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SITA1501
Wireless Sensor Network and Architecture

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Unit IV

ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

- Introduction
- Data Dissemination and Gathering
- Routing Challenges and Design Issues in Wireless Sensor Networks
  - Network Scale and Time-Varying Characteristics
  - Resource Constraints
  - Sensor Applications Data Models
- Routing Strategies in Wireless Sensor Networks
  - WSN Routing Techniques
  - Flooding and Its Variants
  - Sensor Protocols for Information via Negotiation
  - Low-Energy Adaptive Clustering Hierarchy
  - Power-Efficient Gathering in Sensor Information Systems
  - Directed Diffusion
  - Geographical Routing

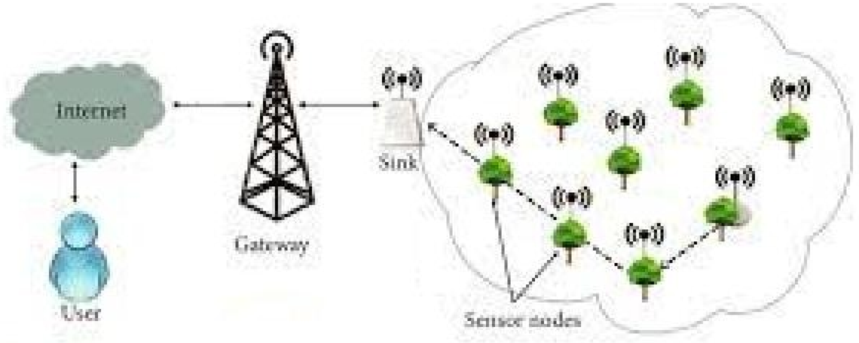
Introduction

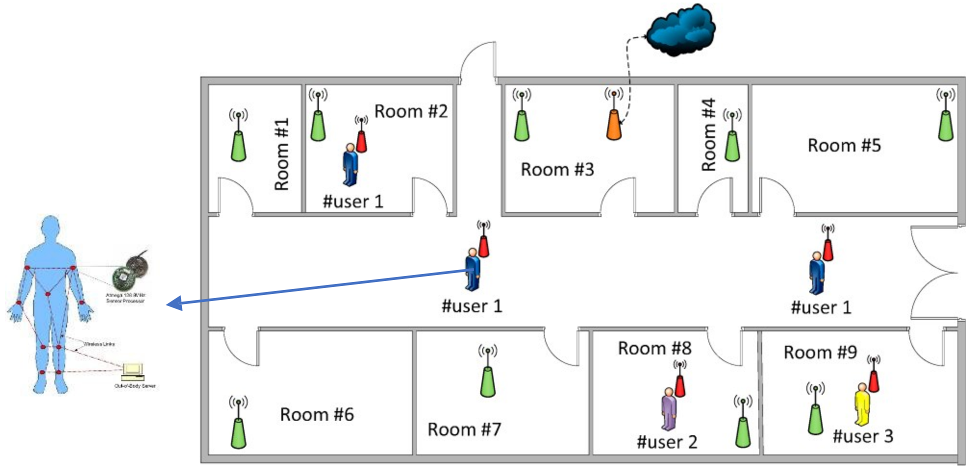
- WSNs are extremely versatile and can be deployed to support a wide variety of applications in many different situations, whether they are composed of stationary or mobile sensor nodes.

- The way these sensors are deployed depends on the nature of the application.

- In environmental monitoring and surveillance applications, for example, sensor nodes are typically deployed in an ad hoc fashion so as to cover the specific area to be monitored (e.g., C1WSNs).

- In health care–related applications, smart wearable wireless devices and biologically compatible sensors can be attached to or implanted strategically within the human body to monitor vital signs of the patient under surveillance.





Introduction

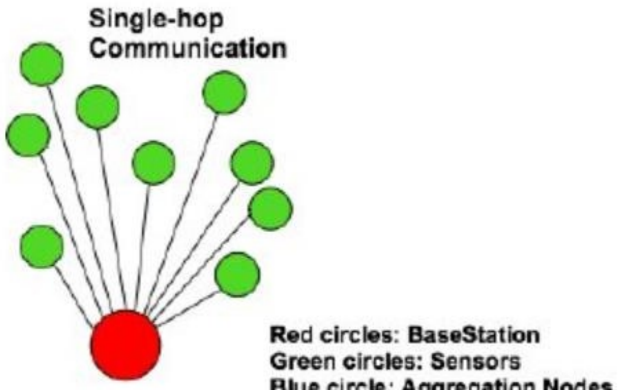
- Once deployed, sensor nodes self-organize into an autonomous wireless ad hoc network, which requires very little or no maintenance.
- Sensor nodes then collaborate to carry out the tasks of the application for which they are deployed.
- Despite the disparity in the objectives of sensor applications, the main task of wireless sensor nodes is to sense and collect data from a target domain, process the data, and transmit the information back to specific sites where the underlying application resides.
- Achieving this task efficiently requires the development of an energy-efficient routing protocol to set up paths between sensor nodes and the data sink.
- The path selection must be such that the lifetime of the network is maximized.
- The characteristics of the environment within which sensor nodes typically operate, coupled with severe resource and energy limitation, make the routing problem very challenging.

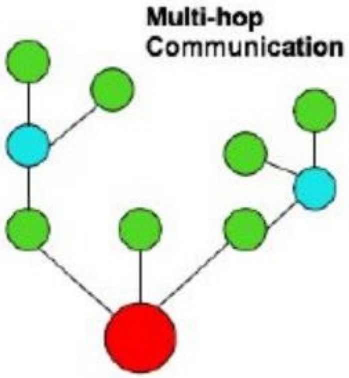
Data Dissemination and Gathering

- The way that data and queries are forwarded between the base station and the location where the target phenomena are observed is an important aspect and a basic feature of WSNs.
- A simple approach to accomplish this task is for each sensor node to exchange data directly with the base station.

Data Dissemination and Gathering

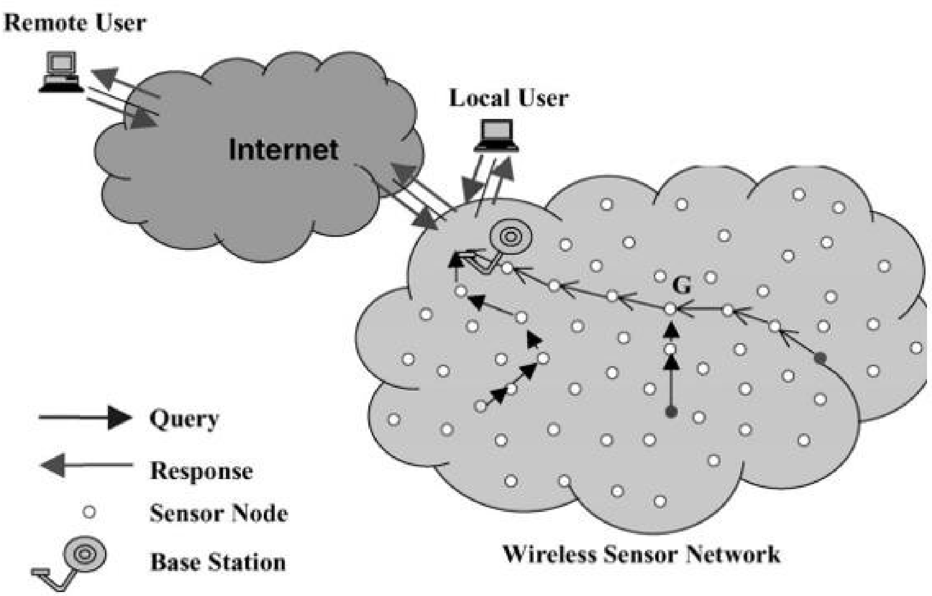
- A single-hop-based approach, however, is costly, as nodes that are farther away from the base station may deplete their energy reserves quickly, thereby severely limiting the lifetime of the network.
- This is the case particularly where the wireless sensors are deployed to cover a large geographical region or where the wireless sensors are mobile and may move away from the base station.
- To address the shortcomings of the single-hop approach, data exchange between the sensors and the base stations is usually carried out using multihop packet transmission over short communication radius.





Data Dissemination and Gathering

- Mutihop approach leads to significant energy savings and reduces considerably communication interference between sensor nodes competing to access the channel, particularly in highly dense WSNs.
- Data forwarding between the sensors where data are collected and the sinks where data are made available is illustrated in figure .
- In response to queries issued by the sinks or when specific events occur within the area monitored, data collected by the sensors are transmitted to the base station using multihop paths.
- It is worth noting that depending on the nature of the application, sensor nodes can aggregate data correlated on their way to the base station.



Multihop data and query forwarding

Data Dissemination and Gathering

- In a multihop WSN, intermediate nodes must participate in forwarding data packets between the source and the destination.
- Determining which set of intermediate nodes is to be selected to form a data-forwarding path between the source and the destination is the principal task of the routing algorithm.
- In general, routing in large-scale networks is inherently a difficult problem whose solution must address multiple challenging design requirements, including correctness, stability, and optimality with respect to various performance metrics.
- The intrinsic properties of WSNs, combined with severe energy and bandwidth constraints, bring about additional challenges that must be addressed to satisfy the traffic requirements of the application supported, while extending the lifetime of the network.

Routing Challenges & Design Issues in WSN

- Although WSNs share many commonalities with wired and ad hoc networks, they also exhibit a number of unique characteristics which set them apart from existing networks.
- These unique characteristics bring to sharp focus new routing design requirements that go beyond those typically encountered in wired and wireless ad hoc networks.
- Meeting these design requirements presents a distinctive and unique set of challenges.
- These challenges can be attributed to multiple factors, including
    - severe energy constraints,
    - limited computing and communication capabilities,
    - the dynamically changing environment within which sensors are deployed,
    - unique data traffic models and
    - application-level quality of service requirements.

Routing Challenges & Design Issues in WSN

Network Scale and Time-Varying Characteristics

- Sensor nodes operate with limited computing, storage, and communication capabilities under severe energy constraints.
- Due to large number of conceivable sensor-based applications, the densities of the WSNs may vary widely, ranging from very sparse to very dense.
- Furthermore, in many applications, the sensor nodes, in some cases numbering in the hundreds if not thousands, are deployed in an ad hoc and often unsupervised manner over wide coverage areas.
- In these networks, the behavior of sensor nodes is dynamic and highly adaptive, as the need to self-organize and conserve energy forces sensor nodes to adjust their behavior constantly in response to their current level of activity or the lack thereof.
- Furthermore, sensor nodes may be required to adjust their behavior in response to the erratic and unpredictable behavior of wireless connections caused by high noise levels and radio-frequency interference, to prevent severe performance degradation of the application supported.

Routing Challenges & Design Issues in WSN

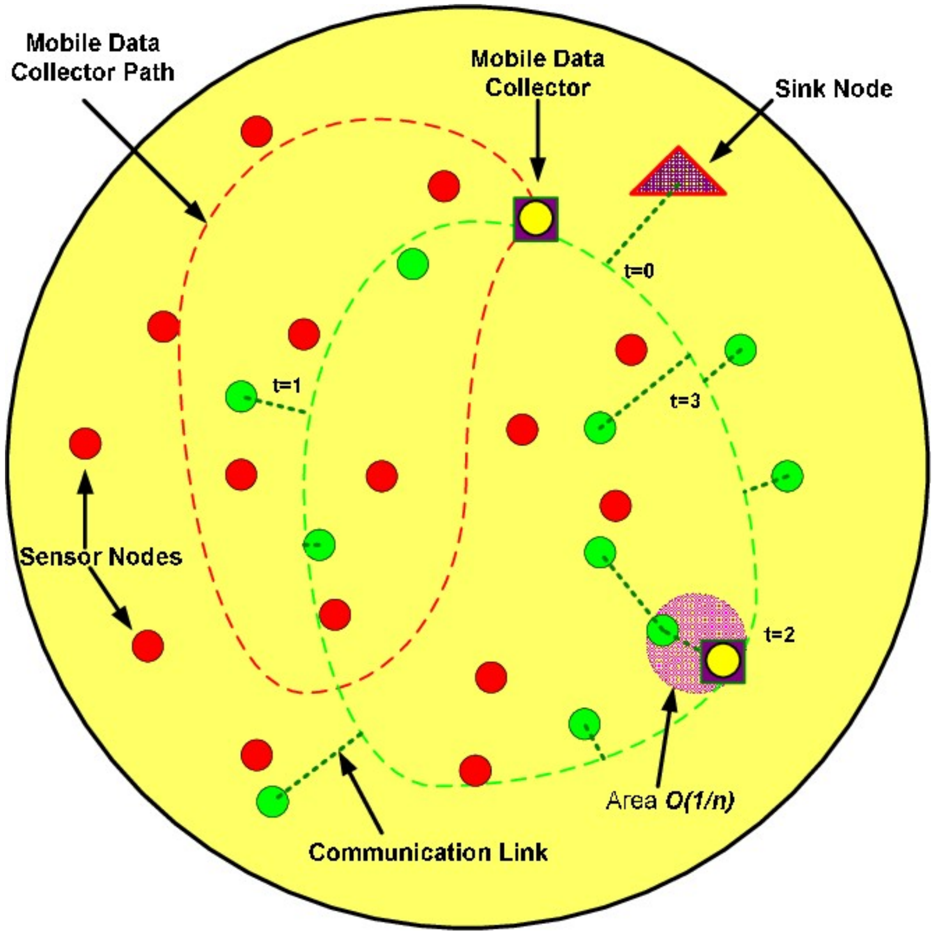
Resource Constraints

- Sensor nodes are designed with minimal complexity for large-scale deployment at a reduced cost.
- Energy is a key concern in WSNs, which must achieve a long lifetime while operating on limited battery reserves. Multihop packet transmission over wireless networks is a major source of power consumption.
- Reducing energy consumption can be achieved by dynamically controlling the duty cycle of the wireless sensors.
- The energy management problem, however, becomes especially challenging in many mission-critical sensor applications.
- The requirements of these applications are such that a predetermined level of sensing and communication performance constraints must be maintained simultaneously.
- Therefore, a question arises as to how to design scalable routing algorithms that can operate efficiently for a wide range of performance constraints and design requirements.
- The development of these protocols is fundamental to the future of WSNs.

Routing Challenges & Design Issues in WSN

Sensor Applications Data Models

- The data model describes the flow of information between the sensor nodes and the data sink.
- These models are highly dependent on the nature of the application in terms of how data are requested and used.
- Several data models have been proposed to address the data-gathering needs and interaction requirements of a variety of sensor applications.
- A class of sensor applications requires data collection models that are based on periodic sampling or are driven by the occurrence of specific events.



Routing Challenges & Design Issues in WSN

Sensor Applications Data Models

- In other applications, data can be captured and stored, possibly processed and aggregated by a sensor node, before they are forwarded to the data sink.
- Yet a third class of sensor applications requires bidirectional data models in which two-way interaction between sensors and data sinks is required.
- The need to support a variety of data models increases the complexity of the routing design problem.
- Optimizing the routing protocol for an application's specific data requirements while supporting a variety of data models and delivering the highest performance in scalability, reliability, responsiveness, and power efficiency becomes a design and engineering problem of enormous magnitude.

Routing Strategies in WSN

- The WSN routing problem presents a very difficult challenge that can be posed as a classic trade-off between responsiveness and efficiency.
- This trade-off must balance the need to accommodate the limited processing and communication capabilities of sensor nodes against the overhead required to adapt to these.
- In a WSN, overhead is measured primarily in terms of bandwidth utilization, power consumption, and the processing requirements on the mobile nodes.
- Finding a strategy to balance these competing needs efficiently forms the basis of the routing challenge.
- Furthermore, the intrinsic characteristics of wireless networks gives rise to the important question of whether or not existing routing protocols designed for ad hoc networks are sufficient to meet this challenge.

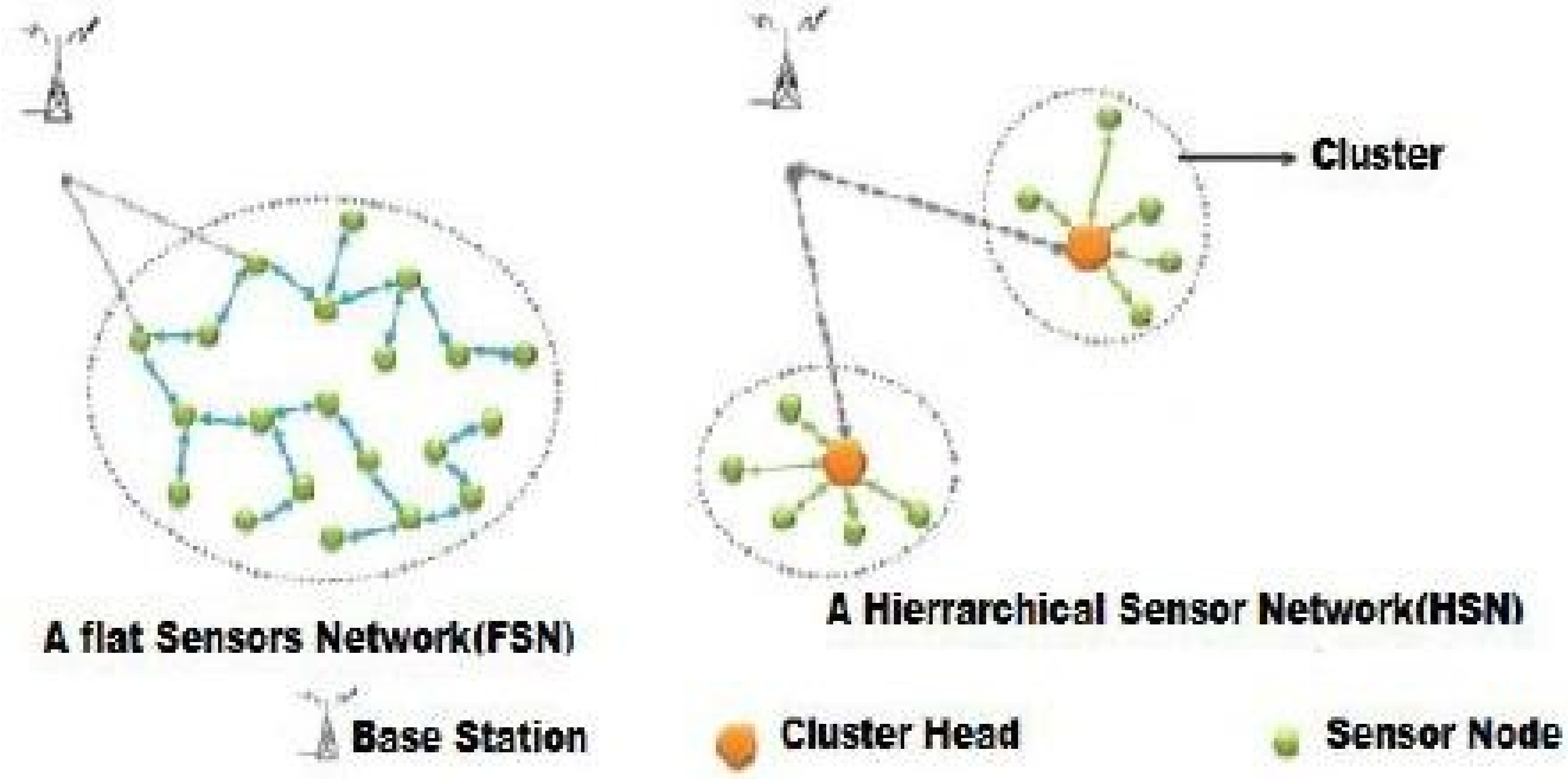
Routing Strategies in WSN

- Routing algorithms for ad hoc networks can be classified according to the manner in which information is acquired and maintained and the manner in which this information is used to compute paths based on the acquired information.

- Three different strategies can be identified:
    - proactive, reactive, and hybrid.

Routing Strategies in WSN

- The proactive strategy, also referred to as table driven, relies on periodic dissemination of routing information to maintain consistent and accurate routing tables across all nodes of the network.
- The **structure of the network** can be either **flat or hierarchical**.
- Flat proactive routing strategies have the potential to compute optimal paths.
- The overhead required to compute these paths may be prohibitive in a dynamically changing environment.
- Hierarchical routing is better suited to meet the routing demands of large ad hoc networks.


Cluster
A flat Sensors Network(FSN)
A Hierrarchical Sensor Network(HSN)
Base Station
Cluster Head
Sensor Node

Routing Strategies in WSN

- Reactive routing strategies establish routes to a limited set of destinations on demand.
- These strategies do not typically maintain global information across all nodes of the network.
- They must therefore, rely on a **dynamic route search to establish paths between a source and a destination.**
- This typically involves flooding a route discovery query, with the replies traveling back along the reverse path.
- The reactive routing strategies vary in the way they control the flooding process to reduce communication overhead and the way in which routes are computed and re-established when failure occurs.

Routing Strategies in WSN

- Hybrid strategies rely on the existence of network structure to achieve stability and scalability in large networks.
- In these strategies the network is organized into mutually adjacent clusters, which are maintained dynamically as nodes join and leave their assigned clusters.
- Clustering provides a structure that can be leveraged to limit the scope of the routing algorithm reaction to changes in the network environment.
- A hybrid routing strategy can be adopted whereby proactive routing is used within a cluster and reactive routing is used across clusters.
- The main challenge is to reduce the overhead required to maintain the clusters

Routing Strategies in WSN

- In summary, traditional routing algorithms for ad hoc networks tend to exhibit their least desirable behavior under highly dynamic conditions.
- Routing protocol overhead typically increases dramatically with increased network size and dynamics.
- A large overhead can easily overwhelm network resources.
- Furthermore, traditional routing protocols operating in large networks require substantial internodal coordination, and in some cases global flooding, to maintain consistent and accurate information, which is necessary to achieve loop-free routing.

Routing Strategies in WSN

- The use of these techniques increases routing protocol overhead and convergence times.
- Consequently, although they are well adapted to operate in environments where the computation and communications capabilities of the network nodes are relatively high compared to sensor nodes, the efficiency of these techniques conflict with routing requirements in WSNs.
- **New routing strategies are therefore required** for sensor networks that are capable of effectively managing the **trade-off between optimality and efficiency**.

WSN Routing Techniques

- The design of routing protocols for WSNs must consider
  - the power and resource limitations of the network nodes,
  - the time-varying quality of the wireless channel, and
  - the possibility for packet loss and delay.
- To address these design requirements, several routing strategies for WSNs have been proposed.
- **One class** of routing protocols adopts a **flat network architecture** in which all nodes are considered peers.
- A flat network architecture has several advantages, including minimal overhead to maintain the infrastructure and the potential for the discovery of multiple routes between communicating nodes for fault tolerance.

WSN Routing Techniques

- **A second class** of routing protocols imposes a structure on the network to achieve energy efficiency, stability, and scalability.
- In this class of protocols, network nodes are organized in **clusters** in which a node with higher residual energy, for example, assumes the role of a cluster head.
- The cluster head is responsible for coordinating activities within the cluster and forwarding information between clusters.
- Clustering has potential to reduce energy consumption and extend the lifetime of the network.

WSN Routing Techniques

- A **third class** of routing protocols uses a **data-centric approach** to disseminate interest within the network.
- The approach uses attribute-based naming, whereby a source node queries an attribute for the phenomenon rather than an individual sensor node.
- The interest dissemination is achieved by assigning tasks to sensor nodes and expressing queries to relative to specific attributes.
- Different strategies can be used to communicate interests to the sensor nodes, including
  - broadcasting,
  - attribute-based multicasting,
  - geo-casting, and
  - anycasting.

WSN Routing Techniques

- A **fourth class** of routing protocols uses **location to address** a sensor node.
- Location-based routing is useful in applications where the position of the node within the geographical coverage of the network is relevant to the query issued by the source node.
- Such a query may specify a specific area where a phenomenon of interest may occur or the vicinity to a specific point in the network environment.

Flooding and its Variants

- Flooding is a common technique frequently used for path discovery and information dissemination in wired and wireless ad hoc networks.
- The routing strategy is simple and does not rely on costly network topology maintenance and complex route discovery algorithms.
- Flooding uses a reactive approach whereby each node receiving a data or control packet sends the packet to all its neighbors.
- After transmission, a packet follows all possible paths.
- Unless the network is disconnected, the packet will eventually reach its destination.
- Furthermore, as the network topology changes, the packet transmitted follows the new routes.

Flooding and its Variants

Figure illustrates the concept of flooding in data communications network.

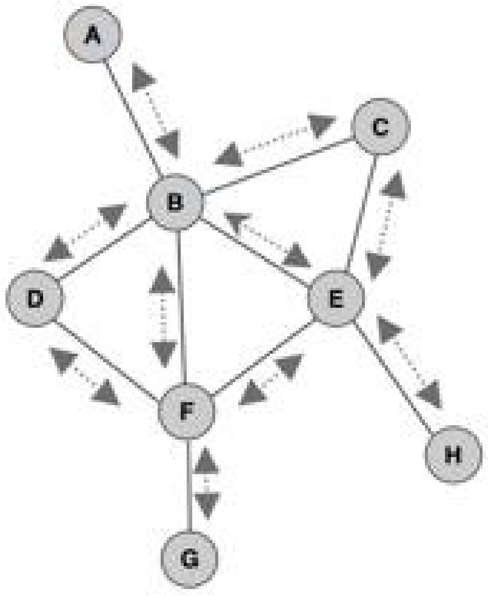


Figure 4.2 Flooding in data communications networks

Flooding and its Variants

- As shown in the figure, flooding in its simplest form may cause packets to be replicated indefinitely by network nodes.
- To prevent a packet from circulating indefinitely in the network, a hop count field is usually included in the packet.
- Initially, the hop count is set to approximately the diameter of the network.
- As the packet travels across the network, the hop count is decremented by one for each hop that it traverses.
- When the hop count reaches zero, the packet is simply discarded.

Flooding and its Variants

- A similar effect can be achieved using a time-to-live field, which records the number of time units that a packet is allowed to live within the network.
- At the expiration of this time, the packet is no longer forwarded.
- Flooding can be further enhanced by identifying data packets uniquely, forcing each network node to drop all the packets that it has already forwarded.
- Such a strategy requires maintaining at least a recent history of the traffic, to keep track of which data packets have already been forwarded.
- Despite the simplicity of its forwarding rule and the relatively low-cost maintenance that it requires, flooding suffers several deficiencies when used in WSNs.

Flooding and its Variants

- The first drawback of flooding is its susceptibility to traffic implosion, as shown in Figure
- This undesirable effect is caused by duplicate control or data packets being sent repeatedly to the same node.

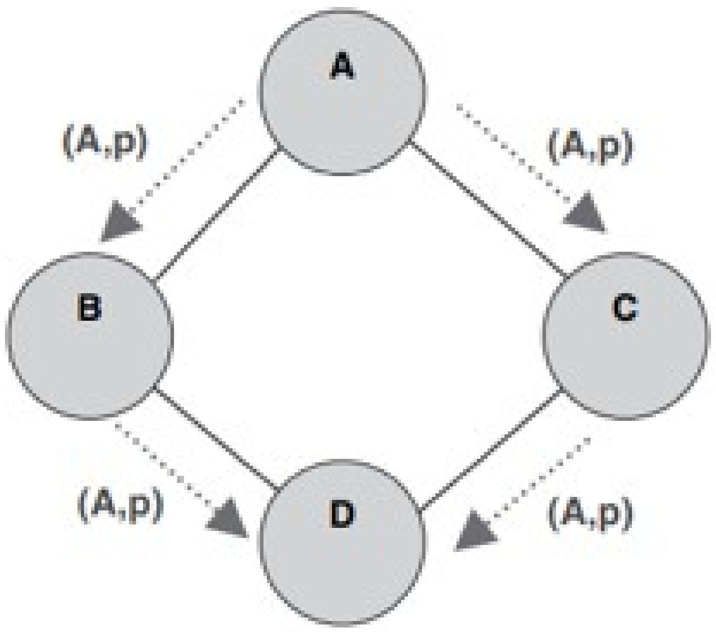


Figure 4.3 Flooding traffic implosion problem

Flooding and its Variants

- The second drawback of flooding is the overlap problem to which it gives rise, as depicted in Figure
- Overlapping occurs when two nodes covering the same region send packets containing similar information to the same node.

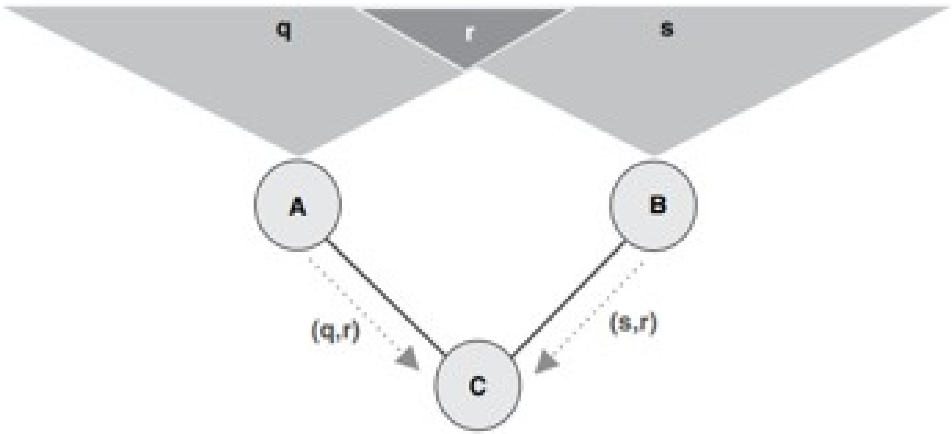


Figure 4.4 Flooding traffic overlapping problem

Flooding and its Variants

- The third and most severe drawback of flooding is resource blindness.
- The simple forwarding rule that flooding uses to route packets does not take into consideration the energy constraints of the sensor nodes.
- As such, the node's energy may deplete rapidly, reducing considerably the lifetime of the network.

Flooding and its Variants

- To address the shortcomings of flooding, a derivative approach, referred to as gossiping, has been proposed.
- Similar to flooding, **gossiping** uses a simple forwarding rule and does not require costly topology maintenance or complex route discovery algorithms.
- Contrary to flooding, where a data packet is broadcast to all neighbors, gossiping requires that each node sends the incoming packet to a randomly selected neighbor.

Gossiping

- Upon receiving the packet, the neighbor selected randomly chooses one of its own neighbors and forwards the packet to the neighbor chosen.
- This process continues iteratively until the packet reaches its intended destination or the maximum hop count is exceeded.
- Gossiping avoids the implosion problem by limiting the number of packets that each node sends to its neighbor to one copy.
- The latency that a packet suffers on its way to the destination may be excessive, particularly in a large network.
- This is caused primarily by the random nature of the protocol, which, in essence, explores one path at a time.

Sensor Protocols for Information via Negotiation

- Sensor protocols for information via negotiation (SPIN) is a data-centric negotiation-based family of information dissemination protocols for WSNs.
- The main objective of these protocols is to efficiently disseminate observations gathered by individual sensor nodes to all the sensor nodes in the network.
- Simple protocols such as flooding and gossiping are commonly proposed to achieve information dissemination in WSNs.
- Flooding requires that each node sends a copy of the data packet to all its neighbors until the information reaches all nodes in the network.
- Gossiping, on the other hand, uses randomization to reduce the number of duplicate packets and requires only that a node receiving a data packet forward it to a randomly selected neighbor.

Sensor Protocols for Information via Negotiation

- The simplicity of flooding and gossiping is appealing, as both protocols use simple forwarding rules and do not require topology maintenance.
- The performance of these algorithms in terms of packet delay and resource utilization, however, quickly deteriorates with the size of the network and the traffic load.
- This performance drawback is typically caused by traffic implosion and geographical overlapping.
- Traffic implosion results in multiple copies of the same data being delivered to the same sensor node.
- Geographical overlapping, on the other hand, causes nodes covering the same geographical area to disseminate, unnecessarily, similar data information items to the network sensor nodes.
- Simple protocols such as flooding and gossiping do not alter their behavior to adapt communication and computation to the current state of their energy resource.

Sensor Protocols for Information via Negotiation

- This lack of resource awareness and adaptation may reduce the lifetime of the network considerably, as highly active nodes may rapidly deplete their energy resources.
- The main objective of SPIN and its related family members is to address the shortcomings of conventional information dissemination protocols and overcome their performance deficiencies.
- The basic tenets of this family of protocols are **data negotiation and resource adaptation**.
- Semantic-based data negotiation requires that nodes running SPIN "learn" about the content of the data before any data are transmitted between network nodes.

Sensor Protocols for Information via Negotiation

- SPIN exploits data naming, whereby nodes associate metadata with data they produce and use these descriptive data to perform negotiations before transmitting the actual data.
- A receiver that expresses interest in the data content can send a request to obtain the data advertised.
- This form of negotiation assures that data are sent only to interested nodes, thereby eliminating traffic implosion and reducing significantly the transmission of redundant data throughout the network.
- Furthermore, the use of meta data descriptors eliminates the possibility of overlap, as nodes can limit their requests to name only the data that they are interested in obtaining.

Sensor Protocols for Information via Negotiation

- Resource adaptation allows sensor nodes running SPIN to tailor their activities to the current state of their energy resources.
- Each node in the network can probe its associated resource manager to keep track of its resource consumption before transmitting or processing data.
- When the current level of energy becomes low, the node may reduce or completely eliminate certain activities, such as forwarding third party metadata and data packets.
- The resource adaptation feature of SPIN allows nodes to extend their longevity and consequently, the lifetime of the network.

Sensor Protocols for Information via Negotiation

- To carry out negotiation and data transmission, nodes running SPIN use three types of messages.
- The first message type, ADV, is used to advertise new data among nodes.
- A network node that has data to share with the remaining nodes of the network can advertise its data by first transmitting an ADV message containing the metadata describing the data.
- The second message type, REQ, is used to request an advertised data of interest.
- Upon receiving an ADV containing metadata, a network node interested in receiving specific data sends a REQ message the metadata advertising node, which then delivers the data requested.
- The third message type, DATA, contains the actual data collected by a sensor, along with a metadata header. The data message is typically larger than the ADV and REQ messages.
- The latter messages only contain metadata that are often significantly smaller than the corresponding data message.

Sensor Protocols for Information via Negotiation

- Limiting the redundant transmission of data messages using semantic-based negotiation can result in significant reduction of energy consumption.
- The basic behavior of SPIN is illustrated in Figure 6.6, in which the data source, sensor node A, advertises its data to its immediate neighbor, sensor node B, by sending an ADV message containing the metadata describing its data.
- Node B expresses interest in the data advertised and sends a REQ message to obtain the data.
- Upon receiving the data, node B sends an ADV message to advertise the newly received data to its immediate neighbors.
- Only three of these neighbors, nodes C, E, and G, express interest in the data.
- These nodes issue a REQ message to node B, which eventually delivers the data to each of the requesting nodes.
- The simplest version of SPIN, referred to as SPIN-PP, is designed for a point-to-point communications network.

Sensor Protocols for Information via Negotiation

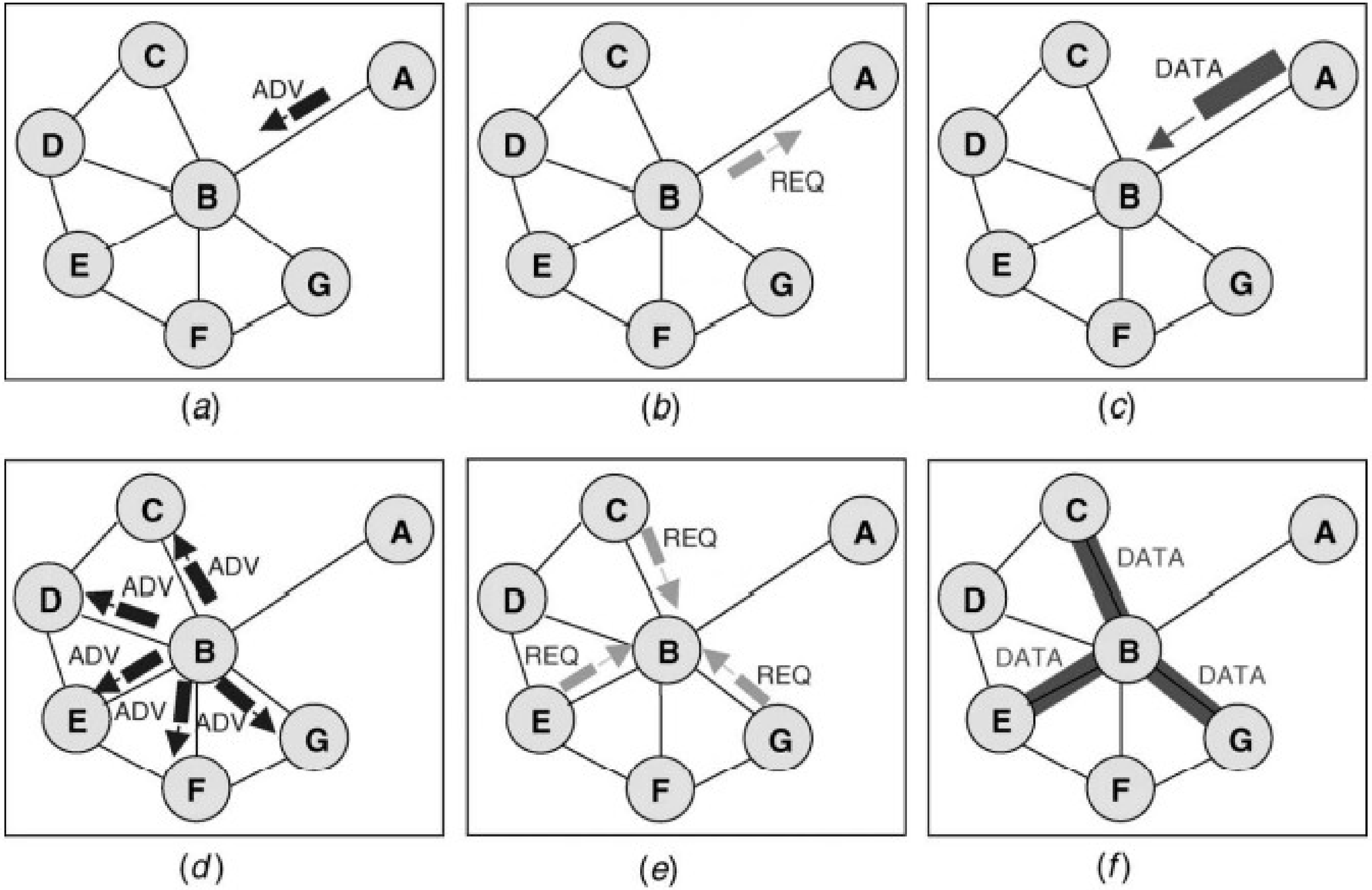


Figure 6.6 SPIN basic protocol operations [6.17].

Sensor Protocols for Information via Negotiation

- The three-step handshake protocol used by SPIN-PP is depicted in Figure 6.7. In step 1, the node holding the data, node A, issues an advertisement packet (ADV).
- In step 2, node B expresses interest in receiving the data by issuing a data request (REQ). In step 3, node A responds to the request and sends a data packet to node B.
- This completes the three-step handshake procedure. SPIN-PP uses negotiation to overcome the implosion and overlap problems of the traditional flooding and gossiping protocols.

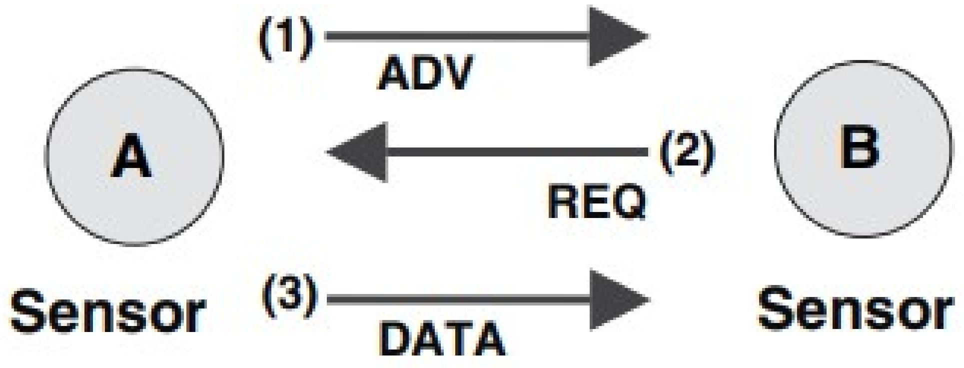


Figure 6.7 SPIN-PP three-way handshake protocol.

Sensor Protocols for Information via Negotiation

- A simulation-based performance study of SPIN-1 shows that the protocol reduces energy consumption by a factor of 3.5 compared to flooding.
- The protocol also achieves high data dissemination rates, nearing the theoretical optimum.
- An extension of this basic protocol, SPIN-EC, additionally incorporates a threshold based resource-awareness mechanism to complete data negotiation.
- When its energy level approaches the low threshold, a node running SPIN-EC reduces its participation in the protocol operations.
- In particular, a node engages in protocol operations only if it concludes that it can complete all the stages of the protocol operations without causing its energy level to decrease below the threshold.

Sensor Protocols for Information via Negotiation

- Consequently, if a node receives an advertisement, it does not send out an REQ message if it determines that its energy resource is not high enough to transmit an REQ message and receive the corresponding DATA message.

- The simulation results of this protocol show that SPIN-EC disseminates 60% more data per unit energy than flooding.

- Furthermore, the data show that SPIN-EC comes very close to the ideal amount of data that can be disseminated per unit energy.

- Both SPIN-PP and SPIN-EC are designed for point-to-point communication. A third member of the SPIN family, SPIN-BC, is designed for broadcast networks.

- In these networks, nodes share a single channel for communications.

Sensor Protocols for Information via Negotiation

- In this class of networks, when a node sends out a data packet on the broadcast channel, the packet transmitted is received by all the other nodes within a certain range of the sending node.
- The SPIN-BC protocol takes advantage of the broadcasting capability of the channel and requires that a node which has received an ADV message does not respond immediately with an REQ message.
- Instead, the node waits for a certain amount of time, during which it monitors the communications channel.
- If the node hears an REQ message issued by another node which is interested in receiving the data, it cancels its own request, thereby eliminating any redundant requests for the same message.
- Furthermore, upon receiving an REQ message, the advertising node sends the data message only once, even when it receives multiple requests for the same message.

Sensor Protocols for Information via Negotiation

- The basic operations of the SPIN-BC protocol are depicted in Figure 6.8.
- In this configuration, the node holding the data, node A, sends a ADV packet to advertise the data to its neighbors.
- All nodes hear the advertisement, but node C is first to issue a REQ packet to request the data from node A. Nodes B and D hear the broadcast request and refrain from issuing their own REQ packets.
- Nodes E and F either have no interest in the data advertised or intentionally delay their requests. Upon hearing node C's request, node A replies by sending the data packet.

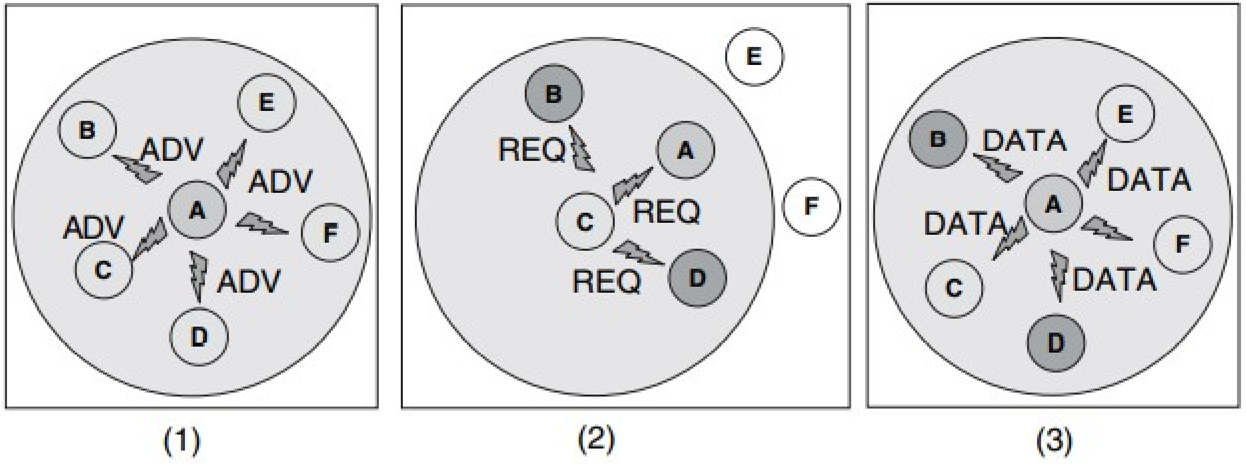


Figure 6.8 SPIN-BC protocol basic operations [6.17].

Sensor Protocols for Information via Negotiation

- All nodes within the transmission range of A receive the data packet, including nodes E and F. In broadcast environments, SPIN-BC has the potential to reduce energy consumption by eliminating redundant exchange of data requests and replies.
- The last protocol of the SPIN family, SPIN-RL, extends the capabilities of SPIN-BC to enhance its reliability and overcome message transmission errors caused by a lossy channel.
- Enhanced reliability is achieved by periodic broadcasting of ADV and REQ messages.
- Each node in SPIN-BC keeps track of the advertisements it hears and the nodes where these advertisements originate.
- If a node requesting specific data of interest does not receive the data requested within a certain period of time, it sends the request again.
- Furthermore, improved reliability can be provided by readvertising metadata periodically. Finally, SPIN-RL nodes limit the frequency with which they resend the data messages.

Sensor Protocols for Information via Negotiation

- After sending out a data message, a node waits for a certain time period before it responds to other requests for the same data message.
- The SPIN protocol family addresses the major drawbacks of flooding and gossiping. Simulation results show that SPIN is more energy efficient than flooding or gossiping.
- Furthermore, the results also show that the rate at which SPIN disseminates data is greater than or equal to the rate of either of these protocols.
- SPIN achieves these gains by localizing topology changes and eliminating dissemination of redundant information through semantic negotiation.
- It is worth noting, however, that localized negotiation may not be sufficient to cover the entire network and ensure that all interested nodes receive the data advertisement and eventually, the data of interest.
- Such a situation may occur if intermediate nodes may not express interest in the data and drop the corresponding ADV message upon receiving it.
- This shortcoming may prevent the use of SPIN for specific applications such as monitoring for intrusion detection and critical infrastructure protection.

Low-Energy Adaptive Clustering Hierarchy

- Low-energy adaptive clustering hierarchy (LEACH) is a routing algorithm designed to collect and deliver data to the data sink, typically a base station.

- The main objectives of LEACH are:
  - Extension of the network lifetime
  - Reduced energy consumption by each network sensor node
  - Use of data aggregation to reduce the number of communication messages

Low-Energy Adaptive Clustering Hierarchy

- To achieve these objectives, LEACH adopts a hierarchical approach to organize the network into a set of clusters.
- Each cluster is managed by a selected cluster head.
- The cluster head assumes the responsibility to carry out multiple tasks.
- The first task consists of periodic collection of data from the members of the cluster.
- Upon gathering the data, the cluster head aggregates it in an effort to remove redundancy among correlated values.
- The second main task of a cluster head is to transmit the aggregated data directly to the base station.
- The transmission of the aggregated data is achieved over a single hop.

Low-Energy Adaptive Clustering Hierarchy

- The network model used by LEACH is depicted in Figure 4.8.
- The third main task of the cluster head is to create a TDMA-based schedule whereby each node of the cluster is assigned a time slot that it can use for transmission.
- The cluster head advertises the schedule to its cluster members through broadcasting.
- To reduce the likelihood of collisions among sensors within and outside the cluster, LEACH nodes use a code-division multiple access–based scheme for communication.

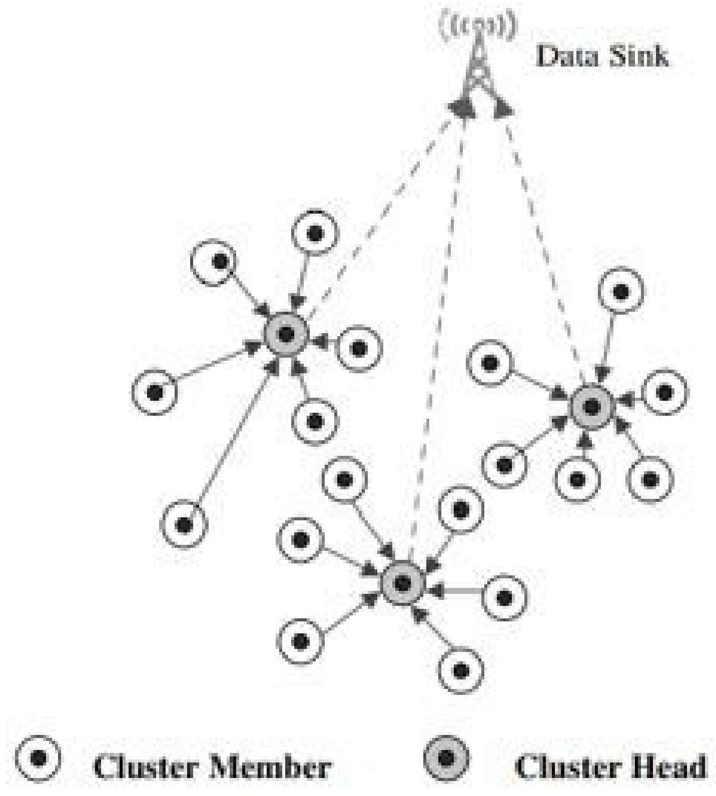


Figure 4.8 LEACH network model

Low-Energy Adaptive Clustering Hierarchy

- The basic operations of LEACH are organized in two distinct phases.
- These phases are illustrated in Figure 4.9.
- The first phase, the setup phase, consists of two steps, cluster-head selection and cluster formation.
- The second phase, the steady-state phase, focuses on data collection, aggregation, and delivery to the base station.
- The duration of the setup is assumed to be relatively shorter than the steady-state phase to minimize the protocol overhead.

Low-Energy Adaptive Clustering Hierarchy

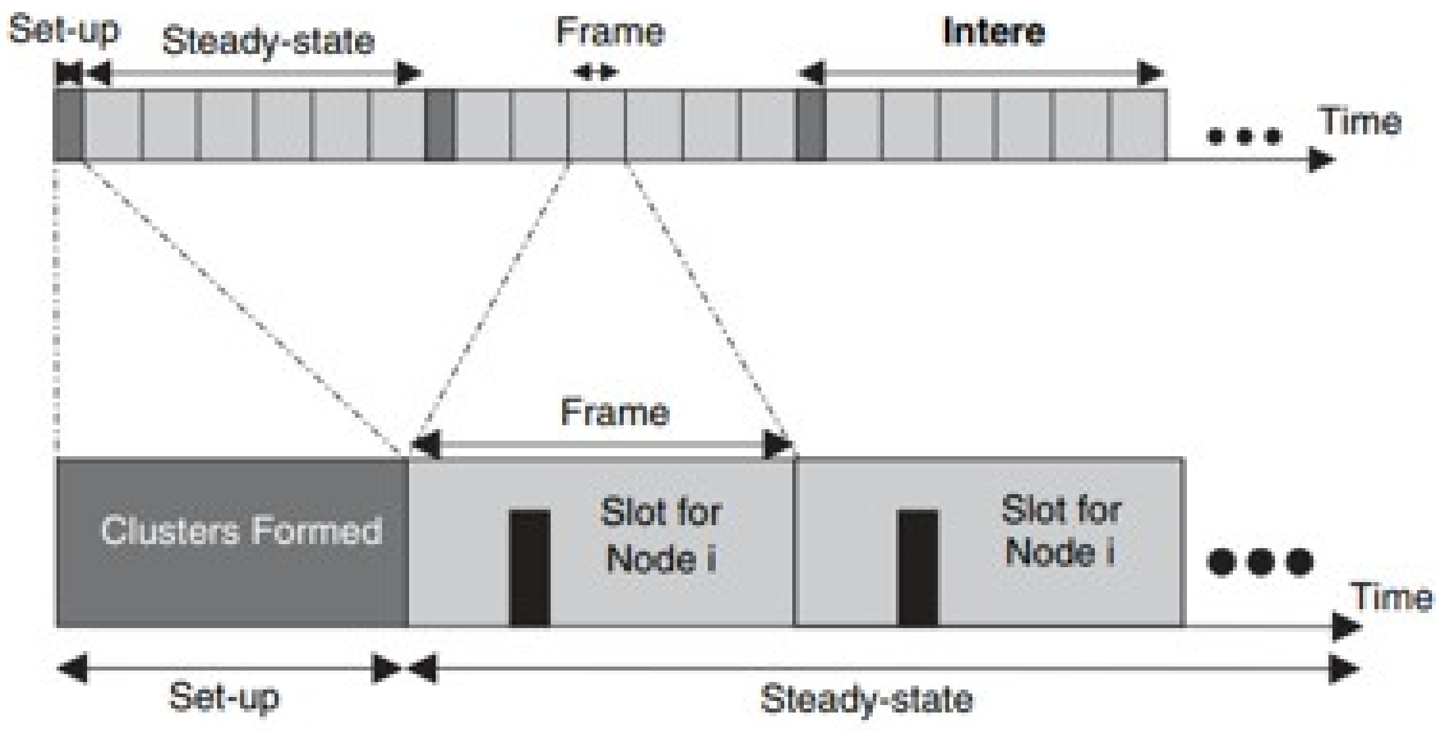


Figure 4.9 LEACH phases

Low-Energy Adaptive Clustering Hierarchy

- At the beginning of the setup phase, a round of cluster-head selection starts.
- The cluster-head selection process ensures that this role rotates among sensor nodes, thereby distributing energy consumption evenly across all network nodes.
- To determine if it is its turn to become a cluster head, a node, n, generates a random number, v, between 0 and 1 and compares it to the cluster-head selection threshold, T(n).
- The node becomes a cluster head if its generated value, v, is less than T(n).

Low-Energy Adaptive Clustering Hierarchy

- The cluster-head selection threshold is designed to ensure with high probability that a predetermined fraction of nodes, P, is elected cluster heads at each round.
- Further, the threshold ensures that nodes which served in the last 1/P rounds are not selected in the current round.
- To meet these requirements, the threshold T(n) of a competing node n can be expressed as follows:

$$T(n) = \begin{cases} 0 & \text{if } n \notin G \\ \dfrac{P}{1 - P(r \bmod (1/P))} & \forall n \in G \end{cases}$$

Low-Energy Adaptive Clustering Hierarchy

- The variable G represents the set of nodes that have not been selected to become cluster heads in the last 1=P rounds, and r denotes the current round.
- The predefined parameter, P, represents the cluster-head probability.
- It is clear that if a node has served as a cluster head in the last 1=P rounds, it will not be elected in this round.
- At the completion of the cluster-head selection process, every node that was selected to become a cluster head advertises its new role to the rest of the network.
- Upon receiving the cluster-head advertisements, each remaining node selects a cluster to join. The selection criteria may be based on the received signal strength, among other factors.
- The nodes then inform their selected cluster head of their desire to become a member of the cluster.

Low-Energy Adaptive Clustering Hierarchy

- Upon cluster formation, each cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member of the cluster.
- Each cluster head also selects a CDMA code, which is then distributed to all members of its cluster.
- The code is selected carefully so as to reduce intercluster interference

Low-Energy Adaptive Clustering Hierarchy

- The completion of the setup phase signals the beginning of the steady-state phase.
- During this phase, nodes collect information and use their allocated slots to transmit to the cluster head the data collected.
- This data collection is performed periodically.
- Simulation results show that LEACH achieves significant energy savings.
- These savings depend primarily on the data aggregation ratio achieved by the cluster heads.

Low-Energy Adaptive Clustering Hierarchy

- Despite these benefits, however, LEACH suffers several shortcomings.
- The assumption that all nodes can reach the base station in one hop may not be realistic, as capabilities and energy reserves of the nodes may vary over time from one node to another.
- Furthermore, the length of the steady-state period is critical for achieving the energy reduction necessary to offset the overhead caused by the cluster selection process.
- A short steady-state period increases the protocol's overhead, whereas a long period may lead to cluster head energy depletion.
- Several algorithms have been proposed to address these shortcomings.

Power-Efficient Gathering in Sensor Information Systems

- Power-efficient gathering in sensor information systems (PEGASIS) and its extension, hierarchical PEGASIS, are a family of routing and information-gathering protocols for WSNs.

- The main objectives of PEGASIS are twofold.
  - First, the protocol aims at extending the lifetime of a network by achieving a high level of energy efficiency and uniform energy consumption across all network nodes.
  - Second, the protocol strives to reduce the delay that data incur on their way to the sink.

Power-Efficient Gathering in Sensor Information Systems

- The network model considered by PEGASIS assumes a homogeneous set of nodes deployed across a geographical area.
- Nodes are assumed to have global knowledge about other sensors' positions.
- Furthermore, they have the ability to control their power to cover arbitrary ranges.
- The nodes may also be equipped with CDMA-capable radio transceivers.
- The nodes' responsibility is to gather and deliver data to a sink, typically a wireless base station.
- The goal is to develop a routing structure and an aggregation scheme to reduce energy consumption and deliver the aggregated data to the base station with minimal delay while balancing energy consumption among the sensor nodes.

Power-Efficient Gathering in Sensor Information Systems

- Contrary to other protocols, which rely on a tree structure or a cluster-based hierarchical organization of the network for data gathering and dissemination, PEGASIS uses a chain structure.
- Based on this structure, nodes communicate with their closest neighbors.
- The construction of the chain starts with the farthest node from the sink.
- Network nodes are added to the chain progressively, starting from the closest neighbor to the end node.
- Nodes that are currently outside the chain are added to the chain in a greedy fashion, the closest neighbor to the top node in the current chain first, until all nodes are included.

Power-Efficient Gathering in Sensor Information Systems

- To determine the closest neighbor, a node uses the signal strength to measure the distance to all its neighboring nodes.
- Using this information, the node adjusts the signal strength so that only the closest node can be heard.
- A node within the chain is selected to be the chain leader.
- Its responsibility is to transmit the aggregated data to the base station.

Power-Efficient Gathering in Sensor Information Systems

- The chain leader role shifts in positioning the chain after each round.
- Rounds can be managed by the data sink, and the transition from one round to the next can be tripped by a high-powered beacon issued by the data sink.
- Rotation of the leadership role among nodes of the chain ensures on average a balanced consumption of energy among all the network nodes.
- It is worth noting, however, that nodes assuming the role of chain leadership may be arbitrarily far away from the data sink.

Power-Efficient Gathering in Sensor Information Systems

- Such a node may be required to transmit with high power in order to reach the base station
- Data aggregation in PEGASIS is achieved along the chain.
- In its simplest form, the aggregation process can be performed sequentially as follows.
  - First, the chain leader issues a token to the last node in the right end of the chain.
  - Upon receiving the token, the end node transmits its data to its downstream neighbor in the chain toward the leader.

Power-Efficient Gathering in Sensor Information Systems

- The neighboring node aggregates the data and transmits them to its downstream neighbor.
- This process continues until the aggregated data reach the leader.
- Upon receiving the data from the right side of the chain, the leader issues a token to the left end of the chain, and the same aggregation process is carried out until the data reach the leader.
- Upon receiving the data from both sides of the chain, the leader aggregates the data and transmits them to the data sink.
- Although simple, the sequential aggregation scheme may result in long delays before the aggregated data are delivered to the base station.
- Such a sequential scheme, however, may be necessary if arbitrarily close simultaneous transmission cannot be carried out without signal interference.

Power-Efficient Gathering in Sensor Information Systems

- A potential approach to reduce the delay required to deliver aggregated data to the sink is to use parallel data aggregation along the chain.
- A high degree of parallelism can be achieved if the sensor nodes are equipped with CDMA-capable transceivers.
- The added ability to carry out arbitrarily close transmissions without interference can be used to ‘‘overlay’ a hierarchical structure onto the chain and use the embedded structure to perform data aggregation.
- At each round, nodes at a given level of the hierarchy transmit to a close neighbor in the upper level of the hierarchy.

Power-Efficient Gathering in Sensor Information Systems

- This process continues until the aggregated data reach the leader at the top level of the hierarchy.
- The latter transmits the final data aggregate to the base station.
- To illustrate the chain-based approach, consider the example depicted in Figure 4.10.
- In this example it is assumed that all nodes have global knowledge of the network and employ a greedy algorithm to construct the chain.

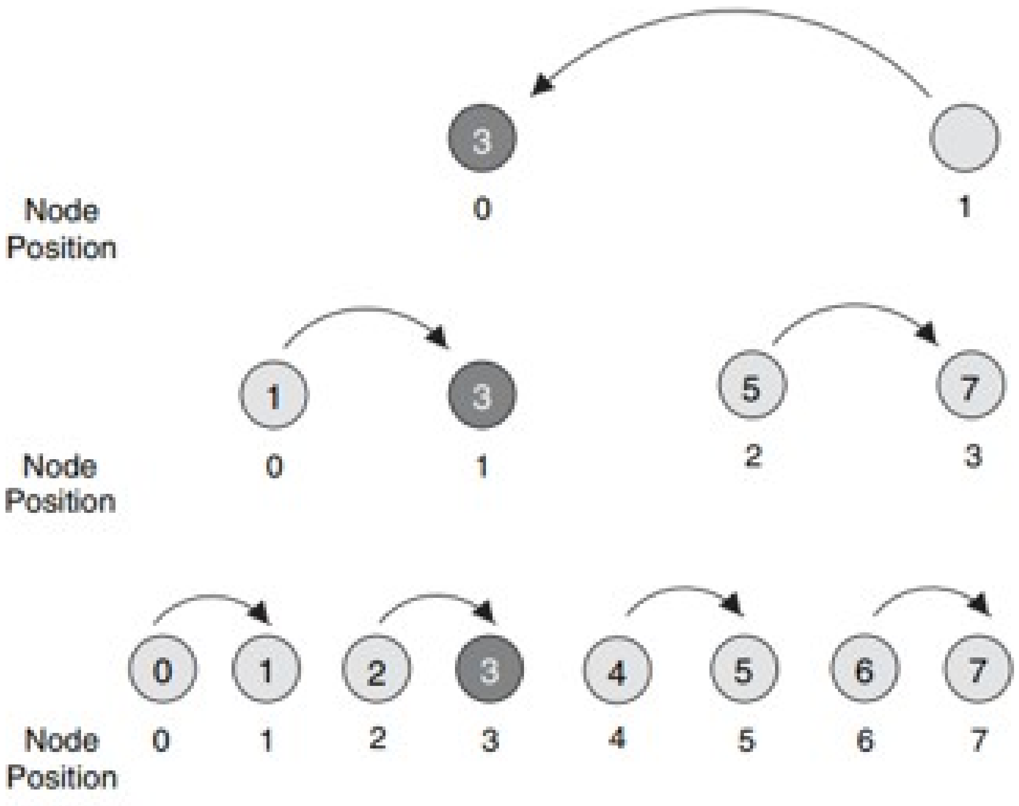


Figure 4.10 Chain-based data gathering and aggregation scheme

Power-Efficient Gathering in Sensor Information Systems

- Furthermore, it is assumed that nodes take turns in transmitting to the base station such that node i mod N, where N represents the total number of nodes, is responsible for transmitting the aggregate data to the base station in round i.
- Based on this assignment, node 3, in position 3 in the chain, is the leader in round 3.
- All nodes in an even position must send their data to their neighbor to the right.
- At the next level, node 3 remains in an odd position.
- Consequently, all nodes in an even position aggregate their data and transmit them to their right neighbors.
- At the third level, node 3 is no longer in an odd position.
- Node 7, the only node beside node 3 to rise to this level, aggregates its data and sends them to node 3.
- Node 3, in turn, aggregates the data received with its own data and sends them to the base station.
- The chain-based binary approach leads to significant energy reduction, as nodes operate in a highly parallel manner.

Power-Efficient Gathering in Sensor Information Systems

- Furthermore, since the hierarchical, treelike structure is balanced, the scheme guarantees that after log2N steps, the aggregated data arrive at the leader.
- The chain-based binary aggregation scheme has been used in PEGASIS as an alternative to achieving a high degree of parallelism.
- With CDMA-capable sensor nodes, it has been shown that the scheme performs best with respect to the energy-delay product needed per round of data gathering, a metric that balances the energy and delay cost.
- The sequential scheme and the CDMA-based fully parallel scheme constitute two endpoints of the design spectrum.

Power-Efficient Gathering in Sensor Information Systems

- A third scheme, which does not require the node transceivers to be equipped with CDMA capabilities, strikes a balance between the two extreme schemes and achieves some level of parallelism.
- The basic idea of the scheme is to restrict simultaneous transmission to nodes that are spatially separated.
- Based on this restriction, hierarchical PEGASIS creates a three-level hierarchy in which the total number of network nodes is divided into three groups.
- Data are aggregated simultaneously within each group and exchanged between groups.
- The data aggregated eventually reach the leader, which delivers them to the data sink.

Power-Efficient Gathering in Sensor Information Systems

- It is worth noting that simultaneous transmission must be carefully scheduled to avoid interference.
- Furthermore, the three-level hierarchy must be restructured properly to allow leadership rotation among group nodes.
- The simulation results of the hierarchical extension of PEGASIS show considerable improvement over schemes such as LEACH.
- Further, the hierarchical scheme has been shown to outperform the original PEGASIS scheme by a factor of 60.

Directed Diffusion

- Directed diffusion is a data-centric routing protocol for information gathering and dissemination in WSNs.
- The main objective of the protocol is to achieve substantial energy savings in order to extend the lifetime of the network.
- To achieve this objective, directed diffusion keeps interactions between nodes, in terms of message exchanges, localized within a limited network vicinity.
- Using localized interaction, direct diffusion can still realize robust multipath delivery and adapt to a minimal subset of network paths.
- This unique feature of the protocol, combined with the ability of the nodes to aggregate response to queries, results into significant energy savings.

Directed Diffusion

- The main elements of direct diffusion include interests, data messages, gradients, and reinforcements.
- Directed diffusion uses a publish-and-subscribe information model in which an inquirer expresses an interest using attribute–value pairs.
- An interest can be viewed as a query or an interrogation that specifies what the inquirer wants.
- Table 6.1 shows an example that illustrates how an interest in hummingbirds can be expressed using a set of attribute–value pairs

TABLE 6.1 Interest Description Using Value and Attribute Pairs

Attribute–Value Pair	Description
Type = Hummingbirds	Detect hummingbird location
Interval = 20 ms	Report events every 20 ms
Duration = 10 s	Report for the next 10 s
Field = $[(x_1, y_1), (x_2, y_2)]$	Report from sensors in this area

Directed Diffusion

- Sensor nodes, which can service the interest, reply with the corresponding data.
- For each active sensing task, the data sink periodically broadcasts an interest message to each neighbor.
- The message propagates throughout the sensor network as an interest for named data.
- The main purpose of this exploratory interest message is to determine if there exist sensor nodes that can service the sought-after interest.
- All sensor nodes maintain an interest cache.
- Each entry of the interest cache corresponds to a different interest.
- The cache entry contains several fields, including a timestamp field, multiple gradient fields for each neighbor, and a duration field.

Directed Diffusion

- The timestamp field contains the timestamp of the last matching interest received.
- Each gradient field specifies both the data rate and the direction in which data are to be sent.
- The value of the data rate is derived from the interval attribute of the interest.
- The duration field indicates the approximate lifetime of the interest.
- The value of the duration is derived from the timestamp of the attribute. Figure 4.11 illustrates interest propagation in a WSN.

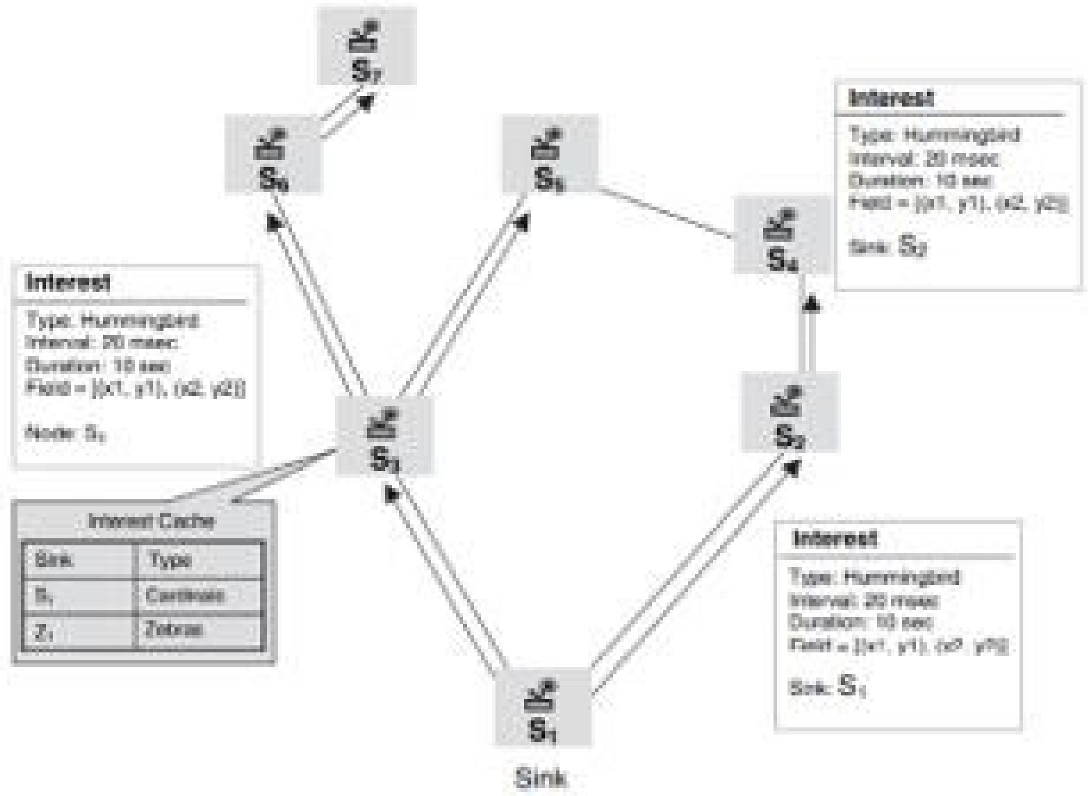


Figure 4.11 Interest propagation

Directed Diffusion

- A gradient can be thought of as a reply link pointing toward the neighboring node from which the interest is received.
- The diffusion of interests across the entire network, coupled with the establishment of gradients at the network nodes, allows the discovery and establishment of paths between the data sinks that are interested in the named data and the nodes that can serve the data.
- A sensor node that detects an event searches its interest cache for an entry matching the interest.
- If a match is identified, the node first computes the highest event rate requested among all its outgoing gradients.
- It then sets its sensing subsystem to sample the events at this highest rate.

Directed Diffusion

- The node then sends out an event description to each neighbor for which it has a gradient.
- A neighboring node that receives a data searches for a matching interest entry in its cache.
- If no match is found, the node drops the data message with no further action.
- If such a match exists, and the data message received does not have a matching data cache entry, the node adds the message to the data cache and sends the data message to the neighboring nodes.

Directed Diffusion

- Upon receiving an interest, a node checks its interest cache to determine if an entry exists in its cache for this interest.
- If such an entry does not exist, the receiving node creates a new cache entry.
- The node then uses the information contained in the interest to instantiate the parameters of the newly created interest field.
- Furthermore, the entry is set to contain a single gradient field, with the event rate specified, pointing toward the neighboring node from which the interest is received.
- If a match exists between the interest received and a cache entry, the node updates the timestamp and duration fields of the matching entry.
- If the entry contains no gradient for the sender of the interest, the node adds a gradient with the value specified in the interest message.

Directed Diffusion

- If the matching interest entry contains a gradient for the interest sender, the node simply updates the timestamp and duration fields.
- A gradient is removed from its interest entry when it expires.
- Figure 4.12 shows the initial gradient setup. During the gradient setup phase, a sink establishes multiple paths.
- The sink can use these paths to higher-quality events by increasing its data rate. This is achieved through a path reinforcement process.

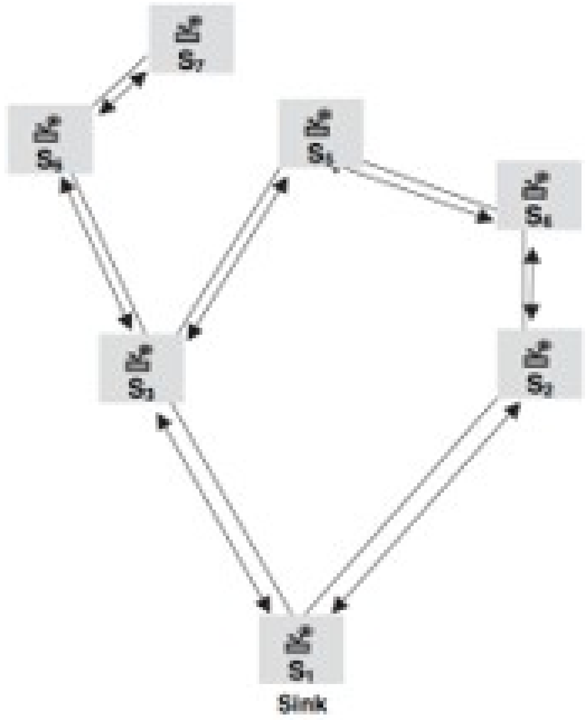


Figure 4.12 Initial gradient setup

Directed Diffusion

- The sink may choose to reinforce one or several particular neighbors.
- To achieve this, the sink resends the original interest message, at a higher data rate, across the paths selected, thereby reinforcing the source nodes on the paths to send data more frequently.
- The path performing most often can then be retained while negatively reinforcing the remaining paths.
- Negative reinforcement can be achieved by timing out all high-data-rate gradients in the network, except for those that are explicitly reinforced. Figure 4.13 shows data delivery along a reinforced path.

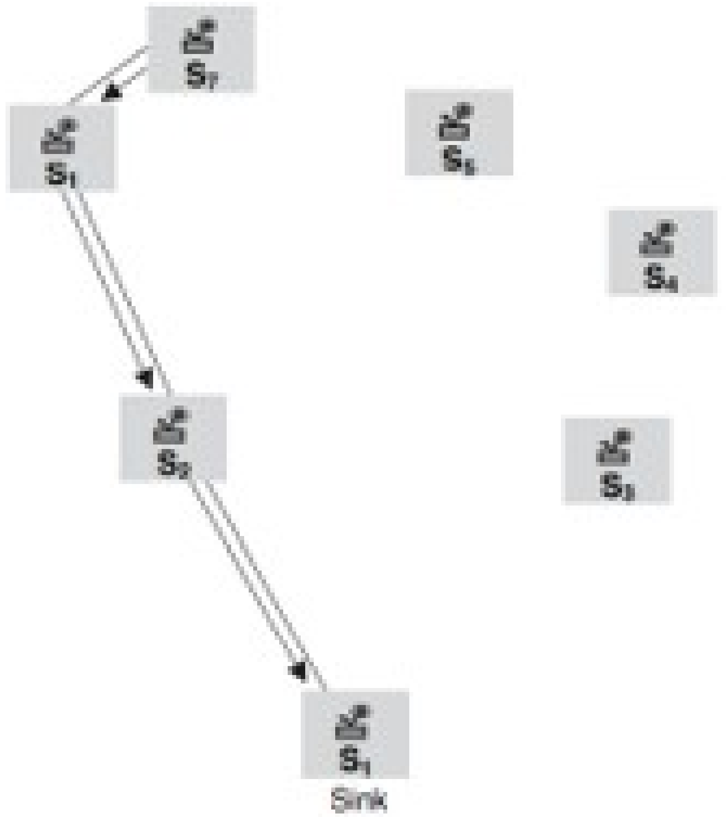


Figure 4.13 Data delivery along a reinforced path

Directed Diffusion

- Link failures caused by environmental factors affecting the communications channel, as well as node failures or performance degradation caused by node energy dissipation or complete depletion, can be repaired in directed diffusion.
- These failures are typically detected by reduced rate or data loss.
- When a path between a sensing node and the data sink fails, an alternative path, which is sending at lower rates, can be identified and reinforced.
- Lossy links can also be negatively reinforced by either sending interests with the exploratory data rate or simply by letting the neighbor's cache expire over time.
- Directed diffusion has the potential for significant energy savings. Its localized interactions allow it to achieve relatively high performance over unoptimized paths.
- Furthermore, the resulting diffusion mechanisms are stable under a range of network dynamics.
- Its data-centric approach obliterates the need for node addressing.
- The directed diffusion paradigm, however, is tightly coupled into a semantically driven query-on-demand data model.
- This may limit its use to applications that fit such a data model, where the interest-matching process can be achieved efficiently and unambiguously.

Geographical Routing

- The main objective of geographical routing is to use location information to formulate an efficient route search toward the destination.
- Geographical routing is very suitable to sensor networks, where data aggregation is a useful technique to minimize the number of transmissions toward the base station by eliminating redundancy among packets from different sources.
- The need for data aggregation to reduce energy consumption shifts the computation and communications model in sensor networks from a traditional address-centric paradigm, where the interaction is between two addressable endpoints of communications, to a data-centric paradigm, where the content of the data is more important than the identity of the node that gathers the data.

Geographical Routing

- In this new paradigm, an application may issue a query to inquire about a phenomenon within a specific physical area or near the vicinity of a landmark.
- For example, scientists analyzing traffic flow patterns may be interested in determining the average number, size, and speed of vehicles that travel on a specific section of a highway.
- The identity of the sensors that collect and disseminate information about traffic flow on a specific section of the highway is not as important as the data content.
- Furthermore, multiple nodes that happen to be located in the targeted section of the highway may participate in collecting and aggregating the data in order to answer the query.

Geographical Routing

- Traditional routing approaches, which are typically designed to discover a path between two addressable endpoints, are not well suited to handling geographically specific multidimensional queries.
- Geographical routing, on the other hand, leverages location information to reach a destination, with each node's location used as its address.
- In addition to its compatibility with data-centric applications, geographical routing requires low computation and communication overhead.
- In traditional routing approaches such as the one used in distributed shortest-path routing protocols for wired networks, knowledge of the entire network topology, or a summary thereof, may be required for a router to compute the shortest path to each destination.

Geographical Routing

- Furthermore, to maintain correct paths to all destinations, routers are called upon to update the state describing the current topology in a periodic fashion and when link failure occurs.
- The need to update the topology state constantly may lead to substantial overhead, proportional to
  - the product of the number of routers and
  - the rate of topological changes in the network.
- Geographical routing, on the other hand, does not require maintaining a “heavy” state at the routers to keep track of the current state of the topology.
- It requires only the propagation of single-hop topology information, such as the position of the “best’ neighbor to make correct forwarding decisions.

Geographical Routing

- The self-describing nature of geographical routing, combined with its localized approach to decision, obliterates the need for maintaining internal data structures such as routing tables.
- Consequently, the control overhead is reduced substantially, thereby enhancing its scalability in large networks.
- These attributes make geographical routing a feasible solution for routing in resource-constrained sensor networks.

Geographical Routing

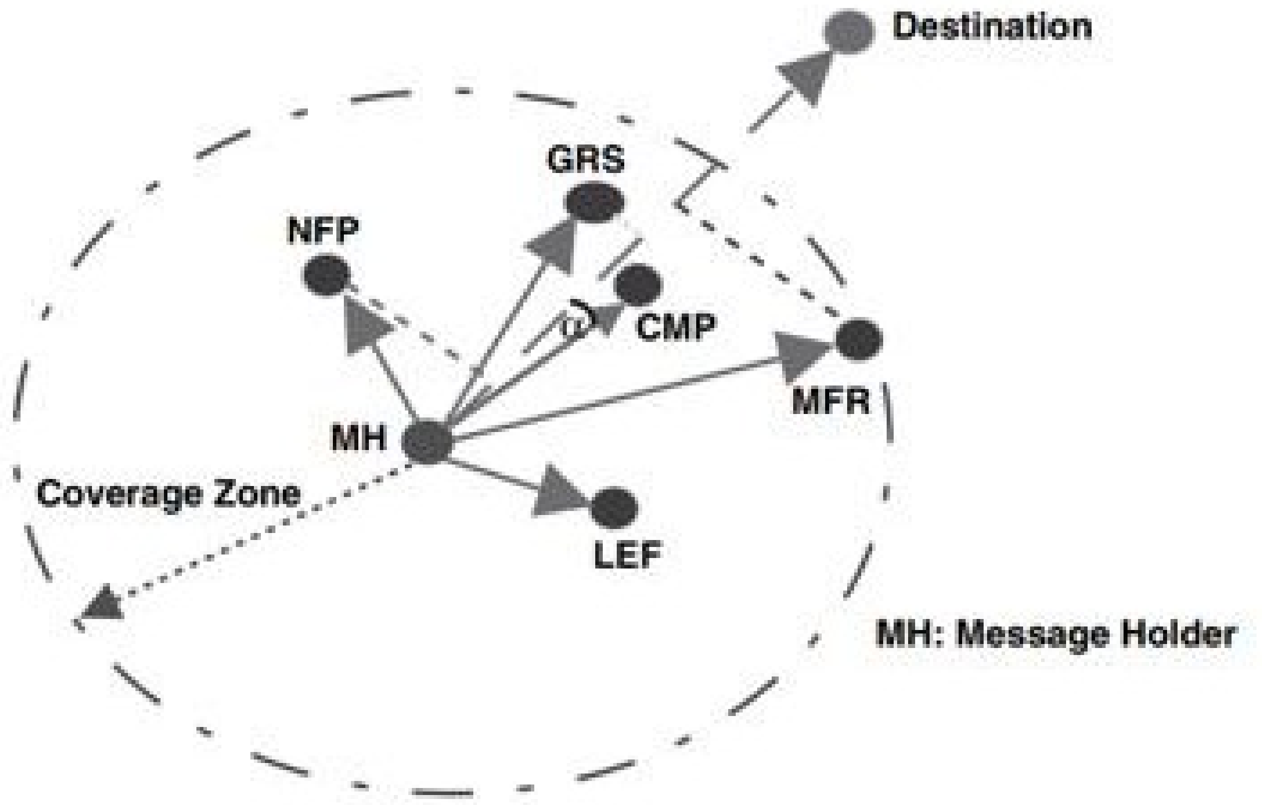


Figure 4.14 Geographical routing forwarding strategies