

Research Article

Energy Saving Mechanisms for MAC Protocols in Wireless Sensor Networks

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Energy efficiency is a primary requirement in a wireless sensor network (WSN). This is a major design parameter in medium access control (MAC) protocols for WSN due to limited resources in sensor nodes that include low battery power. Hence a proposed MAC protocol must be energy efficient by reducing the potential energy wastes. Developing such a MAC protocol has been a hot research area in WSN. To avoid wasting the limited energy, various energy saving mechanisms are proposed for MAC protocols. These mechanisms have a common design objective—to save energy to maximize the network lifetime. This paper presents a survey on various energy saving mechanisms that are proposed for MAC protocols in WSN. We present a detailed discussion of these mechanisms and discuss their strengths and weaknesses. We also discuss MAC protocols that use these energy saving mechanisms.

1. Introduction

A few sensor devices (also called nodes) can be deployed together to create a wireless sensor network (WSN). A WSN can contain few to thousands of these devices at a time. The networks may be dense or sparse with different network topologies. The sensor devices collect data through sensing and monitoring from their respective environment and send to a sink for further processing. As the cost and size of sensor devices decreasing fast, the application areas of such wireless sensor networks have also expanded rapidly. The major application domains [1, 2] are home and office, control and automation, logistics and transportation, environmental monitoring, healthcare, agriculture, security and surveillance, tourism and leisure, military-related activities, education and training, and entertainment. Sensors are now present everywhere including digitally equipped smart homes and buildings, vehicle tracking and detection, monitor of manufacturing process in factories, inventory control, natural habitats, and patients in hospitals, and so on. The requirements in the above applications are as diverse as the application areas themselves. Figure 1 shows typical application areas.

Sensor devices are tiny in size with constrained processors, limited memory size, low bit rate communications with short transmission range and considerably low in energy capacity compared to other wireless devices such as cell phones and PDAs. A survey of hardware systems for wireless sensor networks can be found in [3]. In most cases, sensor nodes run on batteries that are normally not rechargeable. Energy scavenging [4, 5] for sensor nodes is getting attention lately and may gain much momentum in near future. However, this is not an easy task. Hence, most sensor devices still have very limited resources. A block diagram of a sensor device adapted from [6] is shown in Figure 2(b).

Hundreds of MAC protocols are proposed and deployed until now with the sole purpose of saving energy. They use different methodologies to make them energy efficient. Surveys as mentioned in later sections of this paper are found in the literature. We have found that these works are confined on discussing MAC protocols and their working procedures. A comprehensive survey on MAC mechanisms is absent. A detail survey of these techniques and mechanisms is necessary and useful at this stage.

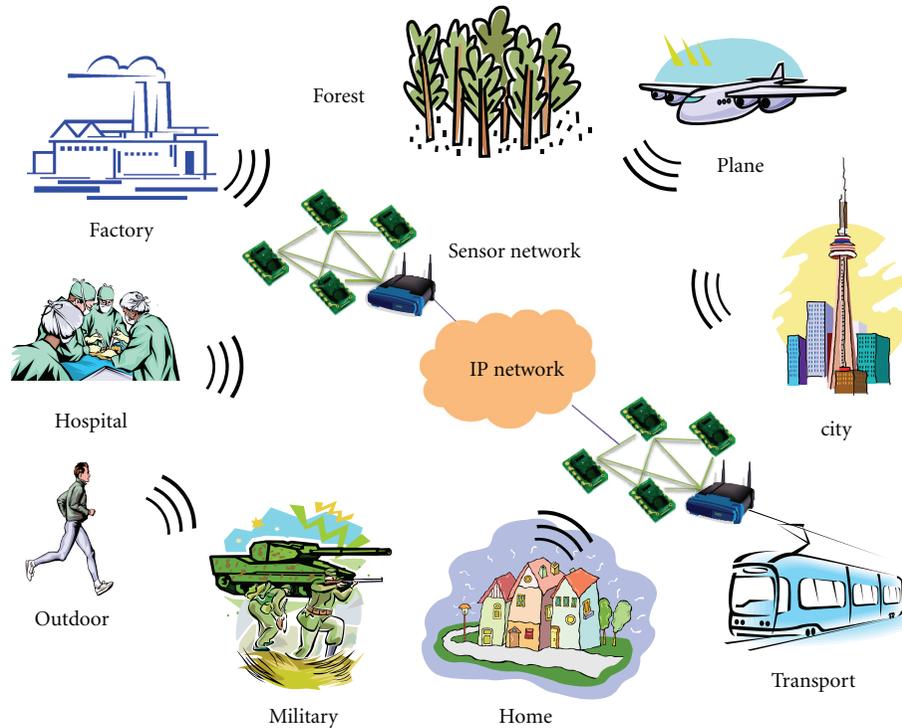


FIGURE 1: Some typical application areas of wireless sensor networks.

In this paper, we have used both energy and power terms to express the same concept. Rest of the paper is organized as follows. In Section 2, we discuss medium access control in wireless sensor networks. In Section 3, we discuss energy management in WSN. Here, we discuss major causes of energy waste and some considerations for energy saving in WSN. Sections 4 and 5 are devoted to energy saving mechanisms in WSN followed by the conclusion of our works in Section 6.

2. Medium Access Control in WSN

A MAC protocol controls the accessing of channel in a network. Due to lack of many of the advantages of infrastructure-based networks, an efficient MAC protocol is of utmost necessity in WSN. Designing a MAC protocol for WSN is not an easy task due to challenging application environment and ad-hoc nature of the network. Among the primary concerns of such a MAC protocol are energy efficiency and effective network control and management. Numerous MAC protocols are proposed for diverse scenarios and application areas of WSN. Due to diversity in their use of methodologies, MAC protocols for WSN classification are complex. Many authors [7–9] have tried to classify WSN MAC protocols in various categories. Authors in [10] have presented a classification for MAC protocols for ad-hoc networks into two broad classes: contention-based and contention-free. They have further presented classification based on other criteria. Authors in [11] have presented a taxonomy of MAC protocols according to time organization and historical development and discussed working of some

of the MAC protocols in detail. One such classification adapted from works in [7, 8, 10] is shown in Figure 3. Authors in [12] have presented a classification table of 34 MACs for ad-hoc mobile networks into six key features. These are channel separation and access, topology, power, transmission initiation, traffic load and scalability, and range. These criteria also effectively apply to MAC protocols in wireless sensor networks. The wide range of methodologies used in various MACs significantly influences the energy consumption in a sensor network. Hence it can be the case where one energy-efficient MAC protocol in a particular application scenario may be inefficient in terms of energy saving in a different application.

3. Energy Management in Sensor Networks

Sensor nodes normally have limited amount of energy and hence need to save energy to maximize the lifetime. A sensor node is assumed to be dead when it is out of battery. Energy is consumed by a sensor node either for sensing purpose, processing the data, or communication which consume the most amount of energy. Efficient energy management is a key requirement in WSN, and many of the strategies assume that the data acquisition consumes significantly less energy than data transmission [13]. Table 1 shows power consumption of some common radio/sensor devices.

Efficient energy management strategies must be devised at sensor nodes and then network levels to prolong the network lifetime as much as possible. Several energy management schemes have been proposed for reducing the energy consumption acting at the radio level. A detailed survey

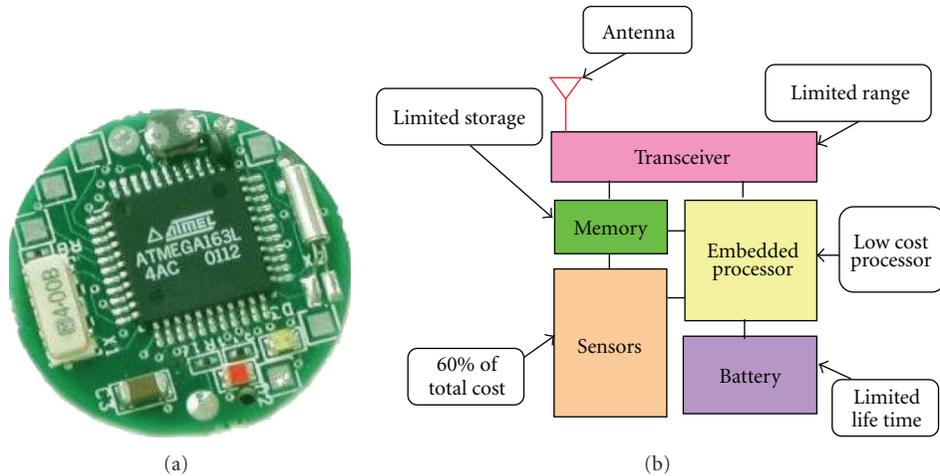


FIGURE 2: (a) A MICA2 dot sensor device. (b) Block diagram of a sensor node.

TABLE 1: Some common sensor devices.

Radio/Sensor	Producer	Power consumption	
		Transmission (mW)	Reception (mW)
CC2420	Texas Instruments	35 (at 0 dBm)	38
CC1000	Texas Instruments	42 (at 0 dBm)	29
TR1000	RF Monolithics	36 (at 0 dBm)	9
JN-DSJN513x	Jennic	111 (at 1 dBm)	111

can be found in [8]. Due to diversity of sensor networks, energy saving and thereby prolonging the lifetime of sensor nodes depend on several key factors and requirements. A summary of requirements influencing network lifetime can be found in [14]. Network lifetime has become the key characteristic for evaluating sensor networks in an application-specific way [14]. Authors in [15] reported that the types of communication patterns, which are observed in sensor network applications should be investigated, since these patterns determine the behavior of the sensor network traffic that has to be handled by a given MAC protocol. Due to these reasons, major research time has been devoted to maximize the lifetime of sensors through efficient energy managed MAC protocols.

3.1. Energy Waste in Sensor Networks. In a typical sensor network, major waste of energy occurs due to several reasons [16, 17]. Foremost of them is *idle listening*. It happens when a node is listening to an idle channel in anticipation of possible arrival of packets. Next major reason is *collision*. Due to the large number of sensor nodes present in a small area, collision is a common occurrence, unless controlled effectively. As collided packets are discarded, packet retransmission causes further loss of energy. *Overhearing* can also cause wasting of energy. It occurs when a node listens or overhears a packet thinking it may be the intended receiver, although in actual fact the packet is meant for some other node. *Overemitting* is also another major cause for energy

wasting. It happens when a sender sends packets to a node but the receiver node is not ready and the packet must be sent again.

Other causes for energy waste include overheads, for example, extra control packets in a network. Presence of too many control packets such as beacons, request to send (RTS), clear to send (CTS), packets in CSMA-based protocols, and acknowledgement (ACK) packets may cause unnecessary use of energy.

3.2. Considerations for Energy Saving. A sensor network is very much different from infrastructure-based network. A device used in such a network is always resource constrained as discussed earlier. This is a major factor affecting design of an energy-efficient MAC protocol. A sensor network also employs a wide range of procedures and requirements that vary according to applications. Application awareness is one of the major criteria for sensor network. Hence MAC protocols should be flexible enough to entertain the need of specific application area while being energy efficient.

Energy saving mechanisms also depend on many other design and deployment factors. These factors are very crucial and ultimately affect the overall working of a MAC protocol. Some considerations while designing energy efficient MAC protocols are as follows:

- (i) network topology,
- (ii) deployment strategy,
- (iii) antenna mode,
- (iv) controlling mechanisms,
- (v) delay,
- (vi) throughput,
- (vii) quality of service (QoS) requirements,
- (viii) number of channels to be used in communication.

Network topology and deployment vary widely. They may be hierarchical, star, or cluster based, single hop or multihop, dense or sparse, and so forth. A network may

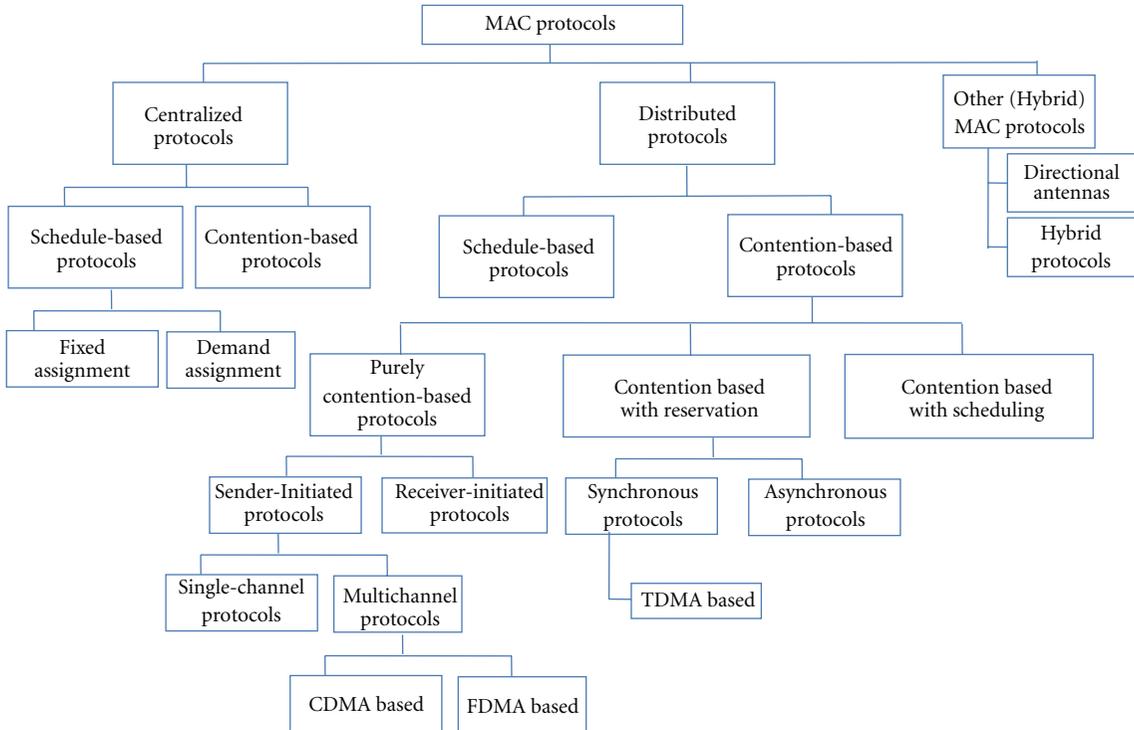


FIGURE 3: MAC protocols classification tree.

be static in nature or dynamically changing due to mobile nodes. Topology can always affect energy consumption by a sensor node. In a particular scenario, a star topology may be more energy efficient than hierarchical topology. Antenna may be omnidirectional or directional. Use of directional antenna can reduce energy consumption significantly in certain networks. Similarly, single channel for both data and control packets or different channels can be used. Out of band wake up signals as discussed in later section can be used to wake up a sensor node from sleeping state. Besides the above factors, sensing area and transmission range also are deciding factors in energy-efficient MAC design. To save the valuable energy in a sensor network, researchers have used various energy saving mechanisms. In next section, we discuss these mechanisms in detail for MAC layer in WSN.

4. Energy Saving Mechanisms in WSN

In the literatures, numerous energy saving mechanisms have been used and explored. The energy saving mechanisms are:

Now we will discuss these mechanisms in detail.

- (i) duty cycling,
- (ii) energy-efficient scheduling,
- (iii) scheduled rendezvous,
- (iv) on-demand wake-up scheme,
- (v) energy efficiency through directional antennae,
- (vi) clustering,
- (vii) others.

TABLE 2: Power characteristics for a MICA2 mote sensor.

Radio state	Power consumption (mW)
Transmit	81
Receive/Idle	30
Sleep	0.003

4.1. Duty Cycling. Duty cycling is one of the most widely used mechanisms for energy-efficient MAC protocols in sensor networks. Authors [9, 12, 18–22] have proposed and discussed duty cycling mechanisms in their MAC protocols. A duty cycling MAC protocol applies suitable sleep/wake up mechanisms to conserve energy. In one of early works, authors in [23] reported that sleep mode power consumption is much less than idle mode power consumption in MICA2 Mote sensors as shown in Table 2. Whenever there is no need for communication, the radio is put to sleep mode. It is definite that one way towards lower energy consumption is to turn off (sleep) all unused components (e.g., transceiver).

Although duty cycling is a popular means to conserve energy, it has some disadvantages. Putting sensors into sleep mode hampers working of whole network or at least certain part of the network. As mentioned by authors of [24], a few issues are needed to overcome such as when a device switch to low power mode or for how long should a device switch to low power mode? To resolve these, efficient and flexible duty-cycling techniques have been proposed as in the works in [18, 25]. Knowledge of traffic patterns can also help to take decisions about wake up easier. This method is known as adaptive duty cycling. In fact, S-MAC [18] is one of the first

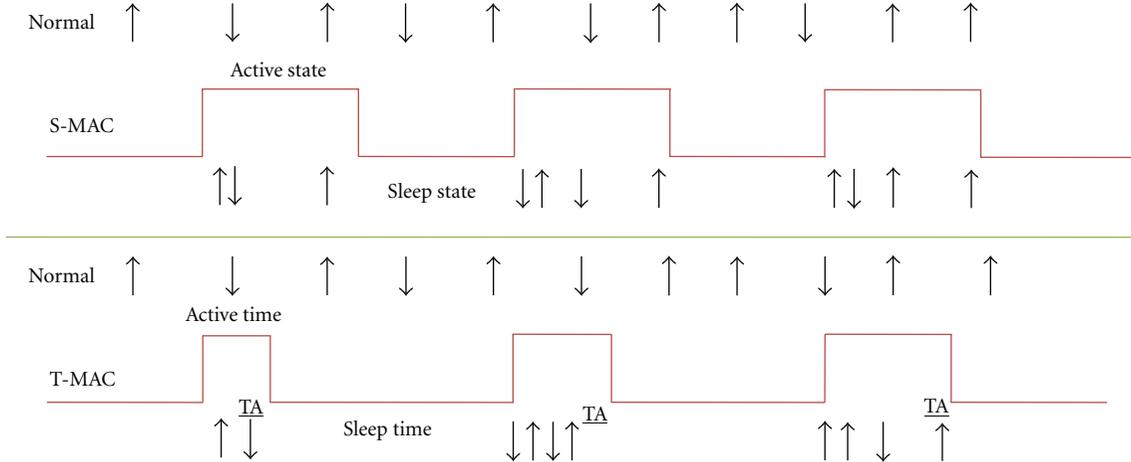


FIGURE 4: Comparison of S-MAC and T-MAC duty cycle.

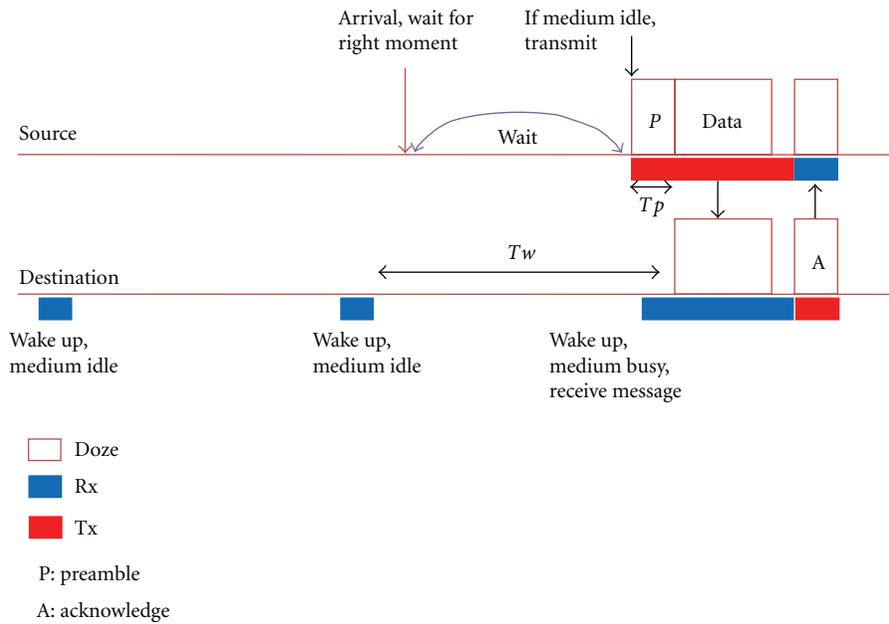


FIGURE 5: WiseMAC mechanism.

major energy-efficient MAC protocols to exploit the idea of adaptive duty cycling proficiently. It uses a periodic sleep-wake up mechanism to conserve energy. If a node has no packet to receive, it can waste large amount of energy by just trying to listen to the channel. Hence, a node can save a significant amount of energy if it simply goes to sleep mode by switching off its radios. T-MAC is an improvement over S-MAC duty cycling. In the T-MAC, listening period ends when no event has occurred for a time threshold TA as well as reduces idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts as shown in Figure 4. Though it improves on S-MAC, T-MAC has the disadvantage where it can face an early sleeping problem where a node can go to sleep even though its neighbor may still have messages for it.

B-MAC [26] uses low power listening or channel sampling to link to a receiver. WiseMAC [27] is another major protocol. It is based on synchronized preamble sampling. It is based on CSMA with a preamble sampling to minimize idle listening and thereby saves energy. Every node regularly samples the medium with a constant period and listens to the radio channel for a short duration of time. It dynamically determines the length of the preamble by using the knowledge of the sleep schedules of a node's neighbors. This saves energy compared to MACs that use fixed length preamble. WiseMAC outperforms S-MAC in variable traffic conditions. Mechanism of WiseMAC is shown in Figure 5 adapted from [27]. It is also observed that CSMA is the preferred method for multiple access for many duty cycling MAC protocols.

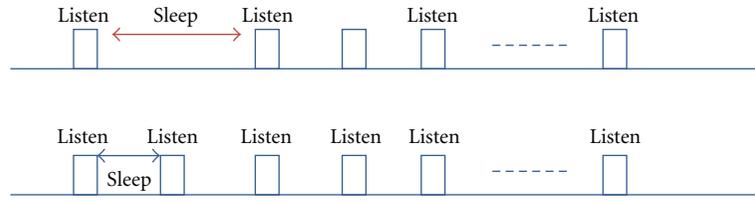


FIGURE 6: Dynamic duty cycling in DSMAC.

TABLE 3: Comparison of some Duty Cycling Protocols.

MAC protocol	Synchronization required	Mechanism	Adaptability	Energy efficiency
SMAC	No	CSMA	Yes	Yes
WiseMAC	No	NP-CSMA	Yes	Yes
T-MAC	No	TDMA/CSMA	Yes	Yes
DSMAC	No	CSMA/CA	Yes	Yes
SCP-MAC	Yes	CSMA	Yes	Yes
B-MAC	No	CSMA	Yes	Yes
X-MAC	No	CSMA	Yes	Yes

Adaptive duty cycling MACs such as [25] where sleep/wake up times of sensor nodes are adaptively determined can help energy saving better way than non-adaptive MAC protocols. Synchronization is also an issue in duty cycling MAC protocols. Authors in [19] have argued that synchronous MACs such as S-MAC [18] and SCP-MAC [28] have low energy consumption for sending packets but are complicated due to the need of synchronization. This overhead makes synchronous MAC algorithms inappropriate for monitoring applications. Conversely, asynchronous MACs, for example, X-MAC [29] and WiseMAC, are very simple, but they spend much energy in finding the neighbor's wake-up time. Due to this reason, under ultra low duty cycle, asynchronous MAC algorithms are also not attractive for monitoring applications. Some solutions to these problems have been proposed too. For example, ADCA [21] is a MAC protocol that adjusts the length of the active period to improve the duty cycle utilization and to reduce the transmission delay.

DSMAC [22] has a mechanism to dynamically change the duty cycling as shown in Figure 6. The major aim of DSMAC protocol is to decrease the latency for delay-sensitive applications and improve performance of S-MAC by introducing dynamic duty cycling. Another major problem in duty cycling MAC protocols is the clock drift. In case of very low duty cycle and traffic load, clock drifts can further degrade the performances of synchronous and asynchronous MAC protocols. Table 3 presents some of the duty cycling MAC protocols.

4.2. Energy-Efficient Scheduling. Efficient scheduling that can adapt to situation demand can reduce the energy consumption at all levels of the network. Authors in [30] have developed several centralized and decentralized energy-efficient scheduling protocols for sensor fusion. By assigning

longer transmission times to sensors experiencing worse channel conditions, they reported to have saved more than 80% of the energy needed by the uniform TDMA protocol. Authors in [31] have provided a detail survey on energy-efficient scheduling mechanisms in sensor networks that have different design requirements than those in traditional wireless networks. A detail survey and design assumptions of scheduling mechanisms can be found in their works. They also have classified these mechanisms based on their design assumptions and design objectives. It is found that different scheduling mechanisms have different assumptions about their sensors, including network structure, deployment strategy, sensing area, transmission range, detection and failure model, time synchronization, and the ability to obtain location and distance information. However, all the mechanisms have a common design goal: to maximize the network lifetime. It is also seen that these scheduling mechanisms have different objectives determined by their target applications. Almost all the surveyed mechanisms take advantage of the energy saving feature of the deep sleep mode. The authors [31] have classified the scheduling mechanisms into two major categories: distributed scheduling mechanisms in a nonhierarchical network and distributed scheduling mechanisms in hierarchical networks. Distributed scheduling mechanisms in nonhierarchical networks include random independent scheduling (RIS), sponsored sector, maximization of sensor network life (MSNL), lightweight deployment-aware scheduling (LDAS), probing environment and adaptive sensing (PEAS), coverage configuration protocol (CCP), probing environment and collaborating adaptive sleeping (PECAS), and optimal geographic density control (OGDC). Distributed scheduling mechanisms in hierarchical networks include low-energy adaptive clustering hierarchy (LEACH), enhanced low-energy adaptive clustering hierarchy (E-LEACH), linear

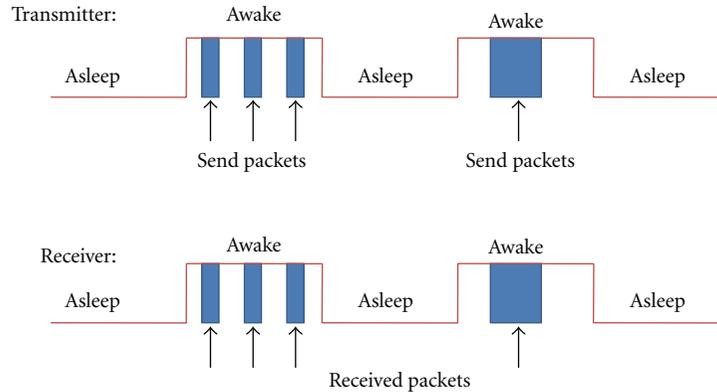


FIGURE 7: A scheduled rendezvous scheme.

distance-based scheduling (LDS), and balanced-energy sleep scheduling (BS).

4.3. Scheduled Rendezvous. This type of MAC protocol requires a prescheduled rendezvous time at which point all neighboring nodes wake up together. In this method, a node wakes up periodically and sleeps until the next rendezvous time. A scheduled rendezvous scheme [17] is shown in Figure 7.

The major advantage of such a scheme is that when a node is awake it is guaranteed that all its neighbors are awake as well. Hence it is easier to send/receive packets. Broadcasting a message to all neighbors is also simpler in scheduled rendezvous schemes. Authors in [32] have proposed one such MAC protocol for environmental monitoring. It considers two design requirements—long network lifetime and a high delivery rate of sampled sensor readings to a central authority using a tree-based structure. RI-MAC [33] is a receiver-initiated asynchronous duty cycle MAC protocol for wireless sensor networks. It uses a receiver-initiated data transmission in order to efficiently and effectively operate over a wide range of traffic loads. It attempts to minimize the time a sender and its intended receiver occupy the wireless medium to find a rendezvous time for exchanging data, while still decoupling the sender and receiver's duty cycle schedules. Among the disadvantages of such a MAC protocol is the requirement to maintain strict synchronization. Clock drifting may significantly affect the rendezvous time.

4.4. On-Demand Wake-Up Scheme. In this scheme, a MAC protocol uses out of band radio signals to wake up a node from sleep state and communicate. Extra wake-up circuit [34] is normally attached to the main sensor in such a case as shown in Figure 8(b).

A wake-up tone is used to wake up neighbors. The tone is broadcasted on special channel for a specified duration. Mostly, no information is encoded in the wake-up tone. Hence these protocols are always employing multiple radio architecture—one for waking up devices and other for sending data. The frequency used in wake-up radio is generally different from normal communication radio of

the node. A wake-up radio uses less energy through low duty cycling and extra low powered hardware device [35]. It has advantages as the receiver has to detect only energy on channel rather than decode a packet and can be implemented using simple hardware. This also helps to maximize sleep time for a node. Figure 8(a) shows a schematic of a design of a simple radio-triggered circuit taken from [35].

The PicoRadio [36] design uses a low-power wake-up channel. It uses a MAC protocol that allows nodes to wake up a neighbor when data needs to be sent. However, due to use of CDMA-based technique, complexity is increased in this protocol. RTWAC [37] is a radio-triggered wake up with addressing capabilities that allow suppressing the idle duration current consumption. It consists of an external low-cost hardware wake-up circuit attached to the microcontroller of a sensor node. The sensor node stays in the sleep mode with its normal communication radio turned off. Authors in [24] proposed a simpler method using two radio channels, primary and wake up. The primary channel is used for sending data and control packets, whereas the wake-up channel is used to wake up neighbors.

Disadvantage for an on-demand wake-up scheme using multiple radios is that a wake-up tone awakes entire neighborhood thereby wasting energy in the unnecessary wake ups. Directional antennae may help solving such a problem while increasing throughput further. Although the cost for such hardware is decreasing significantly nowadays, need of extra hardware is also sometimes considered as a disadvantage.

4.5. Directional Antennae. Directional antennae in sensor networks are receiving increasing interest and research due to the potential to increase throughput and reduce delay and interference, while requiring lower transmission power [38]. Usually the omnidirectional antennae have a uniform gain in each direction, while directional antennae have a different antenna gain in each direction. As a result, the signal level at a receiver can be increased or decreased simply by rotating the orientation of the directional antenna [39]. Many authors [40–45] have used directional antenna in their MAC design for sensor networks. In all such mechanisms, localization and

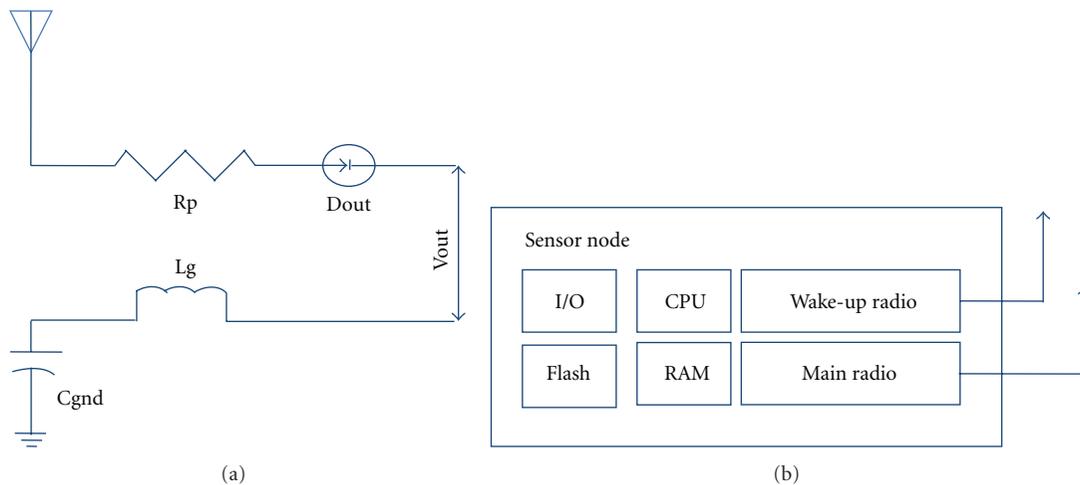


FIGURE 8: (a) A simple wake-up radio circuit. (b) Schematic of a sensor node with wake-up radio.

positioning are major issues. Beamforming technique is used in all directional antennae. A simple sketch of the directional antenna [46] is shown in Figure 9.

A directional antenna is normally capable of receiving/transmitting signals from one direction at a time, which is a basic reason of improvement in transmission and in the direction in which the antenna is pointed. Due to higher gain, a directional antenna has greater transmission range than an omnidirectional antenna [40]. So they can also receive weak signals. In a beacon-based MAC protocol, the anchor node with directional antenna may transmit beacon information more effectively than that with omnidirectional antenna. Authors in [41] show network life improvements of a protocol that uses a directional antenna mounted only on the sink. Similarly, works in [42] show that MAC using a directional antenna can reduce energy consumption over its omnidirectional counterpart. In [43], directional antenna is used in WSN where a time schedule is computed by each node to schedule the directional communication with other neighbors. Furthermore, in [47] it is reported that network life can be notably increased with directional antennas reducing the duty cycle, however, conserving the throughput higher than the omnidirectional solution. SAMAC [48] is a recent MAC protocol for sensor networks that employs the directional antenna. It is an integrated cross-layer protocol that contains the full set of communication mechanisms for sensor networks equipped with sectorized antennas. The authors also have claimed to have high energy efficiency and predictable End-to-End delay. Authors in [49] gave an example of wake-up call transmissions with and without directional communications as shown in Figure 10. Omnidirectional transmissions block the communication channel and transmit energy in unnecessary directions. On the other hand, a directional communication focuses all the radiated power towards the intended target, reducing the required power for a given range. Multiple communications can occur in close proximity using directional antennae.

Although there are many advantages of using a directional antenna, it is found that signal interference is a prominent issue to resolve. Otherwise, energy waste will still happen. Another disadvantage is that directional antenna may require adjustments. This can happen frequently in case of a mobile node or multichannel environment. Moreover, directional antenna may face the deafness problem. It can be sufficiently serious to offset the advantages of beamforming, if left unaddressed [50].

4.6. Clustering. Clustering is an important mechanism in wireless sensor networks towards energy efficiency and effective data communication. Clustering provides scalability and robustness for the network; it allows spatial reuse of the bandwidth and simpler routing decisions and results in decreased energy dissipation of the whole system by minimizing the number of nodes that takes part in long distance communication [51]. Clustering-based approaches are showing the most exiting result through their ability to reduce energy consumption by multiple ways [52]. Many works and researches [51–57] on clustering mechanism in sensor networks to save energy have been found in the literature making it a very active research area.

A cluster is managed and coordinated by a cluster head (CH) as shown in Figure 11. Cluster heads collect, aggregate and forward data. Communications are either intracluster, that is, between nodes and cluster head inside a cluster or intercluster which can occur between one node in a cluster and a different node in another cluster. In later case, cluster heads play a prominent role in successful communication. In most clustering approaches, first a set of cluster heads are selected among the nodes in the network. After that rest nodes are clustered around these CHs. Selecting cluster heads is always a hard problem. It is also found that most clustering approaches use random scheme to select cluster heads. Different clustering uses a different approach to choose CH and form clusters. Besides selection of cluster heads, cost of clustering is also a major design issue in this type of protocol.

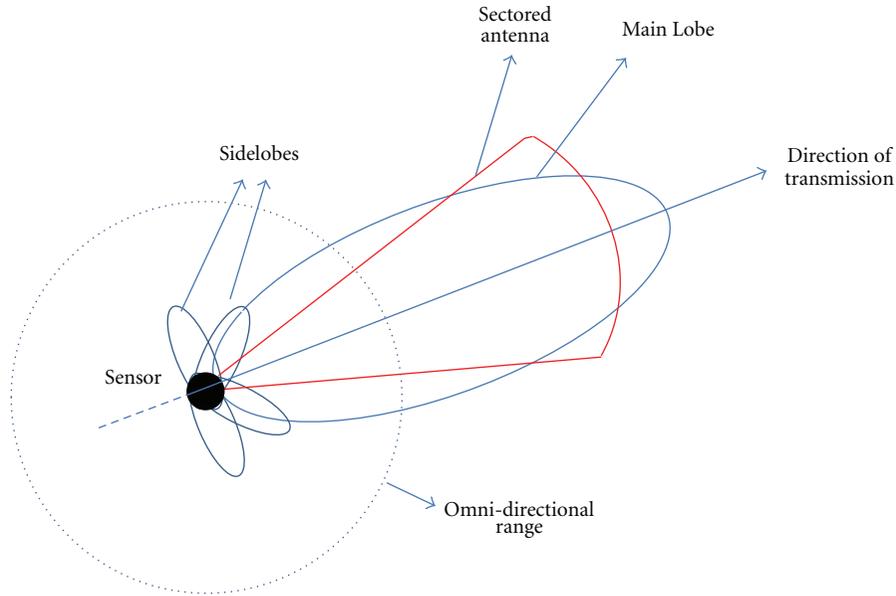


FIGURE 9: Concept of a directional antenna.

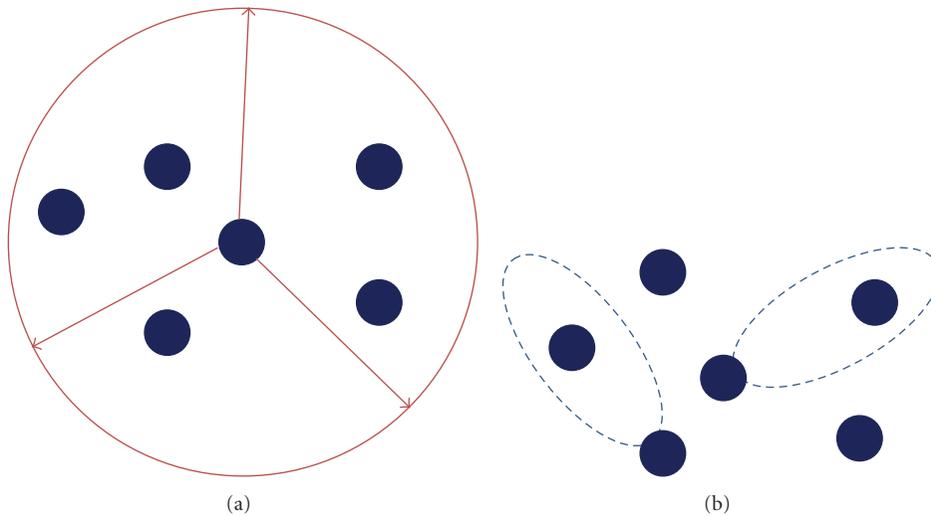


FIGURE 10: (a) Omnidirectional transmissions. (b) Directional communication.

Authors in [58] have provided a comparison of various clustering algorithms used in wireless sensor networks. They have concluded that all of the algorithms are concerned with how to prolong the lifetime of the sensor network and how to make a more efficient use of the critical resources located at the sensor nodes, without decreasing the communication functionalities, but creating more intelligent clusters, minimizing the maximum number of nodes in a cluster, and minimizing clusters with only a single node (i.e., the cluster head). In fact, hierarchical clustering reduces the amount of query packets via intercluster query dissemination and the amount of data packets by aggregating collected data. Classification of the clustering schemes into four categories—*heuristic, hierarchical, weighted, and grid scheme*—is proposed in [57]. LEACH [54] uses a hierarchical

scheme. It is among the first clustering techniques for sensor networks. It is an application-specific data dissemination protocol that uses clustering to prolong the network lifetime with very less overhead. It uses a random mechanism to rotate cluster heads among the nodes. A scheduling mechanism that uses TDMA technique is used to minimize the energy consumption in LEACH. However, it has scalability problems when the range of the network increases. Variants of LEACH protocol are proposed to increase performance and energy efficiency. Authors in [55] proposed HEED to prolong the lifetime of a network by reducing the number of nodes that compete for channel access and better cluster head selection procedure than LEACH. A node selects a cluster head in its range proximity rather than entire network. HEED uses a hybrid method by considering the residual

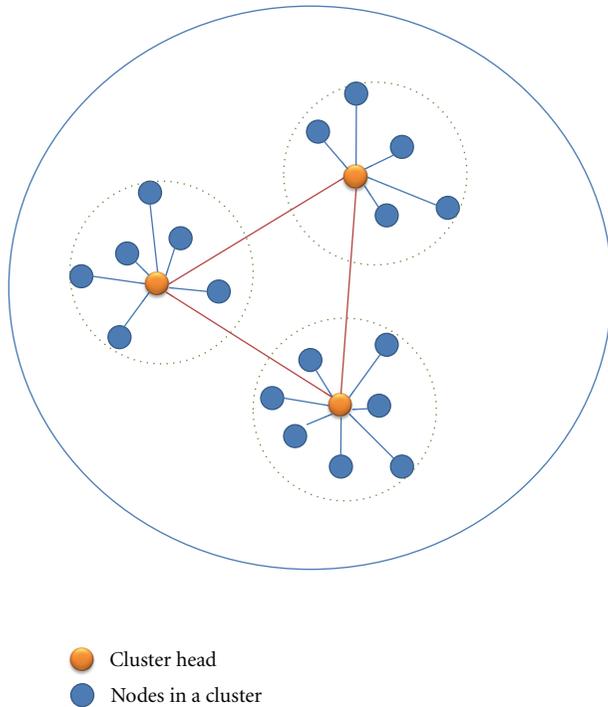


FIGURE 11: Cluster and cluster heads.

energy of a node and other parameters, such as node proximity to its neighbors or node connectivity. DWEHC [59] is a hierarchical clustering protocol. It makes no assumptions on the size and the density of the network. Every node implements DWEHC individually. It generates multilevel clusters. The number of levels depends on the cluster range and the minimum energy path to the head. Within a cluster, TDMA is used. To save energy in DWEHC during intracluster communication, senders relay messages through their parent, achieving optimal energy consumption within a cluster. CLUBS [60] forms clusters through local broadcast and converge in a time proportional to the local density of nodes with a maximum of two hops. It can be implemented in the asynchronous environment without losing efficiency and simplicity. MOCA [61] is a randomized distributed multihop clustering algorithm for organizing the sensors into overlapping clusters. Having overlapping clusters is beneficial in node localization, ensuring intercluster connectivity, and so forth, and can boost the network robustness against cluster head failure or compromise by facilitating and expediting the recovery of nodes, which can join others alternate clusters. Comparison of some popular clustering technique is presented in Table 4.

4.7. Others. There are some other mechanisms used in MAC protocols. Data rate adaptation is proposed in [62]. It uses variable rate signaling in WSN as a way to reduce the average network power consumption. Channel polling is another method used in MAC protocols for energy efficiency. Y-MAC [63] is such a MAC protocol for multichannel dense network environment. Hybrid approach is also common and popular in MAC approach to maximize energy saving and

increase overall performance. A hybrid approach makes a MAC protocol flexible and enables to use the benefits of all the approaches it combines. For example, LEACH is a hybrid MAC protocol that uses clustering and routing to maximize its performance. This applies to many other MAC protocols as well.

5. External Mechanisms Supporting Energy Efficiency in MAC

So far, we have discussed the energy saving mechanisms that are directly used in the MAC layer. Besides the above mechanisms, there are other methods that act as supports for energy efficiency in sensor networks for MAC layer. They help to improve the performance of MAC protocol in general even though they do not belong to MAC layer.

These mechanisms are

- (i) energy-efficient routing,
- (ii) energy efficiency through topology control,
- (iii) data aggregation.

5.1. Energy-Efficient Routing. Routing is an essential feature in any multihop sensor network. In such cases, a node acts as a router to relay packets from one neighbor to another neighbor. This surely causes consumption of extra energy. Efficient routing algorithm can save a significant amount of energy in a network where routing occurs frequently. This is why in a multihop sensor network energy is a major factor while creating routes. As per the Friis transmission equation, transmission power depends on distance or range. Hence multihopping can save a significant amount of energy compared to single-hop networks. Similarly, if the network is dense employing multihop topology, efficient routing can save valuable energy. Authors in [64, 65] have mentioned some of the routing protocols for WSN.

Sensor Protocols for Information via Negotiation (SPIN) is one of the earliest adaptive protocols proposed by authors in [66]. SPIN works by disseminating all the information at each node to every node in the network by assuming that all nodes in the network are potential base stations. Many variants of SPIN are proposed to enhance its performance. Gradient-based routing (GBR) is proposed in [67]. In GBR, a gradient value is calculated, which is basically the difference between a node's height and that of its neighbor. A packet is forwarded on a link which has the largest gradient value. GBR working is also based on memorizing the number of hops when the interest is diffused through the entire network. SPEED [68] uses a routing technique called stateless geographic nondeterministic forwarding (SNGF). It is specifically tailored to be a stateless, localized algorithm with minimal control overhead. It also uses a combination of MAC and network layer adaptation to improve the end-to-end delay and provides a good response to congestion and voids. Authors in [69] proposed a routing mechanism based on a set of suboptimal paths to increase the lifetime of the network. Described in [70] is an example of energy-aware routing for cluster-based sensor networks. In this method, the authors have proposed a hierarchical routing algorithm

TABLE 4: Comparison of some Clustering Techniques.

Clustering techniques	Cluster stability	Cluster head selection	Mobility support	Energy efficiency
LEACH	Medium	Random	Yes	No
HEED	High	Random	No	Yes
Extended HEED	High	Random	No	Yes
DWEHC	High	Random	No	Yes
CLUBS	Medium	Random	Yes	No
MOCA	High	Random	No	Yes
ACE	High	Random	Yes	No

TABLE 5: Comparison of some routing protocols.

Protocol	Network type	Energy consumption	Scalability	Mobility	Data aggregation
Flooding	Flat	High	Limited	No	No
SPIN	Data Centric	Low	Limited	Yes	No
Shah & Rabaey	Data Centric	Low	Good	Yes	No
GBR	Data Centric	Low	Limited	Limited	Yes
LEACH	Hierarchical	High	Good	Yes	Yes
PEGASIS	Hierarchical	High	Good	Yes	No
SPEED	Location based	Low	Limited	No	No
GAF	Location based	Low	Good	No	No
GEAR	Location based	Low	Limited	Yes	No

based on three-tier architecture. Sensors are grouped into clusters prior to network operation and uses TDMA-based MAC scheme. Authors in [71] present a solution to the problem of routing in sensor networks based on a network flow approach. The main objective of the approach is to maximize the network lifetime by carefully defining link cost as a function of node's remaining energy and the required transmission energy using that link. Authors in [72] model the data routes setup in sensor networks as the maximum lifetime data gathering problem and present a polynomial time algorithm. A QoS-aware protocol for sensor networks is proposed in [73] using link cost as a function to determine a least cost and energy-efficient path that meets a certain end-to-end delay during the connection.

Almost all the routing protocols can be classified as data-centric, hierarchical, or location based although there are few distinct ones based on network flow and quality of service (QoS) awareness. A brief comparison is presented in Table 5.

The number of energy-aware location-based approaches found in the literature is rather small [64]. It is also found that using the lowest energy path always is not necessarily best for the long-term health of the network. The problem of intelligent utilization of the location information in order to aid energy efficient routing is a major research issue.

5.2. Energy Efficiency through Topology Control. Topology control is one of the most important energy-saving techniques used in wireless sensor networks [74]. Topology issues have been extensively studied in WSNs [74–80]. Topology management mechanism is an effective way to reduce the energy consumption of sensors, which periodically selects some nodes to build up the forwarding backbone and

allow the others to sleep (turn off the radios) for energy conservation [78].

Although works are substantial, authors in [81] have reported that how to construct an optimized coverage topology while maintaining efficient and low cost connectivity is not well understood and deserves further studies. They have provided a simple taxonomy of topology control in WSNs as shown in Figure 12. They have also concluded that by integrating power control and power management, it is possible to provide noticeable improvements on network topology and efficiencies of energy usage. Similarly, authors in [74] have claimed that in order to achieve high energy-efficiency, topology control algorithms and protocols, firstly, must consider power control and sleep scheduling jointly, secondly be aware of traffic load, and lastly be done in conjunction with routing. The research on topology control has evolved into two dominant directions—power control and sleep scheduling. Authors [74] have provided some good comparisons on some of the prominent protocols that use power management mechanism topology control. The key idea of power control is that, instead of transmitting using the maximum power, nodes in a WSN collaboratively determine their transmission power while preserving some required properties. The basic idea of sleep scheduling is to save energy by putting redundant nodes into the sleeping mode.

5.3. Data Aggregation and In-Network Processing. Incorporating sensor nodes with data aggregation capability to transmit fewer data flows, into wireless sensor networks, could reduce the total energy consumption [82]. This field is an active research area, and works are ongoing in this direction.

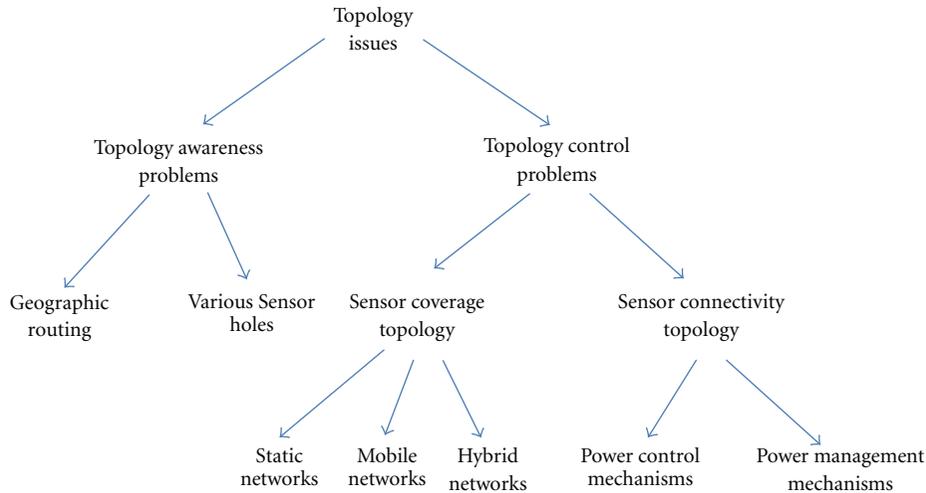


FIGURE 12: A taxonomy of topology issue in WSNs.

Works [79, 83–88] are found in the literature. Since sensor nodes might generate a significant amount of redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions would be reduced [17]. It is reported that [85] whether the sources are clustered near each other or located randomly, significant energy gains are possible with data aggregation. As it is a well-known fact that computation costs less energy than communication, substantial energy savings can be obtained through data aggregation. A simple data aggregation technique is shown in Figure 13.

Data aggregation in sensor networks can be done either using cluster-based or tree-based approach. PEGASIS [84] and LEACH [54] employ a cluster-based data aggregations. PEGASIS organizes all nodes in a chain and lets them play the role of heads in turn to conserve more energy. Each node communicates only with a close neighbor and takes turns transmitting to the base station, thus reducing the amount of energy spent per round. It has only one head node and no simultaneous transmissions. Due to this reason, it has more delay compared to LEACH. Variants of PEGASIS [61] are proposed to enhance its performance by including energy \times delay factor. Hybrid Indirect Transmission or HIT [86] is a hybrid approach based on techniques of LEACH and PEGASIS. It allows multihop routes between cluster heads and other nodes. Routing protocols with clustering techniques as discussed in later section apply this technique frequently to save energy and increase performance of the MAC protocol. Authors in [89] introduced a data-centric paradigm called the directed diffusion for sensor networks. Another early work in this field [90] discusses the application of distributed query execution techniques to efficient communication in sensor networks.

Authors in [82] have proposed a rigorous nonlinear mathematical formulation for MAC aware energy-efficient data centric routing problem in WSN where the objective function is to minimize the total energy consumption subject

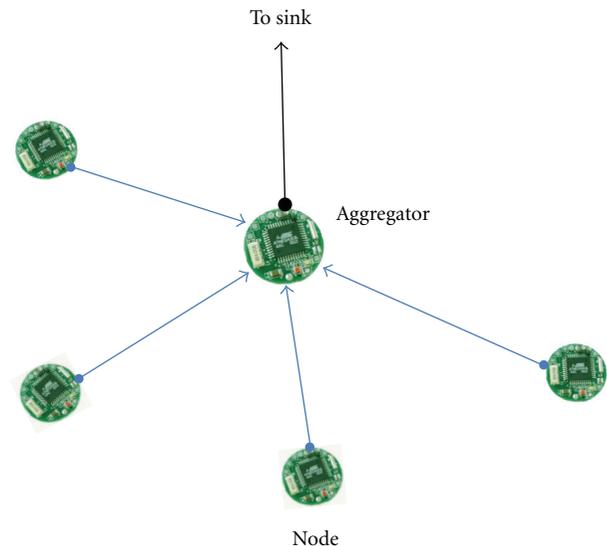


FIGURE 13: Data aggregation.

to the data aggregation tree, routing assignment, transmission radius, and data retransmission constraints. They also argued that the penalty from data retransmission due to collision could jeopardize the advantages from data aggregation. Authors in [87] have proposed a scalable hybrid framework for processing spatial and temporal proximity queries in WSN which they called STP. STP builds a tree structure and reduces the event propagation cost through proximity queries. It reduces energy consumption by reducing the number of aggregator nodes, which ultimately increases the network life time. In more recent works, authors in [88] have proposed energy-efficient data aggregation in WSN with Mobile Sinks. They also proposed a number of motion strategies for the mobile sink(s) to gather real-time data from static sensor network, with the objective to maximize

the network lifetime. Authors in [91] have proposed a TDMA-based MAC protocol for low data rate WSNs with centralized and distributed scheduling algorithms that not only remove the unnecessary listening cost, but also reduce the energy cost for state switching and clock synchronization. Though advantageous in a dense cluster-based network, data aggregation has some disadvantages. Significant among them is the fact that the formation of an optimal data aggregation tree is generally NP-hard [85].

6. Conclusion

To save energy in media access communication is an active research area. In this paper, we have surveyed the existing energy saving mechanisms for MAC protocols. Energy saving mechanisms are diverse in MAC protocols. Due to a wide range of sensor network applications, it is impossible that one particular type of mechanism is used universally. Many MACs use a variety of approaches to save energy and give optimum performance. LEACH protocol is a perfect example for this. It uses clustering, data aggregation, and in-network processing to provide optimum performance. This leads to dissimilar advantages and disadvantages. Application scenario is also a major factor in MAC protocol performance and energy efficiency. In some scenarios, periodic low duty cycle-based hierarchical protocol may work better, and in some other cases cluster-based protocols can perform better. A MAC protocol needs to give optimum performance in the specific application area where it is used. Hence energy efficiency, though a primary requirement in a MAC protocol, depends on a particular network and application area. In our opinion, a hybrid approach would be a necessary development path for energy-efficient MAC protocols. This article can be used as a guideline towards the design and development of a new energy saving MAC for WSN.

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