through data negotiation and elimination of redundant data. These two protocols motivated the design of many other protocols that follow a similar concept. In the rest of this subsection, we summarize these protocols, and highlight their advantages and performance issues.

Sensor Protocols for Information via Negotiation: Heinzelman *et al.* in [9, 10] proposed a family of adaptive protocols called Sensor Protocols for Information via Negotiation (SPIN) that disseminate all the information at each node to every node in the network assuming that all nodes in the network are potential BSs. 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 other nodes do not possess. 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 metadata negoti-

ations before any data is transmitted. This ensures that there is no redundant data sent throughout the network. The semantics of the meta-data format is application-specific and not specified in SPIN. For example, sensors might use their unique IDs to report meta-data if they cover a certain known region. In addition, SPIN has access to the current energy level of the node and adapts the protocol it is running based on how much energy is remaining. 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.

The SPIN family is designed to address the deficiencies of classic flooding by negotiation and resource adaptation. The SPIN family of protocols is designed based on two basic ideas:

1) Sensor nodes operate more efficiently and conserve energy by sending data that describe the sensor data instead of sending all the data; for example, image and sensor nodes must monitor the changes in their energy resources.

2) Conventional protocols like flooding or gossiping-based routing protocols [11] waste energy and bandwidth when sending extra and unnecessary copies of data by sensors covering overlapping areas. The drawbacks of flooding include implosion, which is caused by duplicate messages sent to the same node, overlap when two nodes sensing the same region send similar packets to the same neighbor, and resource blindness in consuming large amounts of energy without consideration for energy constraints. Gossiping avoids the problem of implosion by just selecting a random node to which to send the packet rather than broadcasting the packet blindly. However, this causes delays in propagation of data through the nodes.

SPIN's meta-data negotiation solves the classic problems of flooding, thus achieving a lot of energy efficiency. SPIN is a three-stage protocol as sensor nodes use three types of messages, ADV, REQ, and DATA, to communicate. ADV is used to advertise new data, REQ to request data, and DATA is the actual message itself. The protocol starts when a SPIN node obtains new data 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 a REQ message for the DATA and the DATA is sent to this neighbor node. The neighbor sensor node then repeats this process with its neighbors. As a result, the entire sensor area will receive a copy of the data.

The SPIN family of protocols includes many protocols. The main two are called SPIN-1 and SPIN-2; they incorporate negotiation before transmitting data in order to ensure that only useful information will be transferred. Also, each node has its own resource manager that keeps track of resource consumption and is polled by the nodes before data transmission. The SPIN-1 protocol is a three-stage protocol, as described above. An extension to SPIN-1 is SPIN-2, which incorporates a threshold-based resource awareness mechanism in addition to negotiation. When energy in the nodes is abundant, SPIN-2 communicates using the three-stage protocol of SPIN1. However, when the energy in a node starts approaching a low threshold, it reduces its participation in the protocol; that is, it participates only when it believes it can complete all the other stages of the protocol without going below the low energy threshold. In conclusion, SPIN-1 and SPIN-2 are simple protocols that efficiently disseminate data while maintaining no per-neighbor state. These protocols are well suited to an environment where the sensors are mobile because they base their forwarding decisions on local neighborhood information. Other protocols of the SPIN family are (please refer to [3, 7] for more details):

- SPIN-BC: This protocol is designed for broadcast channels.
- SPIN-PP: This protocol is designed for point-to-point communication (i.e., hop-by-hop routing).
- SPIN-EC: This protocol works similar to SPIN-PP, but with an energy heuristic added to it.
- SPIN-RL: When a channel is lossy, a protocol called SPIN-RL is used where adjustments are added to the SPIN-PP protocol to account for the lossy channel.

One of the advantages of SPIN is that topological changes are localized since each node need know only its single-hop neighbors. SPIN provides more energy savings than flooding, and metadata negotiation almost halves the redundant data. However, SPIN's data advertisement mechanism cannot guarantee delivery of data. To see this, consider the application of intrusion detection where data should be reliably reported over periodic intervals, and assume that nodes interested in the data are located far away from the source node, and the nodes between source and destination nodes are not interested in that data; such data will not be delivered to the destination at all.

Directed diffusion: In [12], C. Intanagonwatt *et al.* proposed a popular data aggregation paradigm for WSNs called directed diffusion. Directed diffusion is a data-centric (DC) and application-aware paradigm in the sense that all data generated by sensor nodes is named by attribute-value pairs. The main idea of the DC paradigm is to combine the data coming from different sources en route (in-network aggrega-

tion) by eliminating redundancy, minimizing the number of transmissions, thus saving network energy and prolonging its lifetime. Unlike traditional end-to-end routing, DC routing finds routes from multiple sources to a single destination that allows in-network consolidation of redundant data.

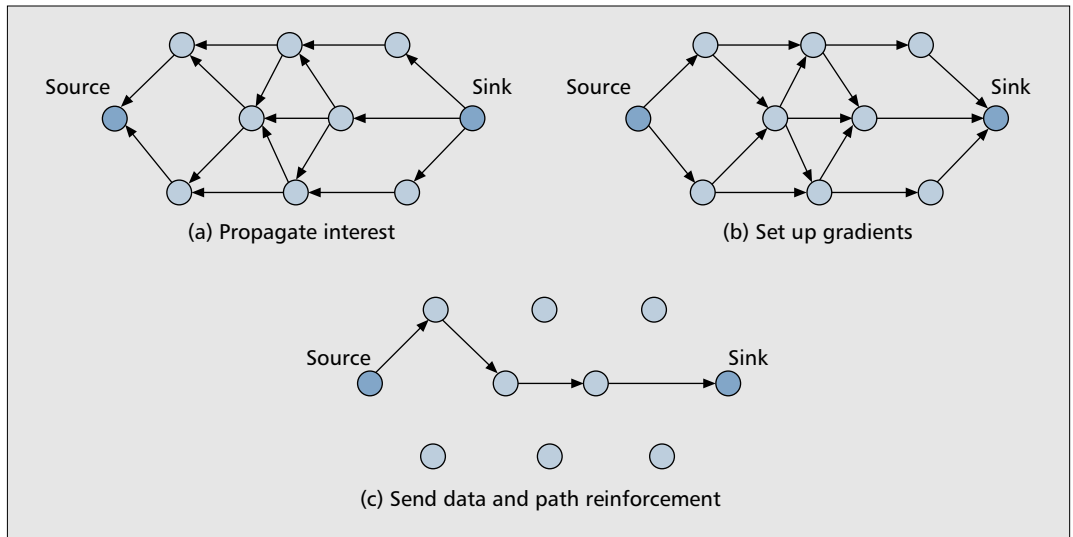
In directed diffusion, sensors measure events and create gradients of information in their respective neighborhoods. The BS requests data by broadcasting interests. An interest describes a task required to be done by the network. An interest diffuses through the network hop by hop, and is broadcast by each node to its neighbors. As the interest is propagated throughout the network, gradients are set up to draw data satisfying the query toward the requesting node (i.e., a BS may query for data by disseminating interests and intermediate nodes propagate these interests). Each sensor that receives the interest sets up a gradient toward the sensor nodes from which it receives the interest. This process continues until gradients are set up from the sources back to the BS. More generally, a gradient specifies an attribute value and a direction. The strength of the gradient may be different toward different neighbors, resulting in different amounts of information flow. At this stage, loops are not checked, but are removed at a later stage. Figure 3 shows an example of the working of directed diffusion (sending interests, building gradients, and data dissemination). When interests fit gradients, paths of information flow are formed from multiple paths, and then the best paths are reinforced to prevent further flooding according to a local rule. In order to reduce communication costs, data is aggregated on the way. The goal is to find a good aggregation tree that gets the data from source nodes to the BS. The BS periodically refreshes and resends the interest when it starts to receive data from the source(s). This is necessary because interests are not reliably transmitted throughout the network.

All sensor 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. Caching can increase the efficiency, robustness, and scalability of coordination between sensor nodes, which is the essence of the data diffusion paradigm. Other usage of directed diffusion is to spontaneously propagate an important event to some sections of the sensor network. Such a type of information retrieval is well suited only to persistent queries where requesting nodes are not expecting data that satisfy a query for a duration of time. This makes it unsuitable for one-time queries, as it is not worth setting up gradients for queries that use the path only once.

The performance of data aggregation methods used in the directed diffusion paradigm is affected by a number of factors, including the positions of the source nodes in the network, the number of sources, and the communication network topology. In order to investigate these factors, two models of source placement (shown in Fig. 4) were studied in [12]. These models are called the event radius (ER) model and the ran-

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The energy savings with aggregation used in the directed diffusion can be transformed to provide a greater degree of robustness with respect to dynamics in the sensed phenomena.



■ **Figure 3.** An example of interest diffusion in a sensor network.

dom sources (RS) model. In the ER model, a single point in the network area is defined as the location of an event. This may correspond to a vehicle or some other phenomenon being tracked by the sensor nodes. All nodes within a distance S (called the sensing range) of this event that are not BSs are considered to be data sources. The average number of sources is approximately $\pi S^2 n$ in a unit area network with n sensor nodes. In the RS model, k of the nodes that are not BSs are randomly selected to be sources. Unlike the ER model, the sources are not necessarily clustered near each other. In both models of source placement, for a given energy budget, a greater number of sources can be connected to the BS. However, each one performs better in terms of energy consumption depending on the application. In conclusion, the energy savings with aggregation used in directed diffusion can be transformed to provide a greater degree of robustness with respect to dynamics in the sensed phenomena.

Directed diffusion differs from SPIN in two aspects. First, directed diffusion issues data queries on demand as the BS sends queries to the sensor nodes by flooding some tasks. In SPIN, however, sensors advertise the availability of data, allowing interested nodes to query that data. Second, all communication in directed diffusion is neighbor to neighbor with each node having the capability to perform data aggregation and caching. Unlike SPIN, there is no need to maintain global network topology in directed diffusion. However, directed diffusion may not be applied to applications (e.g., environmental monitoring) that require continuous data delivery to the BS. This is because the query-driven on-demand data model may not help in this regard. Moreover, matching data to queries might require some extra overhead at the sensor nodes.

Rumor routing: Rumor routing [13] is a variation of directed diffusion and is mainly intended for applications where geographic routing is not feasible. In general, directed diffusion uses flooding to inject the query to the entire network when there is no geographic criterion to

diffuse tasks. However, in some cases there is only a small amount of data requested from the nodes; 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 the event to its local table, called an *events table*, and generates an agent. 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. Hence, 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. Simulation results showed that rumor routing can achieve significant energy savings compared to event flooding and can also handle a 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 BS. 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.

Minimum Cost Forwarding Algorithm: The Minimum Cost Forwarding Algorithm (MCFA) [8] exploits the fact that the direction of routing is always known (i.e., toward the fixed external BS). Hence, a sensor node need not have a

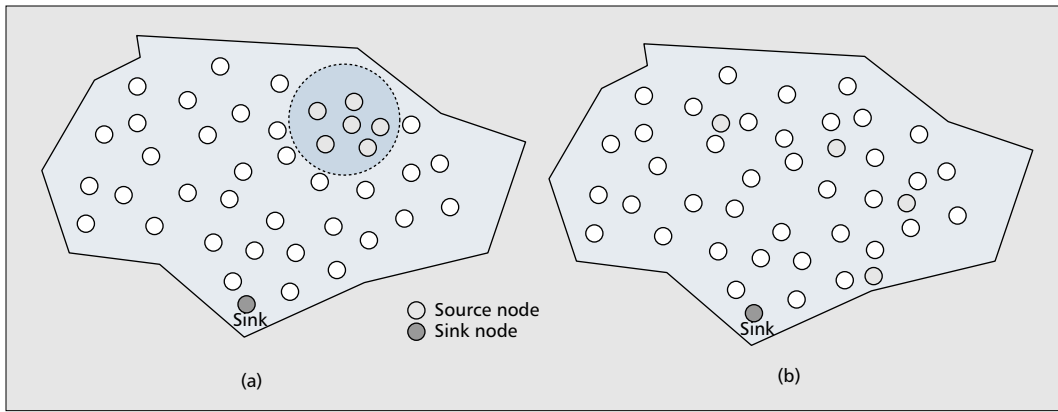


Figure 4. Two models used in a data-centric routing paradigm such as directed diffusion: a) event radius model; b) random source model.

unique ID nor maintain a routing table. Instead, each node maintains the least cost estimate from itself to the BS. Each message to be forwarded by the sensor node is broadcast to its neighbors. When a node receives the message, it checks if it is on the least cost path between the source sensor node and the BS. If this is the case, it rebroadcasts the message to its neighbors. This process repeats until the BS is reached.

In MCFA, each node should know the least cost path estimate from itself to the BS. This is obtained as follows. The BS broadcasts a message with the cost set to zero, while every node initially sets its least cost to the BS to infinity (∞). Each node, upon receiving the broadcast message originated at the BS, checks to see if the estimate in the message plus the link on which it is received is less than the current estimate. If yes, the current estimate and the estimate in the broadcast message are updated. If the received broadcast message is updated, it is resent; otherwise, it is purged and nothing further is done. However, the previous procedure may result in some nodes having multiple updates, and those nodes far away from the BS will get more updates from those closer to the BS. To avoid this, MCFA was modified to run a backoff algorithm at the setup phase. The backoff algorithm dictates that a node will not send the updated message until $a * l_c$ time units have elapsed from the time at which the message is updated, where a is a constant and l_c is the link cost at which the message was received.

Gradient-based routing: Schurgers *et al.* [14] proposed another variant of directed diffusion, called gradient-based routing (GBR). 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:

- A stochastic scheme, where a node picks one gradient at random when there are two or more next hops that have the same gradient
- An 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
- A 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 balanced distribution of the traffic in the network, thus increasing the network lifetime. Simulation results of GBR showed that GBR outperforms directed diffusion in terms of total communication energy.

Information-driven sensor querying and constrained anisotropic diffusion routing: Two routing techniques, information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR), were proposed in [15]. CADR aims to be a general form of directed diffusion. The key idea is to query sensors and route data in the network such that information gain is maximized while latency and bandwidth are minimized. CADR diffuses 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 data routes. The main difference from directed diffusion is the consideration of information gain in addition to 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 was used to model information utility. 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 information are routed between sensors and the BS. Therefore, IDSQ can be seen as a complementary optimization procedure. Simulation results showed that these approaches are more energy-efficient than

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 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.

directed diffusion where queries are diffused in an isotropic fashion and reach nearest neighbors first.

COUGAR: Another data-centric protocol called COUGAR [16] 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 an architecture for the sensor database system where sensor nodes select a leader node to perform aggregation and transmit the data to the BS. The BS is responsible for generating a query plan that specifies the necessary information about the data flow and in-network computation for the incoming query, and sends 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 provides a network-layer-independent method for data query. However, COUGAR has some drawbacks. First, the addition of a query layer on each sensor node may add extra overhead in terms of energy consumption and memory storage. Second, 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. Third, the leader nodes should be dynamically maintained to prevent them from being hotspots (failure-prone).

ACQUIRE: In [17], Sadagopan *et al.* proposed a technique for querying sensor networks called Active Query Forwarding in Sensor Networks (ACQUIRE). Similar to COUGAR, ACQUIRE views the network as a distributed database where complex queries can be further divided into several subqueries. 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 precached information and then forwards it to another sensor node. If the precached information is not up-to-date, the nodes gather information from their neighbors within a lookahead of d hops. Once the query is 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. Note that directed diffusion may not be used for complex queries due to energy considerations as directed diffusion also uses a flooding-based query mechanism for continuous and aggregate queries. On the other hand, ACQUIRE can provide efficient querying by adjusting the value of the lookahead parameter d . When d is equal to network diameter, ACQUIRE behaves similar to flooding. However, the query has to travel more hops if d is too small. A mathematical modeling was used to find an optimal value of the parameter d for a grid of sensors where each node has

four immediate neighbors. However, there is no validation of results through simulation. To select the next node for forwarding the query, ACQUIRE either picks it randomly or the selection is based on maximum potential query satisfaction. Recall that either selection of the next node is based on information gain (CADR and IDSQ) or the query is forwarded to a node that knows the path to the searched event (rumor routing).

Energy-Aware Routing: The objective of the Energy-Aware Routing protocol [18], a destination-initiated reactive 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 is that each path can achieve. 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 class-based addressing that includes the locations and types of the nodes. The protocol initiates a connection through localized flooding, which is used to discover all routes between a source/ destination pair and their costs, thus building up the routing tables. 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 inversely proportional to the node cost. Localized flooding is performed by the destination node to keep the paths alive. Compared to directed diffusion, this protocol provides an overall improvement of 21.5 percent energy saving and a 44 percent increase in network lifetime. However, the approach requires gathering location information and setting up the addressing mechanism for the nodes, which complicate route setup compared to directed diffusion.

Routing protocols with random walks: The objective of the random-walks-based routing technique [19] is to achieve load balancing in a statistical sense by making use of multipath 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. Furthermore, 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 using the distributed asynchronous version of the well-known Bellman-Ford algorithm. An intermediate node would select as the next hop the neighboring node that is closer to the destination according to a computed probability. By carefully manipulating this probability, some

kind of load balancing can be obtained in the network. The routing algorithm is simple as nodes are required to maintain little state information. Moreover, different routes are chosen at different times even for the same pair of source and destination nodes. However, the main concern about this protocol is that the topology of the network may not be practical.

Hierarchical Routing — Hierarchical or cluster-based routing methods, originally proposed in wireline 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. The creation of clusters and assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. Hierarchical routing is an efficient way to lower energy consumption within a cluster, performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS. Hierarchical routing is mainly two-layer routing where one layer is used to select cluster heads and the other for routing. However, most techniques in this category are not about routing, but rather “who and when to send or process/ aggregate” the information, channel allocation, and so on, which can be orthogonal to the multihop routing function.

LEACH protocol: Heinzelman, *et al.* [5] introduced a hierarchical clustering algorithm for sensor networks, called Low Energy Adaptive Clustering Hierarchy (LEACH). 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 CH nodes compress data arriving from nodes that belong to the respective cluster, and send an aggregated packet to the BS in order to reduce the amount of information that must be transmitted to the BS. LEACH uses a TDMA/code-division multiple access (CDMA) MAC to reduce intercluster and intracluster collisions. However, data collection is centralized and 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, and may drain the limited energy of the sensor nodes. After a given interval of time, randomized rotation of the role of CH is conducted so that uniform energy dissipation in the sensor network is obtained. The authors found, based on their simulation model, that only 5 percent of the nodes need to act as CHs.

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 BS takes place. 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 predetermined fraction of nodes, p , elect themselves as CHs as follows. A sensor node chooses a random number, r , between 0 and 1. If this random number is less than a threshold value, $T(n)$, the node becomes a CH for the current round. The threshold value is calculated based on an equation that incorporates the desired percentage to become a CH, the current round, and the set of nodes that have not been selected as a CH in the last $(1/P)$ rounds, denoted G . It is given by

$$T(n) = \frac{p}{1 - p(r \bmod (1/p))} \text{ if } n \in G,$$

where G is the set of nodes that are involved in the CH election. All elected CHs broadcast an advertisement message to the rest of the nodes in the network that they are the new CHs. All the non-CH nodes, after receiving this advertisement, decide on the cluster to which they want to belong. This decision is based on the signal strength of the advertisement. The non-CH nodes inform the appropriate CHs 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 CH 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 CHs. The CH node, after receiving all the data, aggregates it before sending it to the BS. After a certain time, which is determined a priori, the network goes back into the setup phase again and enters another round of selecting new CHs. Each cluster communicates using different CDMA codes to reduce interference from nodes belonging to other clusters.

Although LEACH is able to increase the network lifetime, there are still a number of issues about the assumptions used in this protocol. LEACH assumes that all nodes can transmit with enough power to reach the BS if needed and that each node has computational power to support different MAC protocols. Therefore, it is not applicable to networks deployed in large regions. It also assumes that nodes always have data to send, and nodes located close to each other have correlated data. It is not obvious how the number of predetermined CHs (p) is going to be uniformly distributed through the network. Therefore, there is the possibility that the elected CHs will be concentrated in one part of the network; hence, some nodes will not have any CHs in their vicinity. Furthermore, the idea of dynamic clustering brings extra overhead (head changes, advertisements, etc.), which may diminish the gain in energy consumption. Finally, the protocol assumes that all nodes begin with the same amount of energy capacity in each election round, assuming that being a CH consumes approximately the same amount of energy for each node. The protocol should be extended to account for non-uniform energy nodes (i.e., use an energy-based threshold). An extension to LEACH, LEACH with negotiation, was pro-

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.

PEGASIS assumes that all sensor nodes have the same level of energy and they are likely to die at the same time. Note also that PEGASIS introduces excessive delay for distant node on the chain. In addition, the single leader can become a bottleneck.

	SPIN	LEACH	Directed diffusion
Optimal route	No	No	Yes
Network lifetime	Good	Very good	Good
Resource awareness	Yes	Yes	Yes
Use of meta-data	Yes	No	Yes

■ **Table 1.** Comparison between SPIN LEACH and directed diffusion.

posed in [5]. The main theme of the proposed extension is to precede data transfers with high-level negotiation using meta-data descriptors as in the SPIN protocol discussed earlier. This ensures that only data that provides new information is transmitted to the CHs before being transmitted to the BS. Table 1 compares SPIN, LEACH, and directed diffusion according to different parameters. It is noted from the table that directed diffusion shows a promising approach for energy-efficient routing in WSNs due to the use of in-network processing.

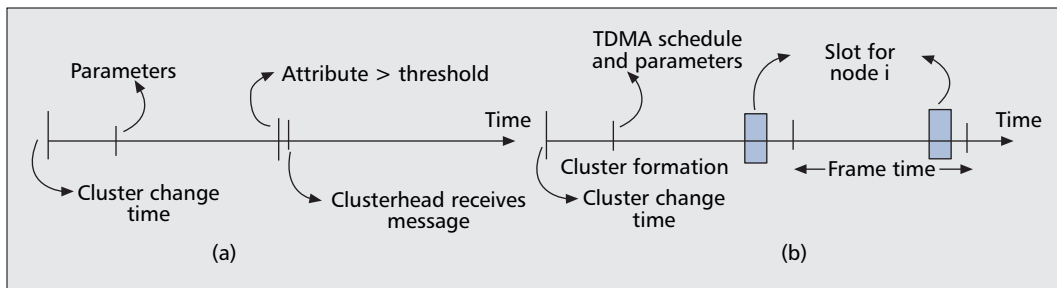
Power-Efficient Gathering in Sensor Information Systems: In [20], an enhancement over the LEACH protocol was proposed. The protocol, called Power-Efficient Gathering in Sensor Information Systems (PEGASIS), is a near optimal chain-based protocol. The basic idea of the protocol is that in order to extend network lifetime, nodes need only communicate with their closest neighbors, and they take turns in communicating with the BS. When the round of all nodes communicating with the BS ends, a new round starts, and so on. This reduces the power required to transmit data per round as the power draining is spread uniformly over all nodes. Hence, PEGASIS has two main objectives. First, increase the lifetime of each node by using collaborative techniques. Second, allow only local coordination between nodes that are close together so that the bandwidth consumed in communication is reduced. Unlike LEACH, PEGASIS avoids cluster formation and uses only one node in a chain to transmit to the BS instead of multiple nodes.

To locate the closest neighbor node in PEGASIS, each node uses the signal strength to measure the distance to all neighboring nodes and then adjusts the signal strength so that only one node can be heard. The chain in PEGASIS will consist of those nodes that are closest to each other and form a path to the BS. The aggregated form of the data will be sent to the BS by any node in the chain, and the nodes in the chain will take turns sending to the BS. The chain construction is performed in a greedy fashion. Simulation results showed that PEGASIS is able to increase the lifetime of the network to twice that under the LEACH protocol. Such performance gain is achieved through the elimination of the overhead caused by dynamic cluster formation in LEACH, and decreasing the number of transmissions and reception by using data aggregation. Although the clustering overhead is avoided, PEGASIS still requires

dynamic topology adjustment since a sensor node needs to know about the energy status of its neighbors in order to know where to route its data. Such topology adjustment can introduce significant overhead, especially for highly utilized networks. Moreover, PEGASIS assumes that each sensor node is able to communicate with the BS directly. In practical cases, sensor nodes use multihop communication to reach the BS. Also, PEGASIS assumes that all nodes maintain a complete database of the location of all other nodes in the network. The method by which the node locations are obtained is not outlined. In addition, PEGASIS assumes that all sensor nodes have the same level of energy and are likely to die at the same time. Note also that PEGASIS introduces excessive delay for distant nodes on the chain. In addition, the single leader can become a bottleneck. Finally, although in most scenarios sensors will be fixed or immobile as assumed in PEGASIS, some sensors may be allowed to move and hence affect the protocol functionality.

An extension to PEGASIS, called Hierarchical PEGASIS, was introduced in [2] with the objective of decreasing the delay incurred for packets during transmission to the BS. For this purpose, simultaneous transmissions of data are studied in order to avoid collisions through approaches that incorporate signal coding and spatial transmissions. In the latter, only spatially separated nodes are allowed to transmit at the same time. The chain-based protocol with CDMA-capable nodes constructs a chain of nodes that forms a tree-like hierarchy, and each selected node at a particular level transmits data to a node in the upper level of the hierarchy. This method ensures data transmitting in parallel and reduces delay significantly. Such a hierarchical extension has been shown to perform better than the regular PEGASIS scheme by a factor of about 60.

Threshold-Sensitive Energy Efficient Protocols: Two hierarchical routing protocols called Threshold-Sensitive Energy Efficient Sensor Network Protocol (TEEN) and Adaptive Periodic TEEN (APTEEN) are proposed in [21, 22]. These protocols were proposed for time-critical applications. In TEEN, sensor nodes sense the medium continuously, but data transmission is done less frequently. A CH sensor sends its members a hard threshold, which is the threshold value of the sensed attribute, and a soft threshold, which is a small change in the value of the sensed attribute that triggers the node to switch on its transmitter and transmit. Thus, the hard threshold tries to reduce the number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The soft threshold further reduces the number of transmissions that might otherwise occur when there is little or no change in the sensed attribute. A smaller value of the soft threshold gives a more accurate picture of the network, at the expense of increased energy consumption. Thus, the user can control the trade-off between energy efficiency and data accuracy. When CHs are to change (Fig. 5a), new values for the above parameters are broadcast. The main drawback of this scheme is that if the



■ **Figure 5.** Time line for the operation of a) TEEN and b) APTEEN.

thresholds are not received, the nodes will never communicate, and the user will not get any data from the network at all.

The nodes sense their environment continuously. The first time a parameter from the attribute set reaches its hard threshold value, the node switches its transmitter on and sends the sensed data. The sensed value is stored in an internal variable called sensed value (SV). The nodes will transmit data in the current cluster period only when the following conditions are true:

- The current value of the sensed attribute is greater than the hard threshold.
- The current value of the sensed attribute differs from SV by an amount equal to or greater than the soft threshold.

Important features of TEEN include its suitability for time-critical sensing applications. Also, since message transmission consumes more energy than data sensing, the energy consumption in this scheme is less than in proactive networks. The soft threshold can be varied. At every cluster change time, fresh parameters are broadcast, so the user can change them as required.

APTEEN, on the other hand, is a hybrid protocol that changes the periodicity or threshold values used in the TEEN protocol according to user needs and the application type. In APTEEN, the CHs broadcast the following parameters (Fig. 5b):

- Attributes (A): a set of physical parameters about which the user is interested in obtaining information
- Thresholds: consists of the hard threshold (HT) and soft threshold (ST)
- Schedule: a TDMA schedule, assigning a slot to each node
- Count time (CT): the maximum time period between two successive reports sent by a node

The node senses the environment continuously, and only those nodes that sense a data value at or beyond HT transmit. Once a node senses a value beyond HT, it transmits data only when the value of that attribute changes by an amount equal to or greater than ST. If a node does not send data for a time period equal to CT, it is forced to sense and retransmit the data. A TDMA schedule is used, and each node in the cluster is assigned a transmission slot. Hence, APTEEN uses a modified TDMA schedule to implement the hybrid network. The main features of the APTEEN scheme include the following. It combines both proactive and reactive policies. It offers a lot of flexibility by allowing

the user to set the CT interval, and the threshold values for energy consumption can be controlled by changing the CT as well as the threshold values. The main drawback of the scheme is the additional complexity required to implement the threshold functions and CT. Simulation of TEEN and APTEEN has shown that these two protocols outperform LEACH. The experiments have demonstrated that APTEEN's performance is somewhere between LEACH and TEEN in terms of energy dissipation and network lifetime. TEEN gives the best performance since it decreases the number of transmissions. The main drawbacks of the two approaches are the overhead and complexity associated with forming clusters at multiple levels, the method of implementing threshold-based functions, and how to deal with attribute-based naming of queries.

Small minimum energy communication network (MECN): In [23], a protocol is proposed that computes an energy-efficient subnetwork, the minimum energy communication network (MECN), for a certain sensor network utilizing low-power GPS. MECN identifies a relay region for every node. The relay region consists of nodes in a surrounding area where transmitting through those nodes is more energy-efficient than direct transmission. The enclosure of a node i is created by taking the union of all relay regions node i can reach. The main idea of MECN is to find a subnetwork that will have fewer nodes and require less power for transmission between any two particular nodes. In this way, global minimum power paths are found without considering all the nodes in the network. This is performed using a localized search for each node considering its relay region. MECN is self-reconfiguring and thus can dynamically adapt to node failure or the deployment of new sensors. The small MECN (SMECN) [24] is an extension to MECN. In MECN, it is assumed that every node can transmit to every other node, which is not possible every time. In SMECN possible obstacles between any pair of nodes are considered. However, the network is still assumed to be fully connected as in the case of MECN. The subnetwork constructed by SMECN for minimum energy relaying is provably smaller (in terms of number of edges) than the one constructed in MECN. Hence, the subnetwork (i.e., subgraph G') constructed by SMECN is smaller than the one constructed by MECN if the broadcast region is circular around the broadcasting node for a given power setting. Subgraph G' of graph G , which represents the

Important features of TEEN include its suitability for time-critical sensing applications. Also, since message transmission consumes more energy than data sensing, the energy consumption in this scheme is less than in proactive networks.

The subnetwork constructed by SMECN makes it more likely that the path used is one that requires less energy consumption. In addition, finding a sub-network with a smaller number of edges introduces more overhead in the algorithm.

sensor network, minimizes the energy usage satisfying the following conditions:

- The number of edges in G' is less than in G while containing all nodes in G .
- The energy required to transmit data from a node to all its neighbors in subgraph G' is less than the energy required to transmit to all its neighbors in graph G . Assume that $r = (u, u_1, \dots, v)$ is a path between u and v that spans $k - 1$ intermediate nodes u_1, \dots, u_{k-1} . The total power consumption of one path like r is given by

$$C(r) = \sum_{i=0}^{k-1} (p(u_i, u_{i+1}) + c)$$

where $u = u_0$ and $v = u_k$, and the power required to transmit data under this protocol is

$$p(u, v) = t \cdot d(u, v)^n$$

for some appropriate constant t , n is the path loss exponent of outdoor radio propagation models $n \geq 2$, and $d(u, v)$ is the distance between u and v . It is assumed that a reception at the receiver takes a constant amount of power denoted c . The subnetwork computed by SMECN helps in sending messages on minimum-energy paths. However, the proposed algorithm is local in the sense that it does not actually find the minimum-energy path, it just constructs a subnetwork in which it is guaranteed to exist. Moreover, the subnetwork constructed by SMECN makes it more likely that the path used is one that requires less energy consumption. In addition, finding a subnetwork with a smaller number of edges introduces more overhead in the algorithm.

Self-organizing protocol: Subramanian *et al.* [25] describes a self-organizing protocol (SOP) and an application taxonomy that was used to build architecture to support heterogeneous sensors. Furthermore, these sensors can be mobile or stationary. Some sensors probe the environment and forward the data to a designated set of nodes that act as routers. Router nodes are stationary and form the backbone for communication. Collected data are forwarded through the routers to the more powerful BS nodes. Each sensing node should be able to reach a router in order to be part of the network. A routing architecture that requires addressing of each sensor node has been proposed. Sensing nodes are identifiable through the address of the router node to which they are connected. The routing architecture is hierarchical where groups of nodes are formed and merge when needed. The Local Markov Loops (LML) algorithm, which performs a random walk on spanning trees of a graph, was used to support fault tolerance and as a means of broadcasting. Such an approach is similar to the idea of a virtual grid used in some other protocols discussed later under location-based routing protocols. In this approach, sensor nodes can be addressed individually in the routing architecture; hence, it is suitable for applications where communication to a particular node is required. Furthermore, this algorithm incurs a small cost for maintaining routing tables and keeping a balanced routing hierarchy. It was also found

that the energy consumed for broadcasting a message is less than that consumed in the SPIN protocol. This protocol, however, is not an on-demand protocol, especially in the organization phase of the algorithm, and thus introduces extra overhead. Another issue is related to the formation of a hierarchy. It could happen that there are many cuts in the network, and hence the probability of applying reorganization phase increases, which is an expensive operation.

Sensor aggregates routing: In [26], a set of algorithms for constructing and maintaining sensor aggregates were proposed. The objective is to collectively monitor target activity in a certain environment (target tracking applications). A sensor aggregate comprises those nodes in a network that satisfy a grouping predicate for a collaborative processing task. The parameters of the predicate depend on the task and its resource requirements. The formation of appropriate sensor aggregates were discussed in [26] in terms of allocating resources to sensing and communication tasks. Sensors in a sensor field are divided into clusters according to their sensed signal strength, so there is only one peak per cluster. Then local cluster leaders are elected. One peak may represent one target, multiple targets, or no target if the peak is generated by noise sources. To elect a leader, information exchanges between neighboring sensors are necessary. If a sensor, after exchanging packets with all its one-hop neighbors, finds that it is higher than all its one-hop neighbors on the signal field landscape, it declares itself a leader. This leader-based tracking algorithm assumes that the unique leader knows the geographical region of the collaboration.

Three algorithms were proposed in [26]. First was a lightweight protocol, Distributed Aggregate Management (DAM), for forming sensor aggregates for a target monitoring task. The protocol comprises a decision predicate P for each node to decide if it should participate in an aggregate and a message exchange scheme M about how the grouping predicate is applied to nodes. A node determines if it belongs to an aggregate based on the result of applying the predicate to the data of the node as well as information from other nodes. Aggregates are formed when the process eventually converges. Second, Energy-Based Activity Monitoring (EBAM) estimates the energy level at each node by computing the signal impact area, combining a weighted form of the detected target energy at each impacted sensor, assuming that each target sensor has equal or constant energy level. The third algorithm, Expectation-Maximization Like Activity Monitoring (EMLAM), removes the constant and equal target energy level assumption. EMLAM estimates the target positions and signal energy using received signals, and uses the resulting estimates to predict how signals from the targets may be mixed at each sensor. This process is iterated until the estimate is sufficiently good.

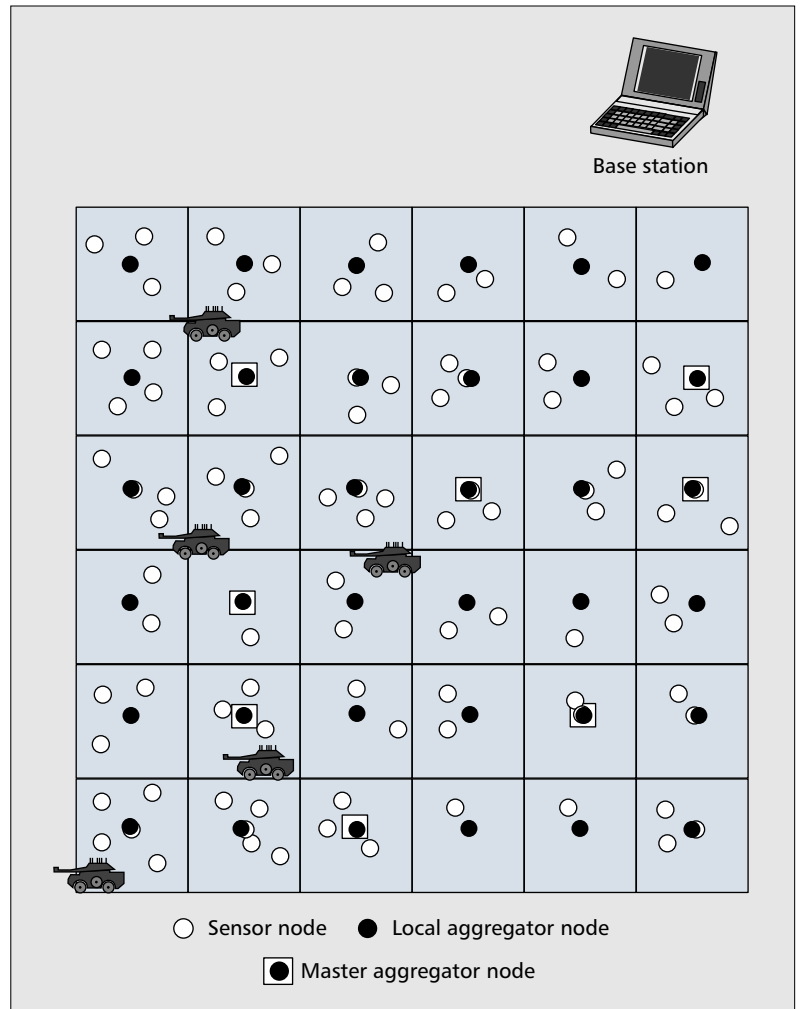
The distributed track initiation management scheme, combined with the leader-based tracking algorithm described in [26], forms a scalable system. The system works well in tracking multiple targets when the targets are not interfering,

and it can recover from intertarget interference once the targets move apart.

Virtual grid architecture routing: An energy-efficient routing paradigm is proposed in [27] that utilizes data aggregation and in-network processing to maximize the network lifetime. Due to the node stationarity and extremely low mobility in many applications in WSNs, a reasonable approach is to arrange nodes in a fixed topology, as briefly mentioned in [28]. A GPS-free approach [2] is used to build clusters that are fixed, equal, adjacent, and nonoverlapping with symmetric shapes. In [27], square clusters were used to obtain a fixed rectilinear virtual topology. Inside each zone, a node is optimally selected to act as CH. Data aggregation is performed at two levels: local and then global. The set of CHs, also called local aggregators (LAs), perform local aggregation, while a subset of these LAs are used to perform global aggregation. However, the determination of an optimal selection of global aggregation points, called master aggregators (MAs), is NP-hard. Figure 6 illustrates an example of fixed zoning and the resulting virtual grid architecture (VGA) used to perform two-level data aggregation. Note that the location of the BS is not necessarily at the extreme corner of the grid; it can be located at any arbitrary place.

Two solution strategies for the routing with data aggregation problem are presented in [27]: an exact algorithm using an integer linear program (ILP) formulation, and some near-optimal but simple and efficient approximate algorithms: a genetics-algorithm-based heuristic, a k -means heuristic, and a greedy-based heuristic. In [29], another efficient heuristic, the Clustering-Based Aggregation Heuristic (CBAH), was also proposed to minimize energy consumption in the network and hence prolong the network lifetime. The objective of all algorithms is to select a number of MAs out of the LAs that maximize network lifetime. For a realistic scenario, it is assumed in [27] that LA nodes form possibly overlapping groups. Members of each group sense the same phenomenon; hence, their readings are correlated. However, each LA node that exists in the overlapping region will send data to its associated MA for each of the groups to which it belongs. It was noted in [29] that the problem of assigning MAs to LAs in CBAH is similar to the classical bin packing problem, a major difference being that neither the identities nor the amount of power each MA will be using for different LAs are known. In CBAH, the set of MAs are selected based on incremental filing of some bins with capacities. Besides being fast and scalable to large sensor networks, the approximate algorithms in [27, 29] produce results not far from the optimal solution.

Hierarchical power-aware routing: In [30], hierarchical power-aware routing was proposed. The protocol divides the network into groups of sensors. Each group of sensors in geographic proximity are 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. Message are



■ Figure 6. Regular shape tessellation applied to the network area.

routed along the path that 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 more expensive than the path with the minimal power consumption. An approximation algorithm, called the *max-min zP_{min}* algorithm, was proposed in [30]. The crux of the algorithm is based on the trade-off between minimizing the total power consumption and maximizing the minimal residual power of the network. Hence, the algorithm tries to enhance a max-min path by limiting its power consumption as follows. First, the algorithm finds the path with the least power consumption (P_{min}) by using the Dijkstra algorithm. Second, the algorithm finds a path that maximizes the minimal residual power in the network. The proposed algorithm tries to optimize both solution criteria. This is achieved by relaxing the minimal power consumption for the message to be equal to zP_{min} with parameter $z \geq 1$ to restrict the power consumption for sending one message to zP_{min} . The algorithm consumes at most zP_{min} while maximizing the minimal residual power fraction.

Another algorithm that relies on *max-min zP_{min}* , called zone-based routing, is also proposed in [30]. Zone-based routing is a hierarchical approach where the area covered by the (sensor)

Hierarchical routing	Flat routing
Reservation-based scheduling	Contention-based scheduling
Collisions avoided	Collision overhead present
Reduced duty cycle due to periodic sleeping	Variable duty cycle by controlling sleep time of nodes
Data aggregation by clusterhead	Node on multihop path aggregates incoming data from neighbors
Simple but non-optimal routing	Routing can be made optimal but with an added complexity.
Requires global and local synchronization	Links formed on the fly without synchronization
Overhead of cluster formation throughout the network	Routes formed only in regions that have data for transmission
Lower latency as multiple hops network formed by cluster-heads always available	Latency in waking up intermediate nodes and setting up the multipath
Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Energy dissipation cannot be controlled	Energy dissipation adapts to traffic pattern
Fair channel allocation	Fairness not guaranteed

■ **Table 2.** Hierarchical vs. flat topologies routing.

network is divided into a small number of zones. To send a message across the entire area, a global path from zone to zone is found. The sensors in a zone autonomously direct local routing and participate in estimating the zone power level. Each message is routed across the zones using information about the zone power estimates. A global controller for message routing is assigned the role of managing the zones. This may be the node with the highest power. If the network can be divided into a relatively small number of zones, the scale for the global routing algorithm is reduced. The global information required to send each message across is summarized by the power level estimate of each zone. A zone graph was used to represent connected neighboring zone vertices if the current zone can go to the next neighboring zone in that direction. Each zone vertex has a power level of 1. Each zone direction vertex is labeled by its estimated power level computed by a procedure, which is a modified Bellman-Ford algorithm. Moreover, two algorithms were outlined for local and global path selection using the zone graph.

Two-Tier Data Dissemination: An approach in [6], called Two-Tier Data Dissemination (TTDD), provides data delivery to multiple mobile BS. In TTDD, each data source proactively builds a grid structure that is used to disseminate data to the mobile sinks by assuming that sensor nodes are stationary and location-aware. In TTDD, sensor nodes are stationary and location-aware, whereas sinks may change their locations dynamically. Once an event occurs, sensors surrounding it process the signal, and one of them becomes the source to generate data reports. Sensor nodes are aware of their mission, which will not change frequently. To build the grid structure, a data source chooses itself as the start crossing point of the grid, and sends a data announcement message to each of its four adjacent crossing points using simple greedy geographical forwarding. When the message reaches the node closest to the crossing point (specified in the message), it will stop.

During this process, each intermediate node stores the source information and further forwards the message to its adjacent crossing points except the one from which the message comes. This process continues until the message stops at the border of the network. The nodes that store the source information are chosen as dissemination points. After this process, the grid structure is obtained. Using the grid, a BS can flood a query, which will be forwarded to the nearest dissemination point in the local cell to receive data. Then the query is forwarded along other dissemination points upstream to the source. The requested data then flows down in the reverse path to the sink. Trajectory forwarding is employed as the BS moves in the sensor field. Although TTDD is an efficient routing approach, there are some concerns about how the algorithm obtains location information, which is required to set up the grid structure. The length of a forwarding path in TTDD is larger than the length of the shortest path. The authors of TTDD believe that the suboptimality in the path length is worth the gain in scalability. Finally, how TTDD would perform if mobile sensor nodes are allowed to move in the network is still an open question. Comparison results between TTDD and directed diffusion showed that TTDD can achieve longer lifetimes and shorter data delivery delays. However, the overhead associated with maintaining and recalculating the grid as network topology changes may be high. Furthermore, TTDD assumed the availability of a very accurate positioning system that is not yet available for WSNs.

The above mentioned flat and hierarchical protocols are different in many aspects. At this point, we compare the different routing approaches for flat and hierarchical sensor networks as shown in Table 2.

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 [1, 2, 31]. Alternatively, the location of nodes may be available directly by communicating with a satellite using GPS if nodes are equipped with a small low-power GPS receiver [28]. To save energy, some location-based schemes demand that nodes should go to sleep if there is no activity. More energy savings can be obtained by having as many sleeping nodes in the network as possible. The problem of designing sleep period schedules for each node in a localized manner was addressed in [32, 28]. In the rest of this section, we review most of the location- or geographic-based routing protocols.

Geographic Adaptive Fidelity: GAF [28] is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. The network area is first divided into fixed zones and form a virtual grid. Inside each zone, nodes collaborate with each other to play different roles. For example, nodes will elect one sensor node to stay awake for a certain period of time, and then the rest go to sleep. This node is responsible for monitoring and reporting data to the BS on behalf of the nodes in the zone. Hence, GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Such equivalence is exploited in keeping some nodes located in a particular grid area in sleeping state in order to save energy. Thus, GAF can substantially increase the network lifetime as the number of nodes increases. There are three states defined in GAF: discovery, for determining the neighbors in the grid; active, reflecting participation in routing; and sleep, when the radio is turned off. In order to handle mobility, each node in the grid estimates its time of leaving the grid and sends this to its neighbors. The sleeping neighbors adjust their sleeping time accordingly in order to keep routing fidelity. Before the leaving time of the active node expires, sleeping nodes wake up and one of them becomes active. GAF is implemented both for nonmobility (GAF-basic) and mobility (GAF-mobility adaptation) of nodes. Figure 7 shows an example of fixed zoning that can be used in sensor networks similar to that proposed in [28]. The fixed clusters in [28] are selected to be equal and square. The selection of the square size is dependent on the required transmitting power and communication direction. Vertical and horizontal communication is guaranteed to happen if the signal travels a distance of $a = r/2\sqrt{2}$, chosen such that any two sensor nodes in adjacent vertical or horizontal clusters can communicate directly. For diagonal communication to happen, the signal has to span a distance of $b = r/2\sqrt{2}$. The issue is how to schedule roles for the nodes to act as CHs. A CH can ask the sensor nodes in its cluster to switch on and start gathering data if it senses an object. Then the CH is responsi-

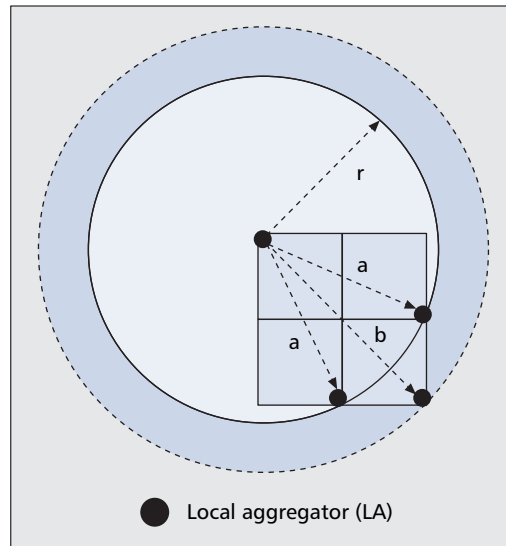


Figure 7. An example of zoning in sensor networks.

ble for receiving raw data from other nodes in its cluster and forwarding it to the BS. The authors in [28] assumed that sensor nodes can know their locations using GPS cards, which is inconceivable with current technology. GAF strives to keep the network connected by keeping a representative node always in active mode for each region on its virtual grid. Simulation results show that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency and packet loss, and increases the lifetime of the network by saving energy. Although GAF is a location-based protocol, it may also be considered a hierarchical protocol, where the clusters are based on geographic location. For each particular grid area, a representative node acts as the leader to transmit the data to other nodes. The leader node, however, does not do any aggregation or fusion as in the case of other hierarchical protocols discussed earlier.

Geographic and Energy Aware Routing: Yu *et al.* [33] discussed the use of geographic information while disseminating queries to appropriate regions since data queries often include geographic attributes. The protocol, Geographic and Energy Aware Routing (GEAR), uses energy-aware and geographically informed neighbor selection heuristics to route a packet toward 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.

Each node in GEAR keeps an estimated cost and a learning cost of reaching the destination through its neighbors. The estimated cost is a combination of residual energy and distance to destination. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network. A hole occurs when a node does not have any closer neighbor to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost. The learned cost is propa-

To save energy, some location based schemes demand that nodes should go to sleep if there is no activity. More energy savings can be obtained by having as many sleeping nodes in the network as possible.

The simulation results show that for an uneven traffic distribution, GEAR delivers 70 percent to 80 percent more packets than GPSR. For uniform traffic pairs GEAR delivers 25 percent to 35 percent more packets than GPSR.

gated one hop back every time a packet reaches the destination so that route setup for the next packet will be adjusted. There are two phases in the algorithm:

- Forwarding packets toward the target region: Upon receiving a packet, a node checks its neighbors to see if there is one neighbor that is closer to the target region than itself. If there are more than one, the nearest neighbor to the target region is selected as the next hop. If they are all further than the node itself, this means there is a hole. In this case, one of the neighbors is picked to forward the packet based on the learning cost function. This choice can then be updated according to the convergence of the learned cost during the delivery of packets
- Forwarding the packets within the region: If the packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is good when the sensors are not densely deployed. In high-density networks, recursive geographic forwarding is more energy-efficient than restricted flooding. In that case, the region is divided into four subregions and four copies of the packet are created. This splitting and forwarding process continues until regions with only one node are left.

In [33], GEAR was compared to a similar non-energy-aware routing protocol, GPSR [34], which is one of the earlier methods in geographic routing and uses planar graphs to solve the problem of holes. In GPSR, the packets follow the perimeter of the planar graph to find their route. Although the GPSR approach reduces the number of states a node should keep, it was designed for general mobile ad hoc networks, and requires a location service to map locations and node identifiers. GEAR not only reduces energy consumption for route setup, but also performs better than GPSR in terms of packet delivery. The simulation results show that for uneven traffic distribution, GEAR delivers 70–80 percent more packets than GPSR. For uniform traffic pairs GEAR delivers 25–35 percent more packets than GPSR.

MFR, DIR, and GEDIR: Stojmenovic and Lin [35] described and discussed basic localized routing algorithms. These protocols deal with basic distance, progress, and direction-based methods. The key issues are forward and backward directions. A source node or any intermediate node will select one of its neighbors according to a certain criterion. The routing methods that belong to this category are Most Forward within Radius (MFR), Geographic Distance Routing (GEDIR) that is a variant of greedy algorithms, the two-hop greedy method, alternate greedy method, and DIR (a compass routing method). GEDIR is a greedy algorithm that always moves the packet to the neighbor of the current vertex whose distance to the destination is minimized. The algorithm fails when the packet crosses the same edge twice in succession. In most cases, the MFR and greedy methods have the same path to the destination. In the DIR method, the best neighbor has the closest direction (i.e., angle) toward the desti-

nation. That is, the neighbor with the minimum angular distance from the imaginary line joining the current node and the destination is selected. In MFR, the best neighbor A will minimize the dot product $\overline{DA} \cdot \overline{DS}$, where S, D are the source and destination nodes, respectively, and \overline{SD} represents the Euclidian distance between the two nodes S, D . Alternatively, one can maximize the dot product $\overline{SD} \cdot \overline{SA}$. Each method stops forwarding the message at a node for which the best choice is to return the message back to a previous node. GEDIR and MFRs are loop-free, while DIR may create loops unless past traffic is memorized or a time-stamp is enforced [35].

A comparison study [35] between these algorithms showed that the three basic algorithms had comparable performance in terms of delivery rate and average dilation. Moreover, simulations revealed that the nodes in MFR and greedy methods select the same forwarding neighbor in more than 99 percent of cases, and the entire selected paths were identical in most cases.

The Greedy Other Adaptive Face Routing: In [36], a geometric ad hoc routing algorithm combining greedy and face routing was proposed. We will now briefly review the key points of Greedy Other Adaptive Face Routing (GOAFR). The greedy algorithm of GOAFR always picks the neighbor closest to a node to be next for routing. However, it can easily be stuck at some local minimum (i.e., no neighbor is closer to a node than the current node). Other Face Routing (OFR) is a variant of Face Routing (FR). The FR algorithm [35] is the first that guarantees success if the source and destination are connected. However, the worst case cost of FR is proportional to the size of the network in terms of number of nodes. The first algorithm that can compete with the best route in the worst case is Adaptive Face Routing (AFR). Moreover, by a lower bound argument, AFR is shown to be asymptotically worst-case optimal. But AFR is not average-case efficient. OFR utilizes the face structure of planar graphs such that the message is routed from node s to node t by traversing a series of face boundaries. The aim is to find the best node on the boundary (i.e., the closest node to the destination t) by using geometric planes. When finished, the algorithm returns to s the best node on the boundary. The simple greedy algorithm behaves well in dense networks, but fails for very simple configurations, as was shown in [36]. It was shown that GOAFR can achieve both worst-case optimality and average-case efficiency. Based on the simulation results of GOAFR, there are several ways to further improve the average-case performance. It was also shown that GOAFR outperforms other prominent algorithms, such as GPSR and AFR.

SPAN: Another position-based algorithm called SPAN [32] selects some nodes as coordinators based on their positions. The coordinators form a network backbone used to forward messages. A node should become a coordinator if two neighbors of a non-coordinator node cannot reach each other directly or via one or two coordinators (three-hop reachability). New and existing coordinators are not

necessarily neighbors in [32], which in effect makes the design less energy-efficient because of the need to maintain the positions of two- or three-hop neighbors in the complicated SPAN algorithm.

ROUTING PROTOCOLS BASED ON PROTOCOL OPERATION

In this section we review routing protocols with different routing functionality. It should be noted that some of these protocols may fall under one or more of the above routing categories.

Multipath Routing Protocols — In this subsection we study routing protocols that use multiple paths rather than a single path in order to enhance network performance. 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 destination at the expense of 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 in maintaining the alternate paths.

The authors in [37] proposed an algorithm that routes data through a path whose nodes have the largest residual energy. The path is changed whenever a better path is discovered. The primary path will be used until its energy falls below the energy of the backup path, at which time the backup path is used. Using this approach, the nodes in the primary path will not deplete their energy resources through continual use of the same route, hence achieving longer life. However, the path switching cost was not quantified in the article.

The authors of [38] proposed the use of a set of suboptimal paths occasionally to increase the lifetime of the network. These paths are chosen by means of a probability that depends on how low the energy consumption of each path is.

The path with the largest residual energy when used to route data in a network may be very energy-expensive too, so there is a trade-off between minimizing the total power consumed and the residual energy of the network. The authors in [30] proposed an algorithm in which the residual energy of the route is relaxed a bit in order to select a more energy-efficient path.

In [39], multipath routing was used to enhance the reliability of WSNs. The proposed scheme is useful for delivering data in unreliable environments. It is known that network reliability can be increased by providing several paths from source to destination and sending the same packet on each path. However, using this technique, traffic will increase significantly. Hence, there is a trade-off between the amount of traffic and the reliability of the network. This trade-off is studied in [39] using a redundancy function that is dependent on the multipath degree and failing probabilities of the available paths. The idea is to split the original data packet into sub-

packets and then send each subpacket through one of the available multipaths. It has been found that even if some of these subpackets are lost, the original message can still be reconstructed. According to their algorithm, it has also been found that for a given maximum node failure probability, using a higher multipath degree than a certain optimal value will increase the total probability of failure.

Directed diffusion [12] is a good candidate for robust multipath routing and delivery. Based on the directed diffusion paradigm, a multipath routing scheme that finds several partially disjoint paths is studied in [40] (alternate routes are not node disjoint, i.e., routes are partially overlapped). It has been found that the use of multipath routing provides a viable alternative for energy-efficient recovery from failures in WSNs. The motivation for using these braided paths is to keep the cost of maintaining the multipaths low. The costs of alternate paths are comparable to the primary path because they tend to be much closer to the primary path.

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 with this data sends the data that matches the query back to the node that initiated the query. Usually these queries are described in natural language or high-level query languages. For example, client C1 may submit a query to node N1 and ask: *Are there moving vehicles in battle space region 1?* All the nodes have tables consisting of the sensing task queries they receive, and send data that matches these tasks when they receive it. Directed diffusion [12] described earlier is an example of this type of routing. In directed diffusion, the BS node sends out interest messages to sensors. As the interest is propagated throughout the sensor network, the gradients from the source back to the BS are set up. When the source has data for the interest, the source sends the data along the interest's gradient path. To lower energy consumption, data aggregation (e.g., duplicate suppression) is performed en route.

The rumor routing protocol [41] uses a set of long-lived agents to create paths that are directed toward the events they encounter. Whenever an agent crosses a path leading to an event it has not encountered yet, it creates a path state that leads to the event. When agents come across shorter paths or more efficient paths, they optimize the paths in routing tables accordingly. Each node maintains a list of its neighbors and an events table that is updated whenever new events are encountered. Each node can also generate an agent in a probabilistic fashion. Each agent contains an events table that is synchronized with every node it visits. The agent has a lifetime of a certain number of hops, after which it dies. A node will not generate a query unless it learns a route to the required event. If there is no route available, the node transmits a query in a random direction. Then the node waits to know if the query reached the destination for a certain amount of time, after which the node floods the network if no response is received from the destination.

It was shown that GOAFR can achieve both worst-case optimality and average-case efficiency.

Based on the simulation results of GOAFR, there are several ways to further improve the average-case performance. It was also shown that GOAFR outperforms other prominent algorithms, such as GPSR or AFR.

The main idea of negotiation-based routing in WSNs is to suppress duplicate information and prevent redundant data from being sent to the next sensor or the base station by conducting a series of negotiation messages before the real data transmission begins.

Negotiation-Based Routing Protocols — These protocols use high-level data descriptors in order to eliminate redundant data transmissions through negotiation. Communication decisions are also made based on the resources available to them. The SPIN family protocols [9] discussed earlier and the protocols in [10] are examples of negotiation-based routing protocols. The motivation is that the use of flooding to disseminate data will produce implosion and overlap between the sent data, so nodes will receive duplicate copies of the same data. This operation consumes more energy and processing by sending the same data by different sensors. The SPIN protocols are designed to disseminate the data of one sensor to all other sensors, assuming these sensors are potential BSs. Hence, the main idea of negotiation-based routing in WSNs is to suppress duplicate information and prevent redundant data from being sent to the next sensor or the BS by conducting a series of negotiation messages before the real data transmission begins.

QoS-based Routing — 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 (delay, energy, bandwidth, etc.) when delivering data to the BS.

Sequential Assignment Routing (SAR) proposed in [42] is one of the first routing protocols for WSNs to introduce the notion of QoS into routing decisions. A routing decision in SAR is dependent on three factors: energy resources, QoS on each path, and the priority level of each packet. To avoid single route failure, a multipath approach and localized path restoration schemes are used. To create multiple paths from a source node, a tree rooted at the source node to the destination nodes (i.e., the set of BSs) is built. The paths of the tree are built while avoiding nodes with low energy or QoS guarantees. At the end of this process, each sensor node will be part of a multipath tree. As such, SAR is a table-driven multipath protocol that aims to achieve energy efficiency and fault tolerance. In essence, SAR calculates a weighted QoS metric as the product of the additive QoS metric and a weight coefficient associated with the priority level of the packet. The objective of SAR is to minimize the average weighted QoS metric throughout the lifetime of the network. If topology changes due to node failures, path recomputation is needed. As a preventive measure, a periodic recomputation of paths is triggered by the BS to account for any changes in topology. A handshake procedure based on a local path restoration scheme between neighboring nodes is used to recover from a failure. Failure recovery is done by enforcing routing table consistency between upstream and downstream nodes on each path. Simulation results showed that SAR offers less power consumption than the minimum energy metric algorithm, which focuses only the energy consumption of each packet without considering its priority. SAR maintains multiple paths from nodes to BS. Although this ensures fault tolerance and easy recovery, the protocol suffers

from the overhead of maintaining the tables and states at each sensor node, especially when the number of nodes is huge.

Another QoS routing protocol for WSNs that provides soft real-time end-to-end guarantees was introduced in [43]. The protocol requires each node to maintain information about its neighbors and uses geographic forwarding to find the paths. In addition, SPEED strives to ensure a certain speed for each packet in the network so that each application can estimate the end-to-end delay for the packets by dividing the distance to the BS by the speed of the packet before making an admission decision. Moreover, SPEED can provide congestion avoidance when the network is congested. The routing module in SPEED is called Stateless Geographic Nondeterministic Forwarding (SNFG) and works with four other modules at the network layer. Delay estimation at each node is basically made by calculating the elapsed time before an ACK is received from a neighbor as a response to a transmitted data packet. By looking at the delay values, SNGF selects the node that meets the speed requirement. If it fails, the relay ratio of the node is checked, calculated by looking at the miss ratios of the neighbors of a node (the nodes that could not provide the desired speed) and is fed to the SNGF module. When compared to DSR and AOVD, SPEED performs better in terms of end-to-end delay and miss ratio. Moreover, the total transmission energy is less due to the simplicity of the routing algorithm; control packet overhead is less. However, SPEED does not consider any further energy metric in its routing protocol. Therefore, for more realistic understanding of SPEED's energy consumption, there is a need to compare it to a routing protocol that is energy-aware.

Coherent and Noncoherent Processing — Data processing is a major component in the operation of wireless sensor networks. Hence, routing techniques employ different data processing techniques. In general, sensor nodes will cooperate with each other in processing different data flooded in the network area. Two examples of data processing techniques proposed in WSNs are coherent and noncoherent data-processing-based routing [42]. In noncoherent data processing routing, nodes will locally process the raw data before it is sent to other nodes for further processing. The nodes that perform further processing are called aggregators. In coherent routing, the data is forwarded to aggregators after minimum processing. The minimum processing typically includes tasks like timestamping and duplicate suppression. To perform energy-efficient routing, coherent processing is normally selected.

Noncoherent functions have fairly low data traffic loading. On the other hand, since coherent processing generates long data streams, energy efficiency must be achieved by path optimality. In noncoherent processing, data processing incurs three phases:

- Target detection, data collection, and preprocessing
- Membership declaration
- Central node election

During phase 1, a target is detected, its data collected and preprocessed. When a node decides to participate in a cooperative function, it will enter phase 2 and declare this intention to all neighbors. This should be done as soon as possible so that each sensor has a local understanding of the network topology. Phase 3 is the election of the central node. Since the central node is selected to perform more sophisticated information processing, it must have sufficient energy reserves and computational capability.

In [42], single and multiple winner algorithms were proposed for noncoherent and coherent processing, respectively. In the single winner algorithm (SWE), a single aggregator node is elected for complex processing. The election of a node is based on the energy reserves and computational capability of that node. By the end of the SWE process, a minimum-hop spanning tree will completely cover the network. In the multiple winner algorithm (MWE), a simple extension to SWE is proposed. When all nodes are sources and send their data to the central aggregator node, a large amount of energy will be consumed; hence, this process has a high cost. One way to lower the energy cost is to limit the number of sources that can send data to the central aggregator node. Instead of keeping a record of only the best candidate node (master aggregator node), each node will keep a record of up to n nodes of those candidates. At the end of the MWE process, each sensor in the network has a set of minimum-energy paths to each source node (SN). After that, SWE is used to find the node that yields the minimum energy consumption. This node can then serve as the central node for coherent processing. In general, the MWE process has longer delay, higher overhead, and lower scalability than that for noncoherent processing networks.

We observed that there are some hybrid protocols that fit under more than one category. We summarize recent results on data routing in WSNs in Table 3. The table shows how different routing protocols fit under different categories and also compares different routing techniques according to many metrics.

ROUTING IN WSNs: FUTURE DIRECTIONS

The future vision of WSNs is to embed numerous distributed devices to monitor and interact with physical world phenomena, and to exploit spatially and temporally dense sensing and actuation capabilities of those sensing devices. These nodes coordinate among themselves to create a network that performs higher-level tasks.

Although extensive efforts have been exerted so far on the routing problem in WSNs, there are still some challenges that confront effective solutions to the routing problem. First, there is tight coupling between sensor nodes and the physical world. Sensors are embedded in *unattended* places or systems. This is different from traditional Internet, PDA, and mobility applications that interface primarily and directly with human users. Second, sensors are characterized by a small footprint, and as such nodes present stringent energy constraints since they are equipped with small finite energy sources. This

is also different from traditional fixed but reusable resources. Third, communications is the primary consumer of energy in this environment where sending a bit over 10 or 100 m consumes as much energy as thousands to millions of operations (known as R^4 signal energy dropoff) [44].

Although the performance of these protocols is promising in terms of energy efficiency, further research is needed to address issues such as QoS posed by video and imaging sensors and real-time applications. Energy-aware QoS routing in sensor networks will ensure guaranteed bandwidth (or delay) through the duration of connection as well as provide the use of the most energy efficient path. Another interesting issue for routing protocols is the consideration of node mobility. Most current protocols assume that the sensor nodes and BS are stationary. However, there might be situations such as battle environments where the BS and possibly the sensors need to be mobile. In such cases, frequent update of the position of the command node and sensor nodes and propagation of that information through the network may excessively drain the energy of nodes. New routing algorithms are needed in order to handle the overhead of mobility and topology changes in such an energy-constrained environment. Future trends in routing techniques in WSNs focus on different directions; all share the common objective of prolonging network lifetime. We summarize some of these directions and give some pertinent references as follows:

- Exploit redundancy: Typically a large number of sensor nodes are implanted inside or beside the phenomenon. Since sensor nodes are prone to failure, fault tolerance techniques come into the picture to keep the network operating and performing its tasks. Routing techniques that explicitly employ fault tolerance techniques in an efficient manner are still under investigation (e.g., [39]).

- Tiered architectures (mix of form/energy factors): Hierarchical routing is an old technique to enhance scalability and efficiency of the routing protocol. However, novel techniques of network clustering that maximize network lifetime are also a hot area of research in WSNs (e.g., [45]).

- Exploit spatial diversity and density of sensor/actuator nodes: Nodes will span a network area that might be large enough to provide spatial communication between sensor nodes. Achieving energy-efficient communication in this densely populated environment deserves further investigation. Dense deployment of sensor nodes should allow the network to adapt to an unpredictable environment.

- Achieve desired global behavior with adaptive localized algorithms (i.e., do not rely on global interaction or information): However, in a dynamic environment, this is hard to model (e.g., [12]).

- Leverage data processing inside the network and exploit computation near data sources to reduce communication (i.e., perform in-network distributed processing): WSNs are organized around naming data, not nodes' identities. Since we have large collections of distributed ele-

The future vision of WSNs is to embed numerous distributed devices to monitor and interact with physical world phenomena, and to exploit spatially and temporally dense sensing and actuation capabilities of those sensing devices.

ments, localized algorithms that achieve system-wide properties in terms of local processing of data before it is sent to the destination are still needed. Nodes in the network will store named data and make it available for processing. There is a high need to create efficient processing points in the network (e.g., duplicate suppression, aggregation, correlation of data). How to efficiently and optimally find those points is still an open research issue (e.g., [27]).

- Time and location synchronization: Energy-efficient techniques for associating time and spatial coordinates with data to support collaborative processing are also required [1].

- Localization: Sensor nodes are randomly deployed into an unplanned infrastructure. The problem of estimating spatial coordinates of the

node is referred to as localization. GPS cannot be used in WSNs as GPS can work only outdoors and not in the presence of any obstruction. Moreover, GPS receivers are expensive and unsuitable for the construction of small cheap sensor nodes. Hence, there is a need to develop other means of establishing a coordinate system without relying on an existing infrastructure. Most of the proposed localization techniques today depend on recursive trilateration/multilateration techniques (e.g., [46]), which would not provide enough accuracy in WSNs.

- Self-configuration and reconfiguration are essential to the lifetime of unattended systems in a dynamic and energy constrained environment. This is important for keeping the network up and running. As nodes die and leave the net-

	Classification	Mobility	Position awareness	Power usage	Negotiation-based	Data aggregation	Localization	QoS	State complexity	Scalability	Multi-path	Query-based
SPIN	Flat	Poss.	No	Ltd.	Yes	Yes	No	No	Low	Ltd.	Yes	Yes
Direct diffusion	Flat	Ltd.	No	Ltd.	Yes	Yes	Yes	No	Low	Ltd.	Yes	Yes
Rumor routing	Flat	Very Ltd.	No	N/A	No	Yes	No	No	Low	Good	No	Yes
GBR	Flat	Ltd.	No	N/A	No	Yes	No	No	Low	Ltd.	No	Yes
MCFA	Flat	No	No	N/A	No	No	No	No	Low	Good	No	No
CADR	Flat	No	No	Ltd.	No	Yes	No	No	Low	Ltd.	No	No
COUGAR	Flat	No	No	Ltd.	No	Yes	No	No	Low	Ltd.	No	Yes
ACQUIRE	Flat	Ltd.	No	N/A	No	Yes	No	No	Low	Ltd.	No	Yes
EAR	Flat	Ltd.	No	N/A	No	No	No	No	Low	Ltd.	No	Yes
LEACH	Hierarchical	Fixed BS	No	Max.	No	Yes	Yes	No	CHs	Good	No	No
TEEN & APTEEN	Hierarchical	Fixed BS	No	Max.	No	Yes	Yes	No	CHs	Good	No	No
PEGASIS	Hierarchical	Fixed BS	No	Max.	No	No	Yes	No	Low	Good	No	No
MECN & SMECN	Hierarchical	No	No	Max.	No	No	No	No	Low	Low	No	No
OP	Hierarchical	No	No	N/A	No	No	No	No	Low	Low	No	No
HPAR	Hierarchical	No	No	N/A	No	No	No	No	Low	Good	No	No
VGA	Hierarchical	No	No	N/A	Yes	Yes	Yes	No	CHs	Good	Yes	No
Sensor aggregate	Hierarchical	Ltd.	No	N/A	No	Yes	No	No	Low	Good	No	Poss.
TTDD	Hierarchical	Yes	Yes	Ltd.	No	No	No	No	Mod.	Low	Poss.	Poss.
GAF	Location	Ltd.	No	Ltd.	No	No	No	No	Low	Good	No	No
GEAR	Location	Ltd.	No	Ltd.	No	No	No	No	Low	Ltd.	No	No
SPAN	Location	Ltd.	No	N/A	Yes	No	No	No	Low	Ltd.	No	No
MFR, GEDIR	Location	No	No	N/A	No	No	No	No	Low	Ltd.	No	No
GOAFR	Location	No	No	N/A	No	No	No	Low	Good	No	No	No
SAR	Location	No	No	N/A	Yes	Yes	No	Yes	Mod.	Ltd.	No	Yes
SPEED	QoS	No	No	N/A	No	No	No	Yes	Mod.	Ltd.	No	Yes

■ **Table 3.** Classification and comparison of routing protocols in wireless sensor networks.

work, update and reconfiguration mechanisms should take place. A feature that is important in every routing protocol is to adapt to topology changes very quickly and to maintain the network functions (e.g., [9]).

• Secure routing: Current routing protocols optimize for the limited capabilities of nodes and the application-specific nature of networks, but do not consider security. Although these protocols have not been designed with security as a goal, it is important to analyze their security properties. One aspect of sensor networks that complicates the design of a secure routing protocol is in-network aggregation. In WSNs, in-network processing makes end-to-end security mechanisms harder to deploy because intermediate nodes need direct access to the contents of the messages (e.g., [47, 48]).

Other possible future research for routing protocols includes the integration of sensor networks with wired networks (i.e., the Internet). Most applications in security and environmental monitoring require the data collected from sensor nodes to be transmitted to a server so that further analysis can be done. On the other hand, the requests from the user should be made to the BS through the Internet. Since the routing requirements of each environment are different, further research is necessary for handling these kinds of situations.

CONCLUSIONS

Routing in sensor networks is a new area of research, with a limited but rapidly growing set of research results. In this article we present a comprehensive survey of routing techniques in wireless sensor networks that 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, and QoS-based routing techniques depending on protocol operation. We also highlight the design trade-offs 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 sensor networks. We highlight those challenges and pinpoint future research directions in this regard.

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ADDITIONAL READING

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