1. MAC LAYER

- The MAC and the routing layers are the most active research areas in WSNs
- There are two types of schemes available to allocate a single broadcast channel among competing nodes: Static Channel Allocation and Dynamic Channel Allocation
    - **Static Channel Allocation:** In this category of protocols, if there are N SNs, the bandwidth is divided into N equal portions in frequency (FDMA), in time (TDMA), in code (CDMA), in space (SDMA) or in schemes such as OFDM or ultra-wideband and since each SN is assigned a private portion, there is no or minimal interference amongst multiple SNs
    - **Dynamic Channel Allocation:** In this category of protocols, there is no fixed assignment of bandwidth
- When the number of active SNs changes dynamically and data becomes bursty at arbitrary SNs, it is most advisable to use dynamic channel allocation scheme
- These are contention-based schemes, where SNs contend for the channel when they have data while minimizing collisions with other SNs' transmissions

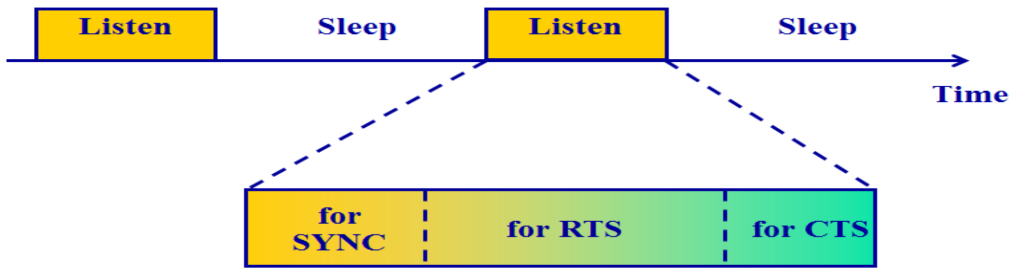
MAC Protocols:

- WSNs are designed to operate for long time as it is rather impractical to replenish the batteries
- However, nodes are in idle state for most time when no sensing occurs
- Measurements have shown that a typical radio consumes the similar level of energy in idle mode as in receiving mode
- Therefore, it is important that nodes are able to operate in low duty cycles

1.1 The Sensor-MAC

- The Sensor-MAC (S-MAC) protocol explores design trade-offs for energy-conservation in the MAC layer
- It reduces the radio energy consumption from the following sources: collision, control overhead, overhearing unnecessary traffic, and idle listening
- The basic scheme of S-MAC is to put all SNs into a low-duty-cycle mode –listen and sleep periodically
- When SNs are listening, they follow a contention rule to access the medium, which is similar to the IEEE 802.11 DCF
- In S-MAC, SNs exchange and coordinate on their sleep schedules rather than randomly sleep on their own
- Before each SN starts the periodic sleep, it needs to choose a schedule and broadcast it to its neighbors
- To prevent long-term clock drift, each SN periodically broadcasts its schedule as the SYNC packet

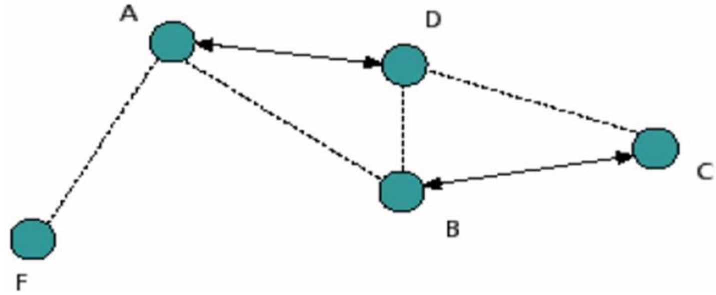
- To reduce control overhead and simplify broadcasting, S-MAC encourages neighboring SNs to choose the same schedule, but it is not a requirement
- A SN first listens for a fixed amount of time, which is at least the period for sending a SYNC packet
- If it receives a SYNC packet from any neighbor, it will follow that schedule by setting its own schedule to be the same
- Otherwise, the SN will choose an independent schedule after the initial listening period

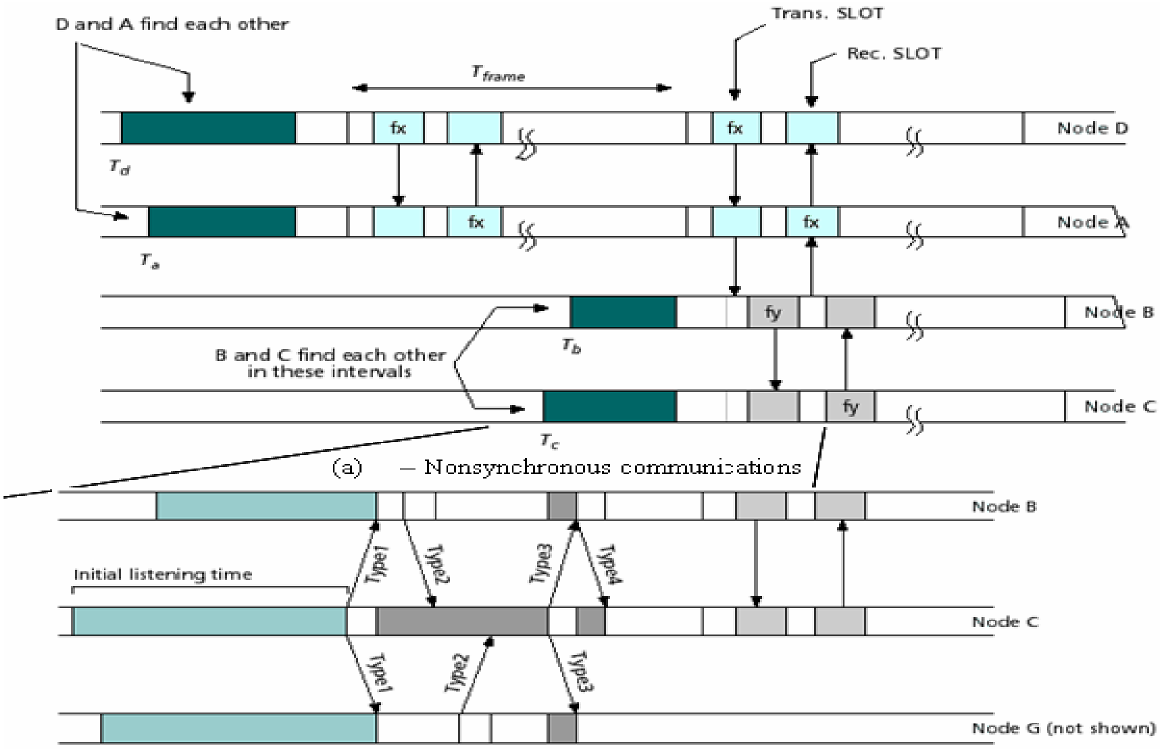


- Figure depicts the low-duty-cycle operation of each SN
- The listen interval is divided into two parts for both SYNC and data packets
- There is a contention window for randomized carrier sense time before sending each SYNC or data (RTS or broadcast) packet

1.2 SMACS:

- The SMACS is an infrastructure-building protocol that forms a flat topology (as opposed to a cluster hierarchy) for sensor networks
- SMACS is a distributed protocol which enables a collection of SNs to discover their neighbors and establish transmission/reception schedules for communicating with them without the need for any local or global master nodes
- In order to achieve this ease of formation, SMACS combines the neighbor discovery and channel assignment phases
- SMACS assigns a channel to a link immediately after the link's existence is discovered
- This way, links begin to form concurrently throughout the network
- By the time all nodes hear all their neighbors, they would have formed a connected network
- In a connected network, there exists at least one multihop path between any two distinct nodes
- Since only partial information about radio connectivity in the vicinity of a SN is used to assign time intervals to links, there is a potential for time collisions with slots assigned to adjacent links whose existence is not known at the time of channel assignment





- To reduce the likelihood of collisions, each link is required to operate on a different frequency
- This frequency band is chosen at random from a large pool of possible choices when the links are formed
- This idea is described in Figure 9.6(a) for the topology of Figure 9.5
- Here, nodes A and D wake up at times T_a and T_d
- After they find each other, they agree to transmit and receive during a pair of fixed time slots
- This transmission/reception pattern is repeated periodically every T_{frame}
- Nodes B and C, in turn, wake up later at times T_b and T_c, respectively
- The method by which SNs find each other and the scheme by which time slots and operating frequencies are determined constitute an important part of SMACS
- To illustrate this scheme, consider nodes B, C, and D shown in Figure 9.6(b)
- These nodes are engaged in the process of finding neighbors and wake up at random times

- Upon waking up, each node listens to the channel on a fixed frequency band for some random time duration
- A node decides to transmit an invitation by the end of this initial listening time if it has not heard any invitations from other nodes
- This is what happens to node C, which broadcasts an invitation or TYPE1 message
- Nodes B and D hear this TYPE1 message and broadcasts a response, or TYPE2, message addressed to node C during a random time following reception of TYPE1.

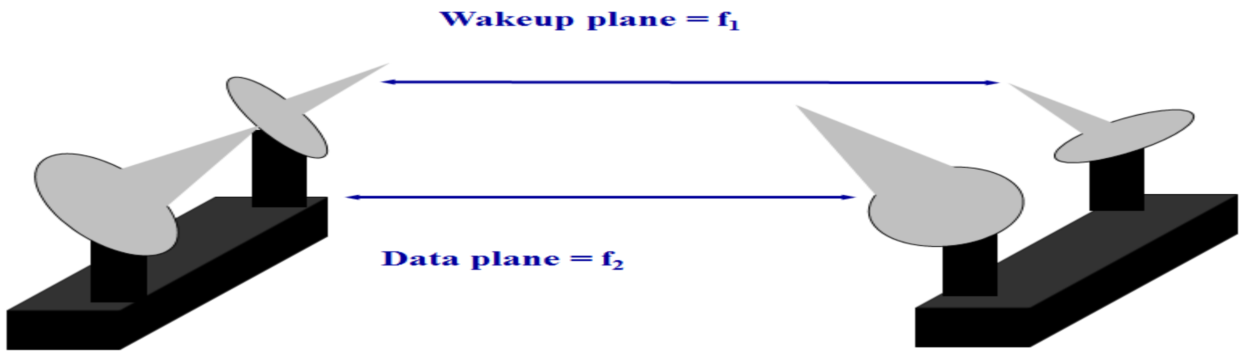
1.3 EAR (Eaves-drop-And-Register):

- Mobility can be introduced into a WSN as extensions to the stationary sensor network
- Mobile connections are very useful to a WSN and can arise in many scenarios where either energy or bandwidth is a major concern
- Where there is the constraint of limited power consumption, small, low bit rate data packets can be exchanged to relay data to and from the network whenever necessary
- At the same time, it cannot be assumed that each mobile node is aware of the global network state and/or node positions
- Similarly, a mobile node may not be able to complete its task (data collection, network instruction, information extraction) while remaining motionless
- Thus, the EAR protocol attempts to offer continuous service to these mobile nodes under both mobile and stationary constraints
- EAR is a low-power protocol that allows for operations to continue within the stationary network while intervening at desired moments for information exchange
- The EAR algorithm employs the following four primary messages:
- **Broadcast Invite (BI) –** This is used by the stationary node to invite other nodes to join and if multiple BIs are received, the mobile node continues to register every stationary node encountered, until its registry becomes full
- **Mobile Invite (MI)** – This message is sent by the mobile node in response to the BI message from the stationary node for establishing connection
- **Mobile Response (MR)** – This is sent by the stationary node in response to a MI message, and indicates the acceptance of the MI request which causes the stationary node to select slots along the TDMA frame for communication and the stationary node will enter the mobile node in its own registry
- **Mobile Disconnect (MD)** – With this message, the mobile node informs the stationary node of a disconnection and for energy saving purposes, no response is needed from the stationary node

1.4 The STEM:

- The Sparse Topology and Energy Management (STEM) protocol is based on the assumption that most of the time the sensor network is only sensing the environment, waiting for an event to happen

- In other words, STEM may be seen as better suitable for reactive sensor networks where the network is in the monitoring state for vast majority of time
- One example of such an application is a sensor network designed to detect fires in a forest
- These networks have to remain operational for months or years, but sensing only on the occurrence of a forest fire
- Clearly, although it is desirable that the transfer state be energy-efficient, it may be more important that the monitoring state be ultra-low-power as the network resides in this state for most of the time
- This observation holds true for many other applications as well
- The idea behind STEM is to turn on only a node's sensors and some preprocessing circuitry during monitoring states
- Whenever a possible event is detected, the main processor is woken up to analyze the sensed data in detail and forward it to the data sink
- However, the radio of the next hop in the path to the data sink is still turned off, if it did not detect the same event

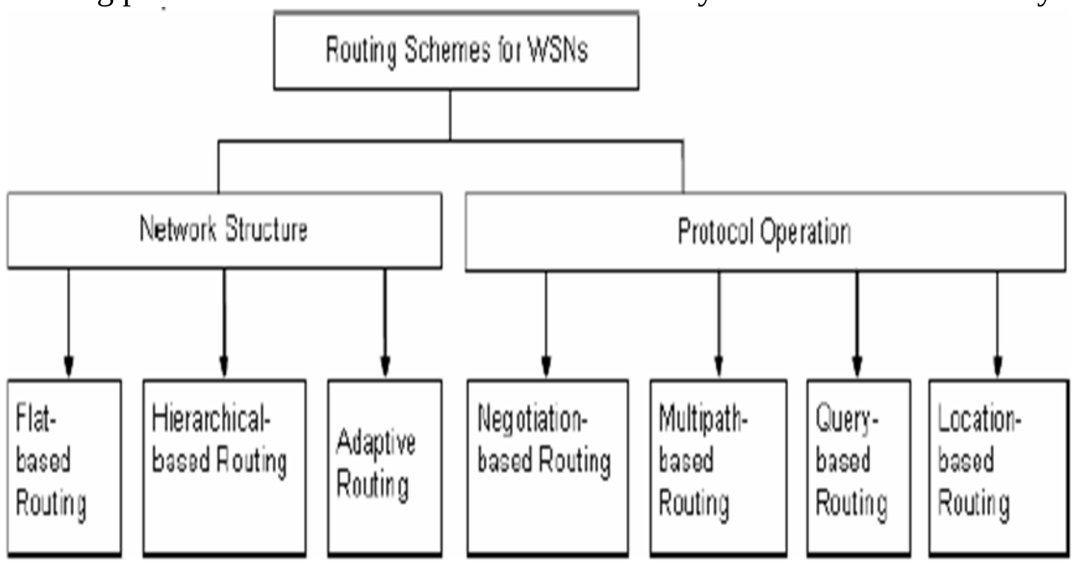


- STEM solves this problem by having each node to periodically turn on its radio for a short time to listen if someone else wants to communicate with it
- The node that wants to communicate, i.e. , the initiator SN, sends out a beacon with the ID of the node it is trying to wake up, i.e. , the target SN
- This can be viewed as a procedure by which the initiator SN attempts to activate the link between itself and the target SN
- As soon as the target SN receives this beacon, it responds back to the initiator node and both keep their radio on at this point

2. ROUTING LAYER

- Routing in sensor networks is usually multi-hop
- The goal is to send the data from source node(s) to a known destination node
- The destination node or the sink node is known and addressed by means of its location
- A BS may be fixed or mobile, and is capable of connecting the sensor network to an existing infrastructure where the user can have access to the collected data

- 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 unpredictable topological changes
- Thus, the main objective of routing techniques is to minimize the energy consumption in order to prolong WSN lifetime
- To achieve this objective, routing protocols proposed in the literature employ some well-known routing techniques as well as tactics special to WSNs
- To preserve energy, strategies like data aggregation and in-network processing, clustering, different node role assignment, and data-centric methods are employed
- In sensor networks, conservation of energy is considered relatively more important than quality of data sent
- Therefore, energy-aware routing protocols need to satisfy this requirement
- Routing protocols for WSNs have been extensively studied in the last few years



- Routing protocols for WSNs can be broadly classified into flat-based, hierarchical-based, and adaptive, depending on the network structure
- In flat-based routing, all nodes are assigned equal role
- In hierarchical-based routing, however, nodes play different roles and certain nodes, called cluster heads (CHs), are given more responsibility
- In adaptive routing, certain system parameters are controlled in order to adapt to the current network conditions and available energy levels
- Furthermore, these protocols can be classified into multipath-based, query-based, negotiation-based, or location-based routing techniques

2.1Network Structure Based

- In this class of routing protocols, the network structure is one of the determinant factors

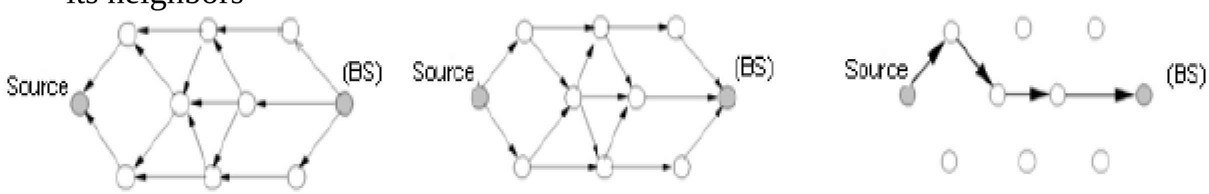
- In addition, the network structure can be further subdivided into flat, hierarchical and adaptive depending upon its organization

Flat Routing

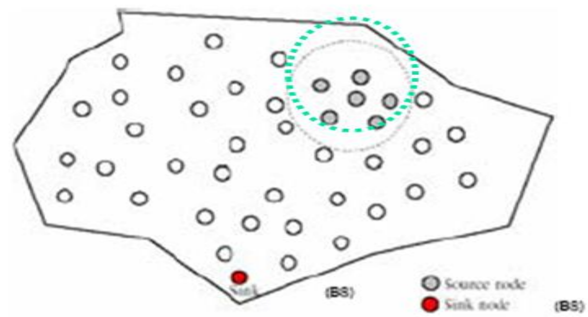
- In flat routing based protocols, all nodes play the same role and we present the most prominent protocols falling in this category

2.1.1 Directed Diffusion

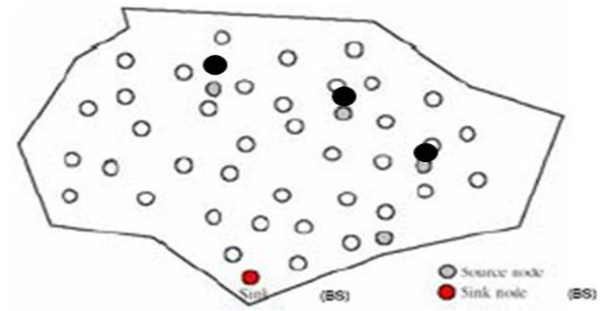
- Directed Diffusion is a data aggregation and dissemination paradigm for sensor networks
- It is a data-centric (DC) and application-aware approach in the sense that all data generated by sensor nodes is named by attribute-value pairs
- Directed Diffusion is very useful for applications requiring dissemination and processing of queries
- The main idea of the DC paradigm is to combine the data coming from different sources en-route (in-network aggregation) 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 (BS) 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, which describes a task to be done by the network
- 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 setup to draw data satisfying the query towards the requesting node
- Each SN that receives the interest setup a gradient toward the SNs from which it receives the interest
- This process continues until gradients are setup from the sources back to the BS
- Sensor nodes in a directed diffusion-based network are application-aware, which enables diffusion to achieve energy savings by choosing empirically good paths and by caching and processing data in the network
- An application of directed diffusion is to spontaneously propagate an important event to regions of the sensor network
- Such type of information retrieval is well suited for persistent queries where requesting nodes expect data that satisfy a query for a period of time



Event Radius (ER) model



Randum source (RS) model

2.1.2 Sequential Assignment Routing (SAR)

- The routing scheme in SAR depends on three factors: energy resources, QoS on each path, and the priority level of each packet
- To avoid single route failure, a multi-path approach coupled with a localized path restoration scheme is employed
- 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 constructed
- The paths of the tree are defined by avoiding nodes with low energy or QoS guarantees
- At the end of this process, each sensor node is a part of multi-path tree
- For each SN, two metrics are associated with each path: delay (which is an additive QoS metric); and energy usage for routing on that path
- The energy is measured with respect to how many packets will traverse that path
- 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 goal of SAR is to minimize the average weighted QoS metric for the network

2.1.3 Minimum Cost Forwarding Algorithm

- The minimum cost forwarding algorithm (MCFA) exploits the fact that the direction of routing is always known, that is, towards fixed and predetermined external BS
- Therefore, a SN need not have a unique ID nor maintain a routing table
- Instead, each node maintains the least cost estimate from itself to the BS
- Each message forwarded by the SN is broadcast to its neighbors
- When a node receives the message, it checks if it is on the least cost path between the source SN and the BS
- If so, it re-broadcasts the message to its neighbors
- This process repeats until the BS is reached
- In MCFA, each sensor node should know the least cost path estimate from itself to the BS

2.1.4 Coherent and Non-Coherent Processing:

- Data processing is a major component in the operation of any WSN
- In general, sensor nodes cooperate with each other in processing different data flooded throughout the network
- Two examples of data processing techniques are coherent and non-coherent data processing-based routing
- In non-coherent data processing routing, nodes locally process the raw data before being sent to other nodes for further processing
- The nodes that perform further processing are called the aggregators
- In coherent routing, the data is forwarded to aggregators after minimum processing of time stamping and duplicate suppression
- To perform energy-efficient routing, normally coherent processing is selected

2.1.5 Energy Aware Routing:

- This protocol is similar to directed diffusion (discussed earlier) with the difference that it maintains a set of paths instead of maintaining or enforcing one optimal path
- These paths are maintained and chosen by means of a certain probability, which depends on how low the energy can be conseved for each path
- By selecting different routes at different times, the energy of any single route will not deplete so quickly
- The protocol initiates a connection through localized flooding, which is used to discover all routes between source/destination pair and their costs; thus building up the routing tables
- Next, the high-cost paths are discarded and a forwarding table is constructed by choosing neighboring nodes inversely proportional to their cost
- Then, data is sent to the destination using the forwarding table with a probability that is inversely proportional to the node cost
- Finally, to keep the various paths alive, localized flooding is carried out by the destination node

2.1.6 Hierarchical Routing

- Hierarchical, or cluster-based routing has its roots in wired networks, where the main goals are to achieve scalable and efficient communication
- As such, the concept of hierarchical routing has also been employed in WSN to perform energy-efficient routing
- In a hierarchical architecture, higher energy nodes (usually called cluster heads) can be used to process and send the accumulated information while low energy nodes can be used to sense in the neighborhood of the target and pass on to the CH

- In these cluster-based architectures creation of clusters and appropriate assignment of special tasks to CHs can contribute to overall system scalability, lifetime, and energy efficiency
- Each cluster has a CH which collects data from its cluster members, aggregates it and sends it to the BS or an upper level CH

2.1.7 Cluster Based Routing Protocol (CBRP)

- A simple cluster based routing protocol (CBRP) divides the network nodes into a number of overlapping or disjoint two-hop-diameter clusters in a distributed manner
- The cluster members just send the data to the CH, and the CH is responsible for routing the data to the destination
- The major drawback with CBRP is that it requires a lot of hello messages to form and maintain the clusters, and thus may not be suitable for WSN
- Given that sensor nodes are stationary in most of the applications this is a considerable and unnecessary overhead

Scalable Coordination

- In hierarchical clustering method, the cluster formation appears to require considerable amount of energy as periodic advertisements are needed to form the hierarchy
- Also, any changes in the network conditions or sensor energy level result in re-clustering which may be not quite acceptable as some parameters tend to change dynamically

2.1.8 Low-Energy Adaptive Clustering Hierarchy (LEACH)

- LEACH is a hierarchical clustering algorithm for sensor networks, called Low-Energy Adaptive Clustering Hierarchy (LEACH)
- LEACH is a good approximation of a proactive network protocol, with some minor differences which includes a distributed cluster formation algorithm
- LEACH randomly selects a few sensor nodes as CHs and rotates this role amongst the cluster members so as to evenly distribute the energy dissipation across the cluster
- 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
- LEACH uses a TDMA and CDMA MAC to reduce intra-cluster and inter-cluster collisions, respectively, while data collection is centralized and is performed periodically

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

- The Power-Efficient Gathering in Sensor Information Systems (PEGASIS) is a near optimal chain-based protocol which is an enhancement over LEACH
- In order to prolong network lifetime, nodes employing PEGASIS communicate with their closest neighbors only and they take turns in communicating with the BS
- Whenever a round of nodes communicating with the BS ends, a new round starts
- This decreases the power required to transmit data per round, as energy dissipation is spread uniformly over all nodes and as a result, PEGASIS has two main goals
- First, it aims at increasing the lifetime of each node by using collaborative techniques, as a result, the overall network lifetime is also increased
- Second, it only allows coordination between nodes that are close together, thus reducing the bandwidth consumed for communication
- To locate the closest neighbor SN, SNs use the signal strength to measure the distance to all of its neighboring nodes and then adjust the signal strength so that only one node can be heard

2.1.10 Small Minimum Energy Communication Network (MECN)

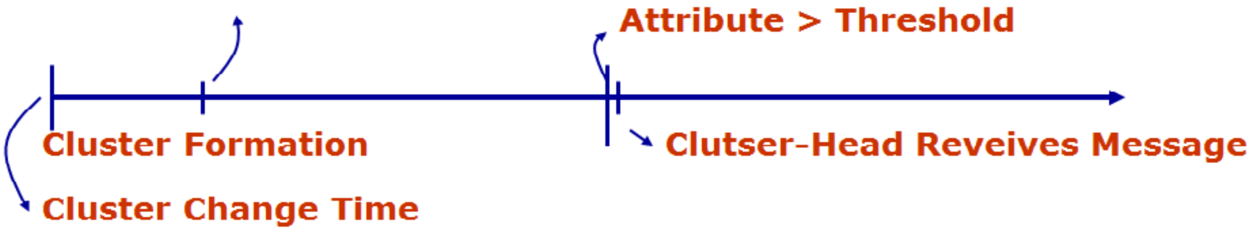
- The minimum energy communication network (MECN) protocol has been designed to compute an energy-efficient subnetwork for a given sensor network
- On top of MECN, a new algorithm called Small MECN (SMECN) has been proposed to construct such a subnetwork
- The subnetwork (i.e. , subgraph G') constructed by SMECN is smaller than the one constructed by MECN if the broadcast region around the broadcasting node is circular for a given power assignment
- The subgraph G' of graph G, which represents the sensor network, minimizes the energy consumption satisfying the following conditions:
    1. The number of edges in G' is less than in G, while containing all nodes in G
    2. 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
- The resulting subnetwork computed by SMECN helps in the task of sending messages on minimum-energy paths

2.1.11 Threshold-sensitive Energy Efficient (TEEN)

- In this scheme, at every cluster change time, the CH broadcasts the following to its members in addition to the attributes:
    1. Hard Threshold (HT): This is a threshold value for the sensed attribute
    2. It is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its CH

3. Soft Threshold (ST): This is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit once the HT has been crossed

- In TEEN, nodes sense their environment continuously, thereby making it appropriate for real time applications



- **Features**
  1. Suited for time critical sensing applications
  2. Time critical data reaches the user almost instantaneously
  3. At every cluster change time, the parameters are broadcast afresh and so, the user can change them as required
  4. Energy consumption can be controlled by changing the threshold values

TEEN Reactive Protocol:

- **Features**

It offers flexibility by allowing the user to set the threshold values for the attributes
Attributes can be changed every cluster change

- **Drawback**

If threshold H_T not reached then user never gets to know about the network

- **Application**

Time critical environment like intrusion detection, etc.

2.1.12 Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol

There are applications in which the user wants time-critical data and also wants to query the network for analysis on conditions other than collecting time-critical data. In other words, the user might need a network that reacts immediately to time-critical situations and also gives an overall picture of the network at periodic intervals, so that it is able to answer analysis queries. Neither of the above networks can do both the jobs satisfactorily since they have their own limitations.

APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol) [Manjeshwar 2002] is able to combine the best features of proactive and reactive networks while minimizing their limitations to create a new type of network called a *Hybrid network*. In this network, the nodes not only send data periodically, they also respond to sudden changes in attribute values. This uses the same model as the above protocols with following changes. In APTEEN, once the cluster heads are decided the following events take place, in each cluster period. The cluster head first broadcasts the following parameters:

- *Attributes* (A): This is a set of physical parameters which the user is interested in obtaining data about.
- *Thresholds*: This parameter consists of a hard threshold (HT) and a soft threshold (ST). HT is a value of an attribute beyond which a node can be triggered to transmit data. ST is a small change in the value of an attribute which can trigger a node to transmit.
- *Schedule*: This is a TDMA schedule similar to the one used in [Heinzelman 2000b], assigning a slot to each node.
- *Count Time* (CT): It is the maximum time period between two successive reports sent by a node. It can be a multiple of the TDMA schedule length and it introduces them proactive component in the protocol.

The nodes sense their environment continuously. However, only those nodes which sense a data value at or beyond the hard threshold, transmit. Furthermore, once a node senses a value beyond HT, it next transmits data only when the value of that attribute changes by an amount equal to or greater than the soft threshold ST. The exception to this rule is that if a node does not send data for a time period equal to the count time, it is forced to sense and transmit the data, irrespective of the sensed value of the attribute. Since nodes near to each other may fall in the same cluster and sense similar data, they may try sending their data simultaneously, leading to collisions between their messages. Hence, a TDMA schedule is used and each node in the cluster is assigned a transmission slot, as shown in Figure. In the sections to follow, we will refer to data values exceeding the threshold value as critical data.

The main features of this scheme are as follows:

- It combines both proactive and reactive policies. By sending periodic data, it gives the user a complete picture of the network, like a proactive scheme. It also senses data continuously and responds immediately to drastic changes, thus making it responsive to time critical situations. It, thus, behaves as a reactive network also.
- It offers a lot of flexibility by allowing the user to set the time interval (CT) and the threshold values for the attributes.
- Changing the count time as well as the threshold values can control energy consumption.
- The hybrid network can emulate a proactive network or a reactive network, based on the application, by suitably setting the count time and the threshold values.

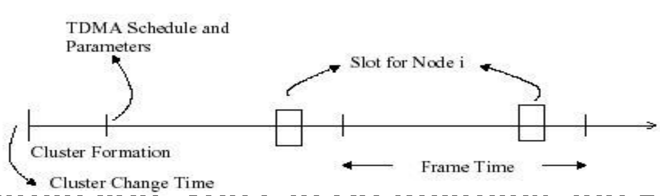
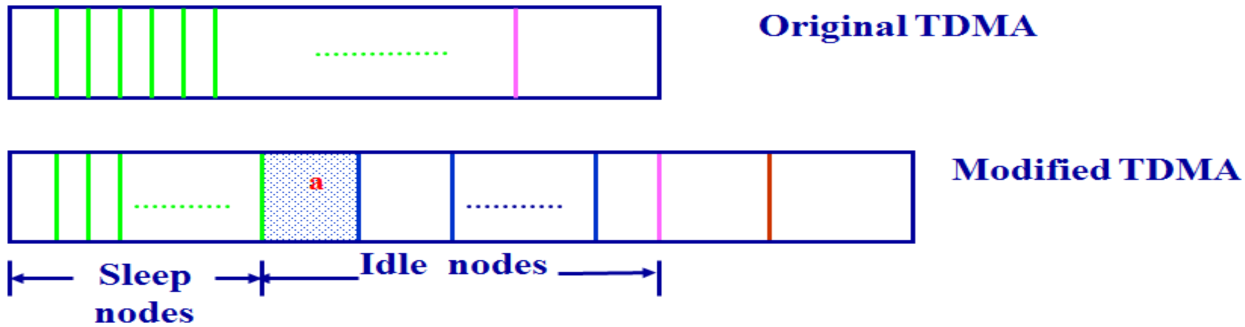


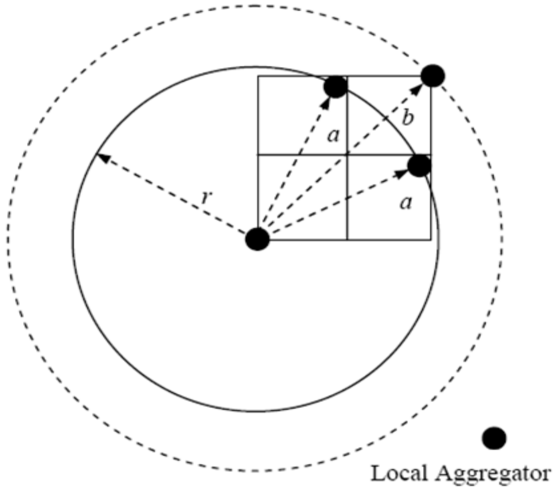
Figure 21 – Time line for APTEEN

The main drawback of this scheme is the additional complexity required to implement the threshold functions and the count time. However, this might be seen as a trade-off.



2.1.13 Routing in Fixed-size Clusters:

- Routing in sensor networks can also take advantage of geography-awareness
- One such routing protocol is called Geography Adaptive Fidelity (GAF) where the network is firstly divided into fixed zones
- Within each zone, nodes collaborate with each other to play different roles
- For example, nodes elect one SN to stay awake for a certain period of time while the others sleep
- This particular elected SN is responsible for monitoring and reporting data to the BS on behalf of all nodes within the zone
- Here, each SN is positioned randomly in a two dimensional plane
- When a sensor transmits a packet for a total distance r, the signal is strong enough for other sensors to hear it within the Euclidean distance r from the sensor that originates the packet. Figure 9.14 depicts an example of fixed zoning that can be applied to WSN
- A fixed cluster of each side *a* can be selected and is connected if:
    - If the signal travels a distance of a = r/(sqrt of 5) in adjacent vertical or horizontal directions, two sensors can communicate directly
    - For a diagonal communication to take place, the signal has to span a distance of a = r/(2 sqrt of 2)



- r is the distance of packet transmission by each sensor

2.1.14 Sensor Aggregates Routing

- A sensor aggregate includes those SNs 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
- Here, the formation of appropriate sensor aggregate is considered in terms of resource allocation for communication and sensing
- Sensors in the network are divided into clusters according to their sensed signal strength
- After that, local cluster leaders (CH) are elected by exchanging information between neighboring sensors
- Once a sensor node has exchanged packets with all its one-hop neighbors, if it finds that its signal strength is higher than all its one-hop neighbors, it declares itself as a leader
- This leader-based tracking algorithm assumes a unique leader to know surrounding geographical region for collaboration

2.1.15 Hierarchical Power-Aware Routing

- A hierarchical power-aware routing scheme divides the network into groups of sensors
- The groups in a geographic proximity, are clustered together as a zone and each zone is treated as an entity
- Routing is performed by allowing each zone to decide how it routes a message hierarchically across other zones
- In this scheme, messages are routed along the path with the maximal fraction of the remaining power after the message is transmitted, and this is called the max-min path

- One of the concerns with the max-min path is that traversal through the SNs with high residual power may be expensive as compared to the path with the minimal power consumption
- Too much power consumption decreases the overall power level of the system, thereby decreasing the lifetime of the network

2.1.16 Sensor Protocols for Information via Negotiation (SPIN)

- Disseminates all the information of each SN to every other SN in the network
- All SNs in the network are potential BS
- A user is able to query any SN and get the required information immediately
- These protocols make use of the property that SNs in close proximity have similar data and thus transmit only the data that the other SNs do not have
- SPIN assigns a high-level name to appropriately describe their collected data, called meta-data, and perform meta-data negotiations before any data is transmitted
- This ensures that no redundant data is transmitted throughout the network
- The format of the meta-data is application-specific and is not specified in SPIN
- SPIN works in a time-driven manner wherein it distributes the information all over the network, even when a user does not request any data
- The SPIN family of protocols includes two protocols, namely, SPIN-1 and SPIN-2, which incorporate negotiation before transmitting data so as to ensure that only useful information is transferred

Flat versus Hierarchical

Hierarchical	**Flat**
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 cluster head	Node on multi-hop path aggregates incoming data from neighbors
Simple but non-optimal routing	Routing is complex but optimal
Requires global and local synchronization	Links formed in the fly, without synchronization

Overhead of cluster formation throughout the network	Routes formed only in regions that have data for transmission
Lower latency as multi-hop network formed by cluster heads is always available	Latency in waking up intermediate nodes and setting up the multi-hop path
Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Energy dissipation cannot be controlled	Energy dissipation adapts to traffic pattern

Comparison of SPIN, LEACH and Directed Diffusion

Protocol →	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	Yes	Yes

2.2 Operation Based protocols

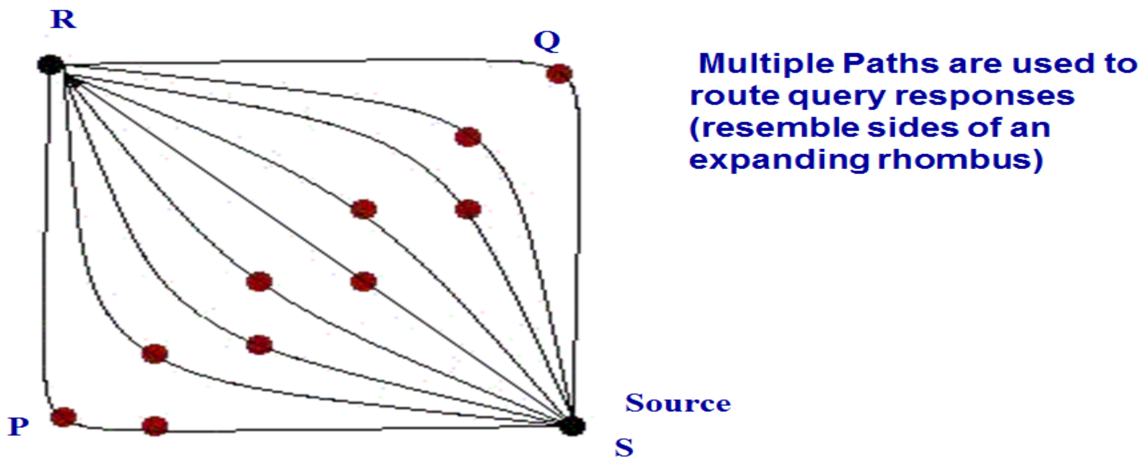
2.2.1 Negotiation-based Routing

- Negotiation-based routing protocols use high level data descriptors in order to eliminate redundant data transmissions
- Communication decisions are also made based on the available resources
- The motivation here is that the use of flooding to disseminate data produces implosion and data overlap, leading to scenarios where nodes receive duplicate copies of the same data
- If the same data is transmitted by several sensors, considerable energy is consumed
- The main idea behind negotiation-based routing in WSNs is to suppress duplicate information and prevent redundant data from being sent to the next sensor or the BS
- This is done by conducting a series of negotiation messages before the actual data transmission begins

2.2.2 Multipath-based Routing

- Network performance, and possibly lifetime, in WSNs can be significantly improved if the routing protocol is able to maintain multiple paths to a destination

- The fault tolerance (resilience) is considerably increased, which is measured by the likelihood that an alternate path exists between a source and a destination when the primary path fails
- Clearly, this can be increased if we maintain multiple paths between the source and the destination at the expense of an increased energy consumption and traffic generation (i.e., overhead), as alternate paths are kept alive by sending periodic messages
- We would also like to note here that multipath routes between a source and a destination can be node-disjoint or not
- Multiple paths between a source and destination are said to be node-disjoint when there is no node overlap amongst them
- An extension of the multi-path algorithm is described that contains several important characteristics
- The idea is to reduce the complexity of finding the paths by defining the rectangular region bounded by the responding sensor and the BS as the routing region and defining the paths passing through cross-diagonal sensors as multiple paths
- One such example for a rectangular mesh-based WSN, is shown in Figure 9.15
- This identifies many paths, with different path lengths in terms of number of intermediate SNs in the path and hence, reduce the delay between the responding SN and the BS by the process of data store-and-forward along the selected path
- The path along the diagonal, is shortest in length and if this path is used all the time in responding the persistent query, the energy of the sensors lying on this path, could get depleted at a much faster rate then rest of the network



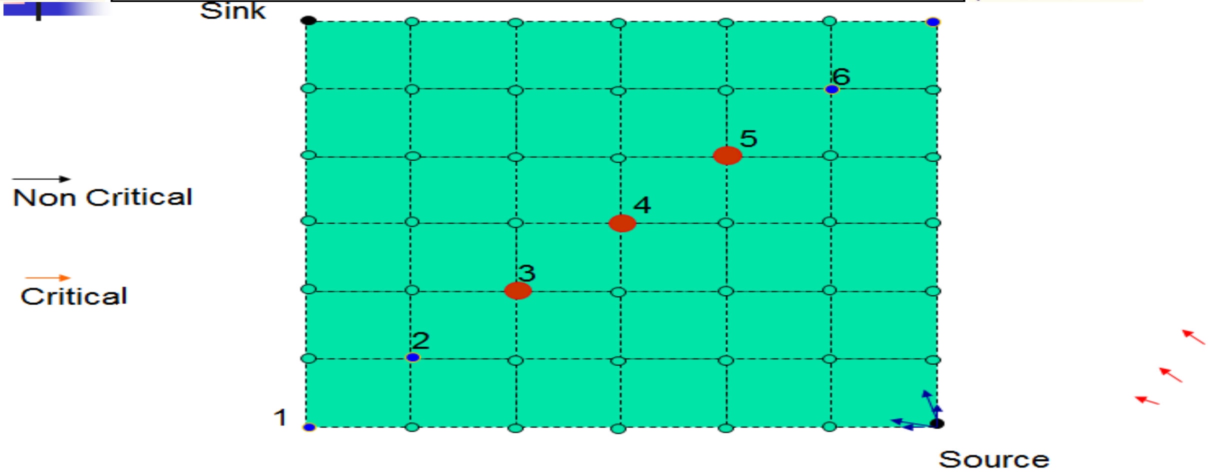


Figure: Load Shedding

2.2.3 Query-based Routing

- In query-based routing, the destination nodes propagate a query for data (sensing task) from a node throughout the network
- A node having the data matching the query sends it back to the node which requested it
- Usually, these queries are described in natural language or in high-level query languages
- For example, a BS B1 may submit a query to node N1 inquiring: "Are there moving vehicles in battlefield region 1?"
- In query-based routing, all the nodes have tables consisting of the sensing tasks queries that they received, and send back data matching these tasks whenever they receive it
- Directed diffusion is an example of this type of routing
- Here, the sink node sends out messages of interest to SNs
- As the interest is propagated throughout the WSN, the gradients from the source back to the sink (BS) are set up

2.2.4 Location-based Routing

- In location-based routing, SNs are addressed by means of their locations
- Here, the distance between neighboring SNs can be estimated on the basis of incoming signal strengths, and relative coordinates of neighboring SNs can be obtained by exchanging such information
- Alternatively, the location of nodes may be available directly through GPS if we consider nodes are equipped with a small low power GPS receiver
- In order to conserve energy, some location-based schemes demand that SNs should go to sleep if there is no activity
- Clearly, the more sleeping SNs in the network the more energy can be saved
- However, the active SNs should be connected, should cover the entire sensing region, and should provide basic routing and broadcasting functionalities

3. HIGH-LEVEL APPLICATION LAYER SUPPORT

- The protocols we have presented so far are also found, albeit in some different form in traditional wired, cellular, or ad hoc networks
- For specific applications, a higher level of abstraction specifically tailored to WSN appears to be useful

3.1 Distributed Query Processing

- The number of messages generated in distributed query processing is several magnitudes less than in centralized scheme
- There are two approaches for processing sensor queries: warehousing and distributed
- In the warehousing approach, data is extracted in a pre-defined manner and stored in a central database
- In the distributed approach, only relevant data is extracted from the sensor network, when and where it is needed

3.2 Sensor Databases

- One can view the wireless sensor network as a comprehensive distributed database and interact with it via database queries
- This approach solves, en passant, the entire problem of service definition and interfaces to WSNs by mandating, for example, SQL queries as the interface
- The problems encountered here are in finding energy-efficiency ways of executing such queries and of defining proper query languages that can express the full richness of WSNs
- The TinyDB project carried out at the University of California at Berkeley is looking at these issues
- A model for sensor database systems known as COUGAR, defines appropriate user and internal representation of queries
- The sensor queries is also considered so that it is easier to aggregate the data and to combine two or more queries

3.3 Distributed Algorithms

- WSNs are not only concerned with merely *sensing* the environment but also with interacting with the environment
- Once actuators like valves are added to WSNs, the question of distributed algorithms becomes inevitable
- One showcase is the question of distributed consensus, where several actuators have to reach a joint decision

3.4 In-Network Processing

- In-network processing, requires data to be modified as it flows through the network
- It has become one of the primary enabling technologies for WSNs as it has the potential to considerably increase the energy efficiency of the network