3

MEDIUM ACCESS CONTROL

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3.1 INTRODUCTION

Medium access control (MAC) is one of the critical issues in the design of wireless sensor networks (WSNs) [1]. As in most wireless networks, collision, which is caused by two nodes sending data at the same time over the same transmission medium, is a great concern in WSNs. To address this problem, a sensor network must employ a MAC protocol to arbitrate access to the shared medium in order to avoid data collision from different nodes and at the same time to fairly and efficiently share the bandwidth resources among multiple sensor nodes. Therefore, a MAC protocol plays an important role in enabling normal network operation and achieving good network performance.

Medium access control has been extensively studied for traditional wireless networks. A variety of MAC protocols have been proposed to address different network scenarios. From different perspectives, MAC protocols can be classified into different categories, for example, centralized and distributed, single-channel based and multiple-channel based, contention based and contention free, and so on. Time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and carrier sense multiple access (CSMA) are typical MAC protocols that have been widely used in

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traditional wireless networks. However, these protocols do not take into account the unique characteristics of sensor networks, for example, denser levels of node deployment, higher unreliability of sensor nodes, and severe power, computation, and memory constraints. For this reason, traditional MAC protocols cannot be applied directly to sensor networks without modification. To design an efficient MAC protocol for sensor networks, the unique characteristics of sensor networks, in particular, energy efficiency and network scalability must be taken into account. Moreover, delivery latency, network throughput, bandwidth utilization, and fairness, which are the primary concerns in traditional wireless networks, should also be considered, but are of secondary importance in sensor networks [2].

The purpose of this chapter is to help understand the MAC problem in WSNs, discuss its unique characteristics, and present a survey of MAC protocols for WSNs. Section 3.2 gives a brief introduction of fundamental MAC protocols used in traditional wireless networks. Section 3.3 discusses major MAC design issues for WSNs. Section 3.4 presents a survey of MAC protocols for WSNs. Section 3.5 summarizes the chapter with a brief discussion of future research directions.

3.2 FUNDAMENTAL MAC PROTOCOLS

Medium access control is critical for enabling successful network operation in all shared-medium networks. The primary task of a MAC protocol is to arbitrate access to a shared medium or channel in order to avoid collision and at the same time to fairly and efficiently share the bandwidth resources among multiple nodes. According to the underlying control mechanism for collision avoidance, MAC protocols can be typically classified into two broad categories: contention-based and contention free. This section gives a brief introduction of fundamental MAC protocols used in traditional wireless networks.

3.2.1 Contention-Based MAC Protocols

In contention-based MAC, all nodes share a common medium and contend for the medium for transmission. Thus, collision may occur during the contention process. To avoid collision, a MAC protocol can be used to arbitrate access to the shared channel through some probabilistic coordination. Both ALOHA (Additive Link On-Line Hawaii System) and CSMA are the most typical examples of contention-based MAC protocols [3]. In pure ALOHA, a node simply transmits whenever it has a packet to send. In the event of a collision, the collided packet is discarded. The sender just waits a random period of time and then transmits the packet again. In slotted ALOHA, time is divided into discrete timeslots. Each node is allocated a timeslot. A node is not allowed to transmit until the beginning of the next timeslot. Pure ALOHA is easy to implement. However, its problem is that the channel efficiency is only ~10% [3]. Compared with pure ALOHA,

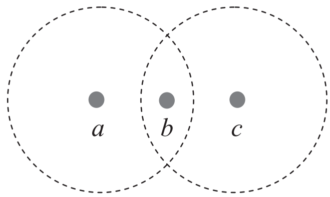

Fig. 3.1 Illustration of the hidden-node problem.

slotted ALOHA can double the channel efficiency. However, it requires global time synchronization, which complicates the system implementation.

CSMA differs from ALOHA in that it uses carrier sense; that is, it allows a node to listen to the shared medium before transmission, rather than simply transmits immediately or at the beginning of the next timeslot. CSMA has several different versions, including non-persistent, 1-persistent, and n-persistent. In non-persistent CSMA, if a node detects a busy medium, it will wait a random period of time and start to listen again. In 1-persistent CSMA, the node will continue to listen until the medium becomes idle. In n-persistent, if a node detects an idle medium, it will transmit with probability p, and back off and restart carrier sense with probability $(1-p)$.

However, CSMA cannot handle the hidden-terminal problem in multihop wireless networks [4]. Figure 3.1 illustrates the hidden-terminal problem in a 2-hop network with three nodes. Suppose that each node can only receive the signal from its immediate node. If node *a* is transmitting data to node *b*, node *c* will not be able to detect this transmission. As a result, if node *c* is also transmitting data to node *b*, the data sent by node *a* and node *c* will be collided at node *b*. To address this problem, CSMA/CA was developed and is adopted in the IEEE 802.11 wireless LAN standard [5], where CA stands for collision avoidance. In CSMA/CA, a handshake mechanism is introduced between a sender and a receiver. Before the sender transmits its data, it must establish a handshake with the receiver. The sender starts the handshake by sending a request-to-send (RTS) packet to the receiver. The receiver then acknowledges with a clear-to-send (CTS) packet. The sender starts transmitting data after it receives the CTS packet from the receiver. Through such a handshake process, the neighbors of both the sender and the receiver can know the transmission that is going on and thus back off without transmitting its own data. In the example of Fig. 3.1, node *c* cannot receive the RTS from node *a*. However, it can receive the CTS from node *b*. Therefore, if a node receives a RTS or CTS to other nodes, it should back off and does not send its own packet. In this case, collisions will mainly happen to RTS packets and can thus be reduced significantly.

To improve the performance of CSMA/CA, a MAC protocol called multiple access with collision avoidance (MACA) was developed for wireless local area networks (LANs) [6], which introduces an additional field in both RTS and CTS packets to indicate the amount of data to be transmitted so that other nodes can know how long they should back off. To further improve the performance of MACA, another protocol called MACAW was developed in Ref. [7], which makes several enhancements to MACA. For example, after each data packet, an acknowledgment (ACK) packet is used to enable fast link-layer recovery in the event of unsuccessful transmissions. The IEEE 802.11 distributed coordination function (DCF) was mainly based on MACAW and adopted all the features of CSMA/CA, MACA, and MACAW. For more details on IEEE 802.11, the reader is referred to Ref. [5].

3.2.2 Contention-Free MAC Protocols

In contention-free MAC, a shared medium is divided into a number of subchannels in terms of time, frequency, or orthogonal pseudo-noise codes. These subchannels are allocated to individual nodes with each node occupying one subchannel. This allows different nodes to access the shared medium without interfering with each other and thus effectively avoids collision from different nodes.

The most typical examples of contention-free MAC protocols are TDMA, FDMA, and CDMA [3]. TDMA divides the shared channel into a fixed number of timeslots and configures these timeslots into a frame that repeats periodically. Each node is allocated a timeslot and is allowed to transmit only in the allocated timeslot in each frame. TDMA has been widely used in wireless cellular systems. In a typical cellular system, the base station in each cell allocates timeslots and provides information for time synchronization to all mobile nodes. The mobile nodes communicate only with the base station without direct peer-to-peer communication between each other. The major advantage of TDMA is its energy efficiency because those nodes that do not transmit can be turned off. However, TDMA has some limitations as compared with other MAC protocols. For example, TDMA usually requires nodes to form clusters like the cells in a cellular communication system. It has limited scalability and adaptability to network changes. It requires strict time synchronization for timeslots.

FDMA divides the shared channel into a number of non-overlapping frequency subbands and allocates these subbands to individual nodes. Each node can transmit at any time, but only at a different frequency to avoid interfering with the others. The major advantage of FDMA is its simplicity in implementation. However, it also has some drawbacks. For example, a guard band is needed between two adjacent subchannels. The reason is that it is not possible for a transmitter to output all its energy only in the main band and nothing in the side bands. The amount of bandwidth wasted in the guard bands can be a substantial fraction of the total bandwidth. The transmitters must be carefully power controlled. If a transmitter outputs too much power in the main band, it will also output too much power in the side bands, causing interference with adjacent channels.

CDMA divides the shared channel by using orthogonal pseudo-noise codes, rather than timeslots in TDMA and frequency bands in FDMA. All nodes can transmit in the same channel simultaneously, but with different pseudo-noise codes. The major advantage of CDMA is that it does not require strict time synchronization and avoids the channel allocation problem in FDMA. However, it also has some disadvantages. For example, it introduces the energy consumption for coding and decoding. The capacity of a CDMA system in the presence of noise is usually lower than that of a TDMA system.

3.3 MAC DESIGN FOR WIRELESS SENSOR NETWORKS

This section introduces the characteristics of WSNs and discusses major MAC design issues in such networks.

3.3.1 Network Characteristics

To better understand WSNs, let us first take a brief look at some conventional wireless networks, for example, wireless cellular networks, mobile ad hoc networks (MANETs), and wireless LANs.

A cellular system is a wireless network consisting of both stationary and mobile nodes. The stationary nodes, or base stations, are connected by wired links, forming a fixed infrastructure. The number of mobile nodes is much larger than that of stationary nodes. Each base station usually covers a large region with little overlap and serves tens to hundreds of mobile nodes in the region. Each mobile node is only a single-hop away from its closest base station. The primary goal of a cellular system is to provide quality of service and bandwidth efficiency. The base stations have sufficient power supply and the mobile users can conveniently replace the batteries in their handsets. Accordingly, energy conservation is only of secondary importance.

A MANET is a peer-to-peer network that usually consists of tens to hundreds of mobile nodes and covers a range of up to hundreds of meters. All nodes are mobile and there is no fixed infrastructure. Hence, the network must organize the nodes to form a communication infrastructure, perform routing to enable effective communication, and maintain the organization and routing under mobile conditions. The primary goal of a MANET is to provide high quality of service in the face of high node mobility. Although each node is a portable battery-powered device, it is always attended by a person, who can replace the battery whenever needed. Hence, energy consumption is also of secondary importance in this system.

Bluetooth [8] is a short-range wireless LAN that was developed to replace the cable between electronic consumer devices with RF links. Bluetooth technology is a star network where a master node is able to have up to seven slave nodes connected to it to form a piconet. Each piconet uses a TDMA schedule and frequency hopping pattern. All slave nodes are synchronized to the master node. Multiple piconets can be interconnected to form a multihop topology. The transmission power is typically ~1 mW and the transmission range is on the order of 10 m. In Bluetooth, the primary goal is also to provide high quality of service for users.

In contrast to all the above conventional networks, WSNs have the following unique characteristics:

- A sensor network typically consists of a larger number of sensor nodes densely deployed in a geographical field. The number of sensor nodes can be several orders of magnitude larger than that of conventional wireless networks.
- Sensor nodes are usually powered by battery and thus are limited in power capacity. It is often difficult or impossible to change or recharge batteries for these nodes. The lifetime of a sensor network largely depends on the lifetime of its sensor nodes.
- Sensor nodes are often deployed in an ad hoc fashion without careful planning and engineering. Hence, they must be able to organize themselves into a communication network.
- The topology of a sensor network changes more frequently due to both node failure and mobility. Sensor nodes are prone to failures. Most sensor nodes are stationery after deployment. But in some applications, some sensor nodes can also be mobile.
- Sensor nodes have very limited computational capacity and memory.

Due to these unique characteristics, in particular, the limited energy resources, traditional MAC protocols are not suitable for being used in WSNs without modification.

3.3.2 Objectives of MAC Design

The basic function of a MAC protocol is to arbitrate access to a shared medium in order to avoid collisions from different nodes. In addition to this basic function, a MAC protocol must also take into account other factors in its design in order to improve network performance and provide good network services for different applications. In WSNs, these mainly include energy efficiency, scalability, adaptability, channel utilization, latency, throughput, and fairness [9].

- *Energy Efficiency.* Energy efficiency is one of the most important factors that must be considered in MAC design for sensor networks. It refers to the energy consumed per unit of successful communication. Since sensor nodes are usually battery powered and it is often very difficult or impossible to change or recharge batteries for sensor nodes, a MAC protocol must be energy efficient in order to maximize not only the lifetime of individual sensor nodes, but also the lifetime of the entire network.
- *Scalability.* Scalability refers to the ability to accommodate the change in network size. In sensor networks, the number of sensor nodes deployed may be on the order of tens, hundreds, or thousands. A MAC protocol must be scalable to such changes in network size.

- *Adaptability.* Adaptability refers to the ability to accommodate the changes in node density and network topology. In sensor networks, node density can be very high. A node may fail, join, or move, which would result in changes in node density and network topology. A MAC protocol must be adaptive to such changes efficiently.
- *Channel Utilization.* Channel utilization refers to the bandwidth utilization for effective communication. Due to limited bandwidth, a MAC protocol should make use of the bandwidth as efficiently as possible.
- *Latency.* Latency refers to the delay from the time a sender has a packet to send until the time the packet is successfully received by the receiver. In sensor networks, the importance of latency depends on different applications. While it is true that latency is not a critical factor for some applications (e.g., data collection for scientific exploration), many applications may have stringent latency requirements (e.g., real-time monitoring of bush fires).
- *Throughput.* Throughput refers to the amount of data successfully transferred from a sender to a receiver in a given time, usually measured in bits or bytes per second. It is affected by many factors, for example, the efficiency of collision avoidance, control overhead, channel utilization, and latency. Like latency, the importance of throughput depends on different applications.
- *Fairness.* Fairness refers to the ability of different sensor nodes to equally share a common transmission channel. In some traditional networks, it is important to achieve fairness for each user in order to ensure the quality of service for their applications. In sensor networks, however, all nodes cooperate to accomplish a single common task. What is important is not to achieve per-node fairness, but to ensure the quality of service for the whole task.

Among all these factors, energy efficiency, scalability, and adaptability are the most important for the MAC design of sensor networks. In particular, energy consumption is the primary factor affecting the operational lifetime of individual nodes and the entire network. The overall performance of a sensor network highly depends on the energy efficiency of the network. Therefore, energy efficiency is of primary importance in sensor networks. For this purpose, it is even worth trading some network performance for energy efficiency.

3.3.3 Energy Efficiency in MAC Design

As mentioned in Section 3.3.2, energy efficiency is of primary importance in WSNs. In general, energy consumption occurs in three aspects: sensing, data processing, and data communication, where data communication is a major source of energy consumption. According to Ref. [10], it consumes 3 J of energy to transmit 1-Kb data over a distance of 100 m. In contrast, a general-purpose processor with a processing capability of 100 million instructions per second can process 300 million instructions with the same amount of energy. For this reason, it is desired to reduce data communication as much as possible in a sensor network. Thus, sensor nodes can use their processing capability to locally perform simple data processing, instead of sending all raw data to the sink(s) for processing, and then transmit partially processed data to the sink(s) for further processing. On the other hand, an efficient MAC protocol can improve energy efficiency in data communication and prolong the lifetime of a sensor network. To design an energy-efficient MAC protocol, it is important to identify the major sources of energy waste in sensor networks from the MAC perspective.

According to Ref. [9], energy waste comes from four major sources: collision, overhearing, control overhead, and idle listening.

- *Collision.* Collision occurs when two sensor nodes transmit their packets at the same time. As a result, the packets are corrupted and thus have to be discarded. Retransmissions of the packets increase both energy consumption and delivery latency.
- *Overhearing.* Overhearing occurs when a sensor node receives packets that are destined for other nodes. Overhearing such packets results in unnecessary waste of energy and such waste can be very large when traffic load is heavy and node density is high.
- *Idle Listening.* Idle listening occurs when a sensor node is listening to the radio channel to receive possible data packets while there are actually no data packets sent in the network. In this case, the node will stay in an idle state for a long time, which results in a large amount of energy waste. However, in many MAC protocols, for example, IEEE 802.11 ad hoc mode or CSMA, a node has to listen to the channel to receive possible data packets. There are reports that idle listening consumes 50–100% of the energy required for receiving data traffic [9]. For example, Stemm and Katz [11] reported that the idle: receive: send ratios are 1:1.05:1.4, while in the Digitan 2-Mbps wireless LAN module (IEEE 802.11/2 Mbps) specification the ratios are 1:2:2.5 [12].
- *Control Overhead.* A MAC protocol requires sending, receiving, and listening to a certain necessary control packets, which also consumes energy not for data communication.

3.4 MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS

In this section, we introduce various MAC protocols for WSNs, including contention-based protocols, contention-free protocols, and hybrid protocols.

3.4.1 Contention-Based Protocols

This section introduces several contention-based MAC protocols that have been proposed for WSNs.

3.4.1.1 S-MAC. The sensor-MAC (S-MAC) protocol proposed by Ye et al. [13,14] is an energy-efficient MAC protocol specifically designed for WSNs. S-MAC considers a sensor network scenario in which most communication occurs between nodes as peers, rather than to a single base station, and its applications have long idle periods and can tolerate latency on the order of network messaging time. The primary goal of the S-MAC design is to improve energy efficiency while maintaining good scalability and collision avoidance. To achieve this goal, S-MAC tries to reduce energy consumption from all the major sources that cause inefficient use of energy. In exchange, it allows some performance degradation in both per-hop fairness and latency. This is implemented by integrating several effective control mechanisms into a contention-based MAC protocol built on top of the IEEE 802.11 standard. These mechanisms include periodic listen and sleep, collision avoidance, coordinated synchronization, and message passing.

To reduce idle listening, S-MAC introduces a periodic listen and sleep mechanism to establish a low-duty-cycle operation on each node. With this mechanism, each node is periodically put into a sleep state for some time, and then wakes up and listens to see if it needs to communicate with any other node. In the sleep state, the radio is completely turned off and a timer is set to awake the node at a later time. A complete cycle of listen and sleep periods is called a frame. Each frame begins with a listen period, during which a node can communicate with the other nodes, followed by a sleep period, during which a node sleeps if it has no data to send or receive, or remains awake if it has data to send or receive, as shown in Fig. 3.2. A duty cycle is defined as the ratio of the listen duration to the whole duration of a frame. The listen period is further divided into smaller intervals for sending or receiving SYNC, RTS, and CTS packets. The duration of the listen period is normally fixed depending on physical- and MAC-layer parameters, for example, the radio bandwidth and the contention window size. The duration of the sleep period can be changed according to different application requirements, which actually changes the duty cycle.

In S-MAC, all nodes are free to choose their own listen and sleep schedules. To reduce control overhead, however, neighboring nodes coordinate their sleep schedules and try to adopt the same schedules to listen and sleep, rather than randomly sleep on their own. To establish coordinated or synchronized sleep schedules, each node exchanges its schedule with other nodes by periodically

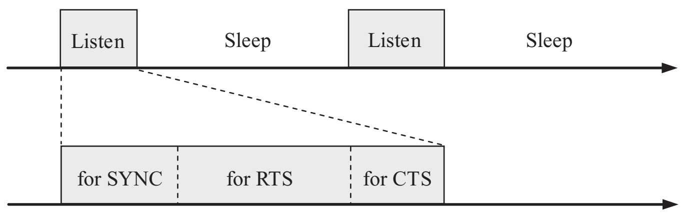

Fig. 3.2 Periodic listen and sleep in S-MAC.

broadcasting a SYNC packet to all its immediate neighbors and maintains a schedule table that stores the schedules of all its known neighbors for listening and sleeping. However, it is not always possible for all neighboring nodes to synchronize their schedules in a multihop network. In this case, S-MAC allows a node to adopt multiple schedules to enable multihop operation in the network.

On the other hand, the clock drift on each node can cause timing errors, which would affect the schedule coordination and synchronization. To address this problem, S-MAC uses relative timestamps instead of absolute ones and at the same time makes the listen period significantly longer than the clock drift. To maintain synchronization, however, each node still needs to periodically update its schedule to prevent long-term clock drift. For this purpose, each node periodically broadcasts its schedule to all its neighbors in a SYNC packet. The SYNC packet is very short and contains the address of the sender and the next sleep time of the sender. The next sleep time is relative to the time when the sender starts to send the SYNC packet. When a node receives the SYNC packet, it will use the new value of the next sleep time to adjust its timer.

In order for a node to receive both SYNC packets and data packets, its listen period is divided into two parts. The first part is for receiving SYNC packets and the second is for receiving RTS packets. Each part is further divided into many timeslots for senders to perform carrier sensing. For example, if a sender has a SYNC packet to send, it starts carrier sensing when the receiver begins listening and randomly selects a timeslot to perform carrier sensing. If it has not detected any transmission by the end of the timeslot, it wins the medium and then starts to send its SYNC packet immediately. Figure 3.3 illustrates the timing relationship between a sender and a receiver in different possible situations, where sender 1 only sends a SYNC packet, sender 2 only sends a unicast data packet, and sender 3 sends both a SYNC packet and a data packet.

The collision avoidance mechanism used in S-MAC is similar to that in the IEEE 802.11 DCF [5]. To avoid collision, S-MAC uses both virtual and physical carrier sensing and adopts the RTS/CTS mechanism to address the hidden terminal problem. In virtual carrier sensing, each transmitted packet carries a duration field that indicates the duration of the transmission. If a node receives a packet destined to another node, it knows how long it needs to keep silent. The node records this value in a variable called network allocation vector (NVA) [5] and sets a timer for it. Every time the NAV timer times out, the node decrements the NAV value until the NVA becomes zero. When a node has data to send, it first checks the NAV value. A nonzero value indicates that the medium is busy. Physical carrier sensing is performed by listening to the channel at the physical layer. The procedure is the same as that for sending SYNC packets. The medium is determined as free if both virtual and physical carrier sensing indicates it is free. All nodes perform carrier sensing before its data transmission. If a node is unable to win the medium, it goes to sleep and wakes up when the receiver becomes free, and listens again. Unicast packets are sent with an exchange of RTS/CTS/DATA/ACK packets between the sender and the receiver, while broadcast packets are sent without exchanging RTS and CTS packets.

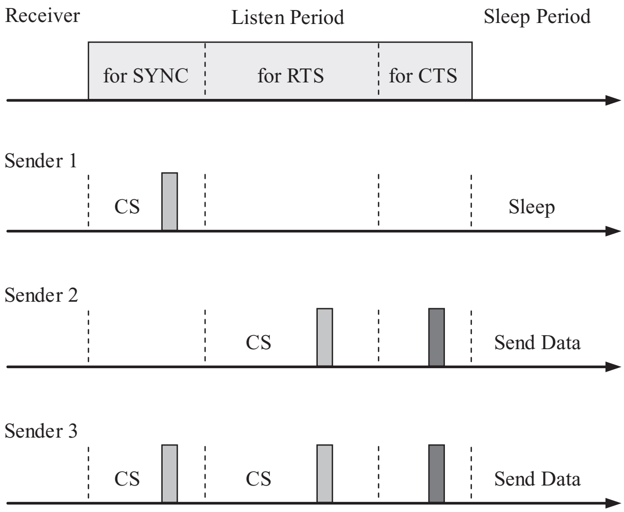

Fig. 3.3 Timing relationship between a receiver and a sender.

To avoid overhearing, S-MAC puts a node into the sleep state after it receives an RTS or CTS packet. Since DATA packets are normally much longer than control packets, this prevents neighboring nodes from overhearing long DATA packets and subsequent ACK packets. A node can wake up after the NAV value becomes zero.

In addition, S-MAC introduces a transmission mechanism called message passing to efficiently transmit a long message in terms of both energy and latency. A message is a collection of meaningful and interrelated units of data, which can be a long series of packets or a short packet. Usually, a receiver needs to obtain all the data units before it can perform in-network data processing or aggregation. In-network data processing or aggregation is an important feature of WSNs, which can greatly save energy consumption by largely reducing the amount of data to be transmitted [15]. However, if a long message is transmitted as a single packet and only a few bits are corrupted, the whole packet needs to be retransmitted, which would result in a high transmission cost. On the other hand, if the long message is segmented into many independent small fragments, it would cause larger control overhead and longer delay because RTS and CTS packets are used in contention for each independent packet. To address this problem, S-MAC segments a long message into many small fragments, and transmits them in a burst. Only one RTS and one CTS are used to reserve the medium for transmitting all fragments. Each fragment is acknowledged separately and is retransmitted if the ACK packet is not received for the fragment. If a neighboring node hears an RTS or CTS packet, it will go to sleep for the time that is needed to transmit all the fragments. Besides RTS and CTS, each fragment or ACK packet also has a duration field, which indicates the time for transmitting all the remaining data fragments and ACK packets and allows a node that wakes up in the middle of the transmission to return to sleep. This is different from 802.11's fragmentation mode, where each fragment only indicates the presence of an additional fragment rather than all of them. If a node wakes up or a new node joins in the middle of a transmission, it can properly go to sleep no matter whether it is the neighbor of the sender or the receiver. If the sender extends the transmission time because of fragment losses or errors, the sleeping neighbors will not be aware of the extension immediately. However, they will learn it from the retransmitted fragments or ACK packets when they wake up.

S-MAC is much more energy efficient than 802.11. However, due to the fixed sleep time/awake time ratio, some portion of the bandwidth is always unusable and the delay is higher. Overhearing is avoided for unicast traffic, but for broadcast or carrier sense traffic, overhearing is still an unsolved problem. The main drawback of S-MAC is high message delivery latency as S-MAC is designed to sacrifice latency for energy savings.

3.4.1.2 DS-MAC. DS-MAC is an S-MAC protocol with a dynamic duty cycle proposed by Lin et al. [16], which aims to achieve a good tradeoff between energy consumption and latency without incurring much overhead. In DS-MAC, each sensor node assumes all functionalities defined in S-MAC and each receiver node keeps track of its own energy consumption level and average latency. To achieve the intended tradeoff, each node attempts to dynamically adjust its sleep–wakeup cycle time based on the current energy consumption level and the average latency it has experienced. The average latency is used as an approximate estimation of the current traffic condition and an indicative parameter for a receiver node.

With DS-MAC, each node uses the SYNC packets to set up and maintain clock synchronization as done similarly in S-MAC. Unlike S-MAC, which adopts a constant duty cycle, DS-MAC adopts a common initial basic duty cycle at all sensor nodes. If a receiver node finds that the latency becomes intolerable, it will double the original duty cycle by reducing the sleeping period accordingly without changing the listening period. As a result, a node with an increased duty cycle can get more chances to receive packets from other senders instead of blocking them while sleeping. Therefore, DS-MAC alleviates the high-latency problem with S-MAC under high-traffic load while still keeping high energy efficiency under low traffic load.

To implement DS-MAC, some additional protocol overhead needs to be introduced, including a "duty cycle" field and a "delay" field in each SYNC packet. Compared with the S-MAC implementation, each sensor node also needs to maintain its own average latency and energy consumption level, which requires additional storage overhead and processing overhead. However, all these overheads are negligible and can actually be compensated by the reduced queuing cost due to the decreased latency.

3.4.1.3 MS-MAC. MS-MAC is an adaptive mobility-aware MAC protocol proposed by Pham and Jha [17] to address the mobility issue in mobile sensor applications like smart patient assistance and rare animal monitoring. In such mobile sensor applications, each sensor node could be highly mobile and the level of mobility may vary significantly during different periods of a day. Before MS-MAC, most MAC protocols proposed for WSNs only consider stationery sensor nodes, which may largely degrade the network performance if directly applied to mobile scenarios. To improve the network performance in mobile scenarios, a MAC protocol must be mobility aware and able to adapt to different levels of mobility. To this end, MS-MAC adopts the design of S-MAC and extends the protocol to support mobile sensor nodes. For a stationery scenario, MS-MAC operates similar to S-MAC in order to conserve energy. For a highly mobile scenario, it switches to an operating mode similar to IEEE 802.11. The protocol uses any change in the received signal levels of periodical SYNC messages as an indication of mobility and if necessary triggers a mobility handling mechanism, which dynamically adjusts the frequency of mobility handling actions based on the presence of mobile nodes and their moving speeds. With such a mobility estimating and handling mechanism, MS-MAC is highly energy efficient for stationery scenarios while also maintaining a certain level of network performance in scenarios with mobile sensor nodes.

3.4.1.4 D-MAC. D-MAC is an energy-efficient and low-latency MAC protocol by Lu et al. [18] for data gathering in WSNs. This protocol was proposed to address the data forwarding interruption problem in multihop data delivery and its primary goal is to achieve both energy efficiency and low latency. To deliver data from a source sensor node to the sink through a multihop path, most MAC protocols that use active–sleep duty cycles (e.g., S-MAC) suffer from a data forwarding interruption problem, where some nodes on the multihop path cannot be aware of the on-going data delivery. For example, in an implicit duty-cycle adjusting mechanism, a node remains active when it overhears ongoing transmissions in the neighborhood [2]. Since the overhearing range of a node is limited by its radio sensibility, a node that is out of the overhearing range of both the sender and the receiver of a data transmission cannot be aware of the ongoing data transmission and thus goes to sleep until the next cycle. As a result, the data forwarding process will be interrupted at a node whose next hop toward the sink is out of the overhearing range. The data packet has to wait in the queue until the next active period, resulting in sleep latency. For an explicit duty-cycle adjusting mechanism [19], it uses duty-cycle adjusting messages to directly adjust the duty cycle. Since the adjusting messages can only be forwarded a limited number of hops in an active period, a node out of the range goes to sleep after its basic duty cycle, leading to the interruption of the data forwarding as well.

To address this problem, D-MAC employs a staggered wake-up schedule to enable continuous data forwarding on a multihop path. In WSNs, the primary traffic is for data gathering from sensor nodes to a sink. The data delivery paths from multiple sources to one sink constitute a data gathering tree [15], in which data flows are unidirectional and all nodes except the sink forward the packets

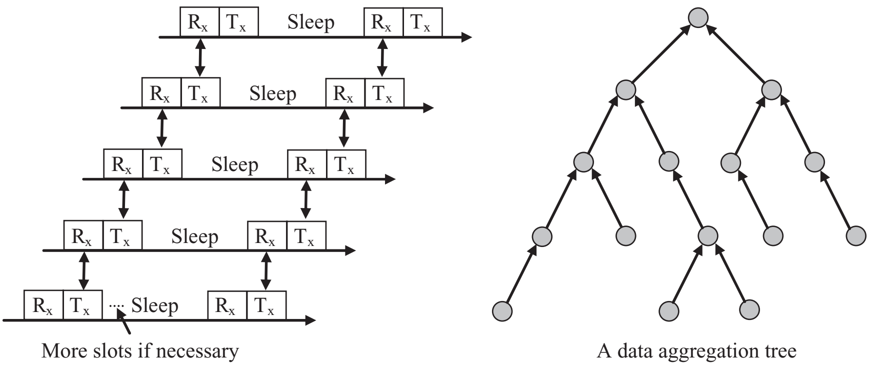

Fig. 3.4 An aggregation tree in D-MAC and its implementation.

they receive to the next hop. To enable continuous data forwarding on a multihop path, D-MAC staggers the schedule of the nodes on the multihop path and allows the nodes to wake up sequentially like a chain reaction, as shown in Fig. 3.4. In the schedule, an interval is divided into three periods (or states): receiving, sending, and sleeping. In the receiving period, a node is expected to receive a packet and send an ACK packet back to the sender. In the sending period, a node tries to send a packet to its next hop and receive an ACK packet. In the sleeping period, a node turns off its radio to save energy. The receiving and sending periods have the same length of μ, which is long enough for transmitting and receiving one packet. Depending on its depth d in the data gathering tree, a node sets its wake-up schedule $d\mu$ ahead from the schedule of the sink.

With the operation like a multihop chain, each node periodically goes into the receiving, sending, and sleeping states. As a result, when there is no collision, a packet will be forwarded sequentially along a multihop path to the sink without sleep latency. However, when a node has multiple packets to send at a sending slot, it needs to increase its own duty cycle, and has to request other nodes on the multihop path to increase their duty cycles as well. For this purpose, D-MAC employs a slot-by-slot renewal mechanism, where a *more data* flag is piggybacked in the MAC header to indicate the request for an additional active period with little overhead. Before a node transmits a packet, it first sets the *more data* flag in the packet if either its buffer is not empty or it received a packet with a *more data* flag from its previous hop. The receiver will check if the *more data* flag is set in the received packet, and if the flag is set, it will also set the *more data* flag of its ACK packet to the sender. With this slot-by-slot renewal mechanism, D-MAC can adaptively adjust the duty cycles to the traffic load.

In addition, D-MAC employs a data prediction mechanism to solve the problem when each single source has a traffic rate low enough for the basic duty cycle to handle, but the aggregated rate at an intermediate node is larger than the basic duty cycle can handle. When multiple children of a node have packets to send in the same sending slot, data prediction is used to request active sending slots. When multiple nodes on the same level of the data gathering tree with different parents compete for the channel, the data prediction mechanism is unable to handle the interference. In that case, an explicit control packet called *More-to-Send* packet is used to adjust the duty cycle under the interference.

3.4.1.5 Sift. Sift is a CSMA based MAC protocol proposed by Jamieson et al. [20] for handling spatially correlated contention in event-driven WSNs. It is motivated by the observations that sensor networks are usually event driven and have spatially correlated contention. In most sensor networks, multiple sensors are deployed in the same geographical area and share the same radio medium. When an event of interest occurs, the sensors that observe the event will send messages to report the event. If multiple sensors have messages to send at the same time, it will cause contention for the radio medium, which is called spatially correlated contention. However, in many sensor applications, not all the sensing nodes that observe an event need to report the event and the number of contending nodes changes over time. For these reasons, a MAC protocol for sensor networks should be able to not only handle spatial correlation, but also adapt to the changes in the number of contending nodes.

The above observations lead to a problem in sensor network MAC protocol design that is different from classical MAC protocol design. For a shared medium with N nodes observing an event and contending for transmission at the same time, a MAC protocol should be designed with the objective to minimize the time taken to send R of N messages without collisions. If $R = N$, this problem becomes the throughput optimization problem in classical MAC protocol design. If $R < N$, the objective is to allow the first R winners in the contention to send their messages through as quickly as possible, with the remaining nodes backing off their transmissions. Sift is a randomized CSMA protocol designed to solve this problem. Unlike traditional MAC protocols, Sift does not use a time-varying contention window from which a node randomly picks a contention slot. Instead, to reduce the latency for delivering event reports, it uses a small and fixed contention window of 32 slots, where the duration of each slot is on the order of tens of microseconds, and a geometrically increasing non-uniform probability distribution for picking a transmission slot in the contention window. The key difference between Sift and traditional MAC protocols, for example, IEEE 802.11, is that the probability distribution for selecting a contention slot is not uniform.

With the non-uniform probability distribution, a node competes for a contention slot within the contention window with other nodes based on a shared *belief* of the current population size N, which changes after every slot with no transmission. This belief starts with some large value and a correspondingly small probability for per node transmission. If no node transmits in the first slot, each node will reduce its belief of the number of competing nodes by multiplicatively increasing its transmission probability for the second slot. This process is repeated for each slot, allowing for the competition to happen at geometrically decreasing possible values in the same small total number of contention slots. As a result, Sift enables the winner to be chosen quickly in a wide range of potential population sizes without incurring long latency due to collisions. If exactly one node happens to select some contention slot, it will start to transmit in that slot. When its transmission is done, all other competing nodes will randomly select new contention slots, and repeat the process of backing off over the fixed contention window. The same process happens if two or more nodes happen to select the same contention slot.

The simulation results show that Sift can offer up to a sevenfold latency reduction compared to IEEE 802.11 as the size of the network scales up to 512.

3.4.1.6 T-MAC. Timeout-MAC (T-MAC) is an adaptive energy-efficient MAC protocol proposed by Dam and Langendoen [21] for WSNs. The basic idea of T-MAC is to reduce idle listening by introducing a dynamic duty cycle and transmitting all messages in bursts of variable size in active periods and sleeping between active periods. To maintain an optimal active period under variable traffic load, T-MAC dynamically determines the length of an active period by simply timing out if nothing is heard.

In T-MAC, each node periodically wakes up to communicate with its neighbors and then go to sleep until the next frame, as shown in Fig. 3.5. The nodes communicate with each other following a RTS-CTS-Data-ACK sequence, which provides both collision avoidance and reliable transmission. A node keeps listening and potentially transmitting as long as it is in an active period. If no *activation event* occurs for a threshold time T_h, an active period will end and the node will go to sleep. An activation event can be (1) the timing out of a periodic frame timer; (2) the reception of a data packet on the radio; (3) the sensing of communication on the radio; (4) the end of transmission of a node's own data packet or acknowledgment; or (5) the end of transmission of a neighbor's data packet. Obviously, T_h determines the minimum amount of idling listening per frame. As a result, all nodes transmit at the beginning of each active period. Since data packets between active periods need to be buffered, the buffer capacity determines an upper bound on the maximum frame time.

The simulation results show that T-MAC and S-MAC achieve similar energy consumption reductions (up to 98%) compared to CSMA. However, T-MAC outperforms S-MAC by a factor of 5 in a sample scenario with variable traffic load.

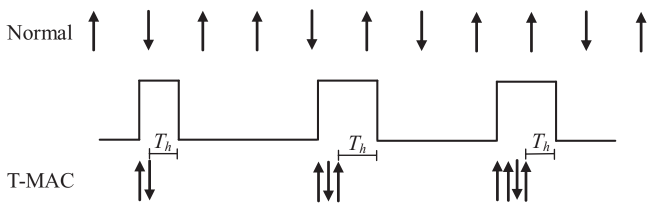

Fig. 3.5 The T-MAC frames with adaptive active periods.

3.4.1.7 WiseMAC. Wireless Sensor MAC (WiseMAC) is an energy-efficient MAC protocol proposed by Hoiydi et al. [22] for both multihop and infrastructure networks. To improve energy efficiency, it combines non-persistent CSMA with synchronized preamble sampling to mitigate idle listening. In the preamble sampling technique, all nodes in a network sample the medium with the same constant period, but their relative sampling schedule offsets are independent. If a node finds the medium busy, it will continue to listen until it receives a data packet or the medium becomes idle again. At a transmitting node, a wake-up preamble of size equal to the sampling period is transmitted ahead of each data packet to alter the receiving node. This technique provides low power consumption when traffic is low. However, the fixed-length preamble leads to high power consumption overhead in both transmission and reception. To reduce the power consumption incurred by the fixed-length preamble, WiseMAC introduces an effective scheme to dynamically reduce the length of the wake-up preamble. This scheme learns the sampling schedules of direct neighbors and exploits these schedules to reduce the length of a wake-up preamble. The nodes learn or refresh their neighbor's sampling schedule during each data communication by piggybacking the remaining time to the next sampling instant in the acknowledgment messages. Each node keeps an updated table of the sampling time offsets of its neighbors. Based on these tables, WiseMAC schedules a transmission such that the middle of the wake-up preamble coincides the sampling time of the destination, as shown in Fig. 3.6.

WiseMAC requires no setup signaling or network-wide time synchronization. The combination of preamble sampling and wake-up preamble-length minimization provides both ultra-low power consumption under low-traffic conditions and high energy efficiency under high-traffic conditions. Although WiseMAC was originally designed for multihop networks, it is also suitable for the downlink of an infrastructure network [23]. It has been shown that under low-traffic conditions, WiseMAC leads to lower power consumption than the power-save scheme

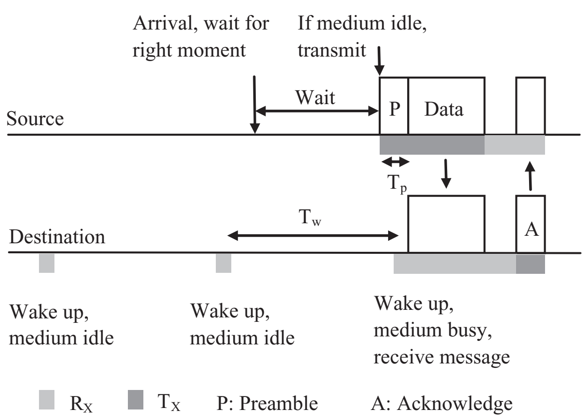

Fig. 3.6 WiseMAC preamble minimization.

in IEEE 802.11 [5] and IEEE 802.15.4 [24]. Therefore, WiseMAC can be used in a hybrid network topology to receive data from both energy-constrained sensor nodes and energy-unconstrained base stations.

3.4.1.8 CSMA Based MAC with Adaptive Rate Control. Woo and Culler [25] proposed a CSMA based MAC protocol that combines CSMA with an adaptive rate control mechanism. This protocol considers a specific network scenario in which a base station collects data from all sensors in a field of interest and the applications generate periodic and highly correlated traffic. It aims at achieving both energy efficiency and fair bandwidth allocation for all nodes in a multihop network. In such a network scenario, the contention for channel bandwidth between originating traffic and pass-through traffic at a node has a direct impact on the multihop fairness in bandwidth allocation. For this reason, a MAC protocol should be able to control the rate of originating data of a node in order to allow pass-through traffic to more easily access the channel and reach the base station. On the other hand, a progressive signaling mechanism is also needed for pass-through traffic to inform the nodes down in the network to lower their rate of originating data. This will in turn decrease the aggregate pass-through traffic and open up the channel for nodes closer to the base station to originating data.

For this purpose, Woo and Culler [25] proposed an adaptive rate control mechanism to balance the rates of originating traffic and pass-through traffic at a node. With this mechanism, a node periodically attempts to transmit a packet into the channel. If the packet is successfully transmitted, it becomes part of the pass-through traffic. As the packet is routed by the node's parent node, it signals that the channel can still accommodate more traffic and thus the node can increase its transmission rate. However, if the packet is not transmitted into the channel successfully, it signals that the channel is congested. In this case, the node decreases its rate of originating data and backoffs in order to achieve a phase change effect. In this way, the originating data rate can adapt to the pass-through traffic. Similarly, the pass-through traffic will also adapt to the originating traffic. Specifically, if a node transmits lots of originating traffic into the channel, the rate of transmitting pass-through traffic will decrease. This information is propagated down into the network, which would ultimately decrease the aggregate path-through traffic. In addition, the rate control mechanism uses a linear increase and multiplicative decrease approach to control the transmission rate. While the linear increase leads to more aggressive channel competition, the multiplicative decrease controls the penalty for a transmission failure. Since it costs more to drop pass-through traffic than to drop originating traffic, the penalty associated with a pass-through data transmission failure is smaller than that with an originating data transmission failure, which ensures that pass-through traffic is more favored over originating traffic.

It has been shown that the CSMA based MAC protocol is most effective in achieving fair bandwidth allocation while being energy efficient for both low- and high-duty cycles of network traffic. However, since it is based on CSMA, it may suffer from high control overheads and the hidden terminal problem.

3.4.2 Contention-Free Protocols

This section introduces several contention-free MAC protocols that have been proposed for WSNs.

3.4.2.1 Traffic-Adaptive Medium Access. The traffic-adaptive medium access (TRAMA) protocol is a TDMA based MAC protocol proposed by Rajendran et al. [26] to provide energy-efficient collision-free channel access in WSNs while maintaining good throughput, acceptable latency, and fairness. In TRAMA, energy efficiency is achieved by ensuring collision-free data transmissions and allowing nodes to switch to a low-power idle state when they are not transmitting or receiving. To maintain throughput and fairness, TRAMA uses a transmitter-election algorithm that is inherently fair and promotes channel reuse as a function of the competing traffic around a given source or receiver.

The TRAMA protocol assumes a single time-slotted channel for both data and signaling transmissions. Time is divided into a series of random-access periods and scheduled-access periods, which alternate with each other, as shown in Fig. 3.7. A random-access period, also referred to as a signaling slot, is further divided into smaller signaling slots and a scheduled-access period, also referred to as a transmission slot, into smaller transmission slots. Since the data rate in a sensor network is relatively low, the bit duration is much larger than typical clock drifts. For this reason, slot synchronization can be implemented by using a simple time-stamp mechanism or a technique, for example, a global positioning system (GPS). The TRAMA protocol starts with a random access period where each node randomly selects a timeslot and then transmits. A node can only join the network during a random access period. The duty cycle of random access and scheduled access depends on the type of network. In a more dynamic scenario, random access periods should occur more often while in a more static scenario the interval between random access periods can be larger because topology changes need to be accommodated only occasionally. Depending on the type of the application, there is little or no mobility in a sensor network. Accordingly, the random access

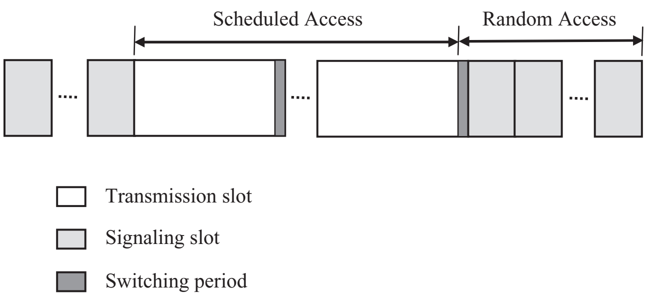

Fig. 3.7 Time-slot structure in TRAMA.

periods are mainly used to allow node addition and deletion. During a random access period, all nodes must be in either a transmitting state or a receiving state so that they can send out their neighborhood information and receive information from neighbors. Due to collisions, signaling packets may be dropped, which can lead to inconsistent neighborhood information between different nodes. To ensure consistent neighborhood information with some degree of confidence, the duration of a random access period and the number of retransmissions of a signaling packet are set accordingly. In addition, time synchronization could also be performed during this period.

The TRAMA protocol consists of three components: the neighbor protocol (NP), the schedule exchange protocol (SEP), and the adaptive election algorithm (AEA). Both the NP and the SEP allow nodes to exchange 2-hop neighborhood information and their schedules. The AEA uses the neighbor and schedule information to select transmitters and receivers for the current timeslot, allowing all other nodes to switch to a low-power mode.

The NP collects 2-hop neighborhood information by exchanging small signaling packets among neighboring nodes during the random access periods. A signaling packet carries incremental neighborhood updates. If there are no updates, it is sent as a "keep alive" beacon. Each node sends incremental updates about its 1-hop neighborhood. These signaling packets are also used to maintain connectivity between the neighbors. A node times out a neighbor if it does not hear from that neighbor for a certain period of time. The updates are retransmitted such that 99% of success is ensured. Since a node knows the 1-hop neighbors of its 1-hop neighbors, consistent 2-hop neighborhood information can eventually be obtained.

Transmission slots are used for transmitting data traffic and also for exchanging traffic-based schedule information between neighboring nodes. The schedule information is required by the transmitter (i.e., slot reuse) and receiver (i.e., sleep-state switching) selection. A node has to announce its schedule via a schedule packet using the SEP before actual data transmissions. The SEP updates the schedule information periodically during the scheduled-access periods and thus maintains consistent schedule information among neighbors.

The AEA is used to select transmitters and receivers to achieve collision-free transmissions using the information obtained by the NP and the SEP. To achieve energy efficiency in a collision-free transmission, it is necessary to select both a transmitter and a receiver(s) for a particular timeslot. Selecting a transmitter randomly may lead to collisions, while selecting a transmitter, but not a receiver(s), may lead to energy waste because all the neighbors around a selected transmitter have to listen in the timeslot even if they are not to receive any data. Moreover, selecting a transmitter without considering its traffic leads to low-channel utilization because the selected transmitter may not have data to send to the selected receiver. Therefore, the AEA uses traffic information in selecting transmitters and receivers in order to improve channel utilization.

According to the simulation results, TRAMA can achieve significant energy savings due to a higher percentage of sleep time. It can also achieve higher throughput compared to contention-based protocols due to reduced collision probability. However, TRAMA has a higher delay than contention-based protocols due to a higher percentage of sleep time and thus is suitable for applications that are not delay sensitive, but require high delivery throughput and energy efficiency.

3.4.2.2 Self-Organizing Medium Access Control. Self-organizing medium access control for sensor networks (SMACS) is a distributed MAC protocol proposed by Sohrabi et al. [27], which enables a collection of nodes to discover their neighbors and establish schedules for communicating with them without the need for any local or global master nodes. In SMACS, each node is able to turn its radio on and off, and tune the carrier frequency to different bands. The number of available bands is relatively large. To form a flat topology, the neighbor discovery and channel assignment phases are combined. A channel is assigned to a link immediately once the existence of the link is discovered. Therefore, by the time all nodes hear from all their neighbors, they will have formed a connected network, where there is at least one multihop path between any two distinct nodes. In SMACS, only partial information about radio connectivity in the vicinity of a node is used to assign timeslots to links. Each node maintains a TDMA-like frame called superframe, in which it schedules different timeslots to communicate with its known neighbors. In each timeslot, a node only communicates with one neighbor. However, there is a potential for time collisions with slots assigned to adjacent links whose existence is unknown at the time of channel assignment. To reduce the likelihood of collisions, each link operates on a different frequency, which is chosen randomly from a large pool of frequencies when the links are established. After a link is established, a node knows when to turn on its transceiver ahead of time to communicate with another node and will turn off when there is no communication. By using such scheduling, energy savings can be achieved at the node. On the other hand, since link assignment is done without a need for collecting global connectivity information or even connectivity information that reaches farther than one hop away, significant energy savings can be achieved. The drawback of SMACS is its low bandwidth utilization. For example, if a node only has packets to be sent to one neighbor, it cannot reuse the timeslots scheduled for other neighbors.

3.4.2.3 Distributed Energy-Aware MAC. The distributed energy-aware MAC (DE-MAC) protocol is a TDMA based MAC protocol proposed by Kalidindi et al. [28] to address the energy management problem in WSNs. The DE-MAC protocol exploits the inherent features of TDMA to avoid energy waste caused by collision and control overhead, and employs a periodical listening and sleeping mechanism to avoid idle listening and overhearing. Unlike some existing MAC protocols that treat all nodes equally with respect to energy conservation, DE-MAC treats those critical nodes (i.e., with lower energy) differently by using them less frequently to achieve load balancing among all nodes. The criticality of a sensor node can be based on local state information, for example, relative energy levels within a group of neighbor nodes. For this purpose, a group of neighbor nodes periodically perform a local election process based on their energy levels to elect the worst-off node(s) as the winner(s) and let the winner(s) sleep more than its (or their) neighbor nodes. The local election process is fully integrated with the regular TDMA schedule and thus would not cause additional throughput loss. More specifically, the protocol initially assigns the same number of transmission slots to each node in a TDM frame. A node can independently decide to initiate an election if its current energy level is below a threshold value. Once an election is initiated, each node sends its energy level to all of its neighbors, which is included to its regularly scheduled transmission packet during its scheduled timeslot. To receive the energy level information from other nodes, all nodes listen to all transmitted packets. There are no sleeping nodes when other nodes are transmitting. This is to enable the integration of leader-election with regular TDMA transmission and thus save bandwidth. At the end of the election process, the node with the minimum energy level is elected as a winner. Once one or more winners are elected, all the losers reduce the number of their timeslots by a constant factor (e.g., two) and the winners have timeslots twice the number of the losers. By performing such slot adjustment, the idling listening time of those critical nodes are reduced, leading to more energy savings in the critical nodes. The simulation results show that DE-MAC achieves a significant gain in energy savings compared to the simple TDMA based MAC protocol in Ref. [29].

3.4.2.4 Implicit Prioritized MAC. The implicit prioritized access protocol is a MAC protocol based on earliest deadline first (EDF), which was proposed by Caccamo et al. [30] to address the MAC problem in a cellular structure network. It considers the periodic nature of sensor network traffic and focuses the network performance in terms of guaranteed bounded delay. For a cellular structure network, the network is spatially divided into multiple cells. Within each cell, the sensor nodes are fully connected in peer to peer and intra-cell messages are exchanged using EDF with implicit contention in a multicast manner. Between adjacent cells, frequency division multiplexing (FDM) is used to avoid conflicts and inter-cell messages are exchanged using more capable router nodes. The inter-cell messages are first sent to the router node within the same cell and then forwarded by the router node through the network hop by hop. For intra-cell communication, the MAC protocol uses a combined deterministic scheduling and local carrier sensing mechanism, which replicates the EDF schedule at each node for data transmission. Since the schedules are identical at different nodes, each node can know which node has the message with the earliest deadline and has the right to transmit next. If a node is not listening to the channel, it is able to select the right frame to transmit simply by counting the frames and assuming that all previous messages used all their scheduled frames. Otherwise, if a node detects an early completion of the previous message by listening to the channel, the unused frames are exploited by using a proposed FRAme SHaring (FRASH) technique, which improves the network utilization.

3.4.2.5 Contention-Free Scheduling TDMA MAC. The contention-free scheduling TDMA MAC protocol proposed by Carley et al. [31] is a TDMA based MAC protocol with a contention-free message scheduler at each node. The message scheduler uses a periodic message model to construct a contention-free schedule for transmitting and receiving the messages of a node to ensure that there is no contention in the transmission medium and even in the message scheduler. Specifically, a contention-free periodic message set is first obtained through message attribute assignment and a periodic task set is then constructed from a given contention-free periodic message set by translating the attributes of each message to task attributes. Since there is no contention in the message scheduler, each node only needs to schedule the messages of its own. For this reason, the complexity of each node only grows with the number of messages transmitted and received by that node, rather than the size of all messages in the network, and therefore is often constant. This largely reduces the space and time complexity of the network scheduler and thus results in memory, processor utilization, and power consumption savings. Moreover, since the message scheduler of each node only schedules the messages that are transmitted or received by that node, it is possible to combine the message scheduler with the task scheduler in that node. Therefore, this MAC protocol is highly scalable to large sensor networks.

3.4.2.6 CDMA Sensor MAC. The CDMA Sensor MAC (CS-MAC) protocol is a self-organizing location-aware MAC protocol proposed by Liu et al. [32] for DS-CDMA based sensor networks, which is suitable for applications with high traffic and stringent latency requirements, for example, battlefield surveillance. The design objectives of the CS-MAC protocol include energy efficiency, low latency, fault tolerance, and scalability. The assumptions for the protocol design include the following: (1) each node starts up at approximately the same time; (2) each node is able to estimate its location using GPS or alternate techniques; (3) each node is static during the network lifetime, which implies that the estimation of its location only needs to be performed once and thus the energy consumption for the location estimation can be ignored.

In CS-MAC, the network formation process consists of several different phases, as shown in Fig. 3.8. In the location broadcast phase, each node broadcasts its location information to the neighbors within its radio range. To ensure that each node can get a chance for a successful transmission, CS-MAC uses a large contention window and allows each node to broadcast several times. At the end of this phase, each node should have a list of neighbors within its radio range with their locations, called *redundant neighbor list* (*RNL*).

In the TORN (turning off redundant node) phase, a node that is redundant for a sensing application is turned off to conserve energy and reduce network interference. Specifically, each node first ranks all neighbors in the RNL based on their distances to the node itself. If sensors are densely deployed, a node will have a high probability to have redundant neighbors within a radius *Sensing Resolution* (SR), which denotes the sensing accuracy required by an application. Note that SR is an application-specific criterion that is different from the sensing

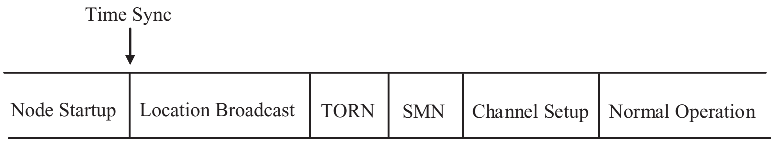

Fig. 3.8 Network formation phases.

range. Then each node uses a contention-based protocol to negotiate who should keep active. A random timer is set to avoid collisions. The first node that gets the medium to transmit will inform its redundant neighbor(s) to turn off by including their ID numbers in a request. A node will turn off itself upon receiving such a request from a neighbor, and will wake up later to check the energy level of the active node and decide whether it should take over, thus providing fault tolerance. Obviously, a node with more redundant neighbors will less likely become an active node during the TORN phase. At the end of the TORN phase, only active nodes are left in the network. The resulting neighbor list in each active node is called *non-redundant neighbor list* (*NNL*), which will be used in the SMN phase (select minimum neighbor).

In the SMN phase, each active node has a list of location information of the active neighbors within its radio range. A node will not select all of them as neighbors. Instead, it only selects a node as its neighbor if there is no other neighbor that can provide a multihop path with lower power consumption. For this purpose, an algorithm is designed for a sensor node (or seed node) to select its neighbors from the NNL. After the SMN phase, each active node only has a minimum set of neighbors called *minimum neighbor list* (MNL). This MNL will be used in the channel setup phase, where a peer-to-peer communication channel will be set up for each neighbor in the MNL and the seed.

In the channel setup phase, each node sets up connections to all its neighbors in the MNL. It first estimates the transmission power required to reach its furthermost neighbor in the MNL and then uses this power level for negotiation. This allows a node that is far enough from this node to initiate another set-up process simultaneously. CSMA/CA is used by nodes to set up connections with each other. Once a node wins the channel, it will hold the channel until it finishes the channel allocation with all its neighbors in the MNL.

CS-MAC uses a combination of DS-CDMA and frequency division in channel allocation to reduce channel interference, and consequently the message latency in the network. The simulation results in Ref. [33] have shown that CS-MAC can significantly reduce average latency and average energy consumption per message compared to traditional MAC protocols for sensor networks.

3.4.3 Hybrid Protocols

This section introduces several hybrid MAC protocols for WSNs, which combine the features of both contention-based and contention-free protocols.

3.4.3.1 Spatial TDMA and CSMA with Preamble Sampling. Spatial TDMA and CSMA with Preamble Sampling is a hybrid MAC protocol proposed by El-Hoiydi [33] for low-power sensor networks. This protocol assumes that data traffic is periodical while signaling traffic is sporadic. All sensor nodes have two communications channels: data channel and control channel. In the data channel, a spatial TDMA protocol is used to transport periodic and frequent data while in the control channel a low-power CSMA protocol is used to transport sporadic signaling traffic. In classic CSMA, a node has to listen to the channel all the time except during its transmission. Since idle listening consumes much energy, classic CSMA is not preferred for a sensor network where the channel is idle most of time. This protocol introduces a low-power CSMA protocol that is obtained by combining it with the preamble sampling technique used in paging systems [34]. With this technique, a node sends a preamble of size T_p before every message. A receiver will sleep and wake up every T_p to check whether the channel is idle or busy. When a preamble is detected, the receiver will continue to listen until the beginning of the packet is found and the packet is received. This allows a node to sleep most of the time when the channel is idle, and can thus improve energy efficiency and prolong network lifetime.

3.4.3.2 Z-MAC. Zebra-MAC (Z-MAC) is a hybrid MAC protocol proposed by Rhee et al. [35], which combines the strengths of TDMA and CSMA while offsetting their weaknesses. The main feature of Z-MAC is its adaptability to the dynamic contention level in the network. Under low contention, it behaves like CSMA and can achieve high channel utilization and low latency. Under high contention, it behaves like TDMA and can achieve high channel utilization and reduce collisions among 2-hop neighbors at a low cost. Moreover, it is also robust to time synchronization errors, slot assignment failures, time-varying channel conditions, and dynamic topology changes.

Zebra-MAC uses CSMA as the basic MAC mechanism and meanwhile uses a TDMA schedule as a "hint" to improve contention resolution. In Z-MAC, timeslot assignment is performed at the time of deployment, which incurs high initial overhead. The argument behind this is that the high initial overhead is distributed over a long period of network operation and eventually can be compensated by improved throughput and energy efficiency. The slot assignment is performed by DRAND [36], an efficient scalable scheduling algorithm, which is a distributed implementation of RAND [37], a centralized channel scheduling algorithm. After the slot assignment, each node reuses its assigned slot periodically in every predetermined period, call frame. A node assigned to a timeslot is called an owner of that slot and the others the non-owners of that slot. Since GRAND allows any two nodes beyond their 2-hop neighborhoods to own the same timeslot, there can be more than one owner per slot.

Unlike TDMA, a node may transmit during any timeslot in Z-MAC. Before a node transmits during a slot (not necessarily at the beginning of the slot), it always performs carrier sensing and transmits a packet when the channel is idle. However, an owner of that slot always has a higher priority over its non-owners in accessing the channel. To implement the priority, Z-MAC adjusts the size of the initial contention window so that the owners are always given earlier chances to transmit than the non-owners. In this way, Z-MAC reduces the chance of collisions during the slots when the owners have data to transmit. For a slot when the owners do not have data to transmit, the non-owners can use it. Therefore, Z-MAC can dynamically adjust the behavior of MAC between CSMA and TDMA, depending on the contention level in the network.

By combining CSMA and TDMA, Z-MAC becomes more robust to time synchronization errors, slot assignment failures, time-varying channel conditions, and dynamic topology changes than a stand-alone TDMA. In the worst case, it comes back to CSMA. Since Z-MAC only requires local synchronization among sending nodes in 2-hop neighborhoods, a simple local synchronization mechanism is employed, in which each sending node adjusts its synchronization frequency based on its current data rate and resource budget. The simulation results show Z-MAC has better performance than B-MAC [38] under medium to high contention, but slightly worse performance under low contention, especially in terms of energy efficiency. Even in the case when clocks are completely unsynchronized and some degree of slot assignment failures occurs, the performance of Z-MAC is comparable to that of CSMA.

3.4.3.3 Funneling-MAC. Funneling-MAC is a hybrid TDMA and CSMA/CA MAC protocol proposed by Ahn et al. [39] for WSNs. It aims at addressing the unique funneling effect [40], where events generated in a sensor field travels hop-by-hop in a many-to-one traffic pattern toward one or more sinks, as shown in Fig. 3.9. This funneling effect results in a significant increase in transit traffic intensity and thus packet congestion, collision, loss, delay, and energy consumption as events move closer toward the sink(s). The sensor nodes closer to the sink, typically within a small number of hops, also called the intensity or funneling region, will loose a larger number of packets and consume much more energy than the nodes further away from the sink, thus largely reducing the operational

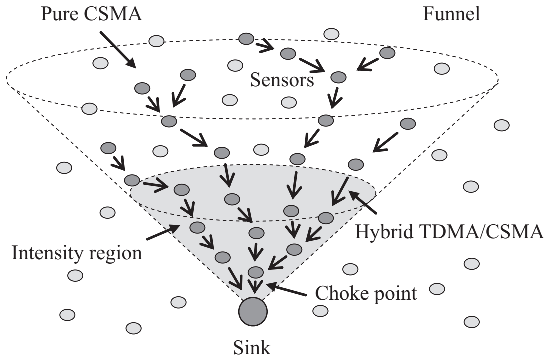

Fig. 3.9 Funneling effect in wireless sensor networks.

lifetime of the entire network. To increase network lifetime, it is desired to reduce the traffic in the intensity region and thus alleviate this funneling effect, which presents a big challenge in the network design.

The funneling MAC protocol is a localized sink-oriented hybrid TDMA and CSMA/CA MAC protocol for operating in the intensity region of the event funnel. It is based on pure CSMA/CA, which is implemented not only in the funneling region, but also network wide. Meanwhile, it uses a local TDMA scheduling in the funneling region only to provide additional scheduling opportunities to the nodes closer to the sink. It is "sink-oriented" because the TDMA scheduling of sensor events in the funneling region is performed by the sink node rather than by resources-limited sensor nodes. It is "localized" in the sense that TDMA only operates in the funneling region close to the sink rather than in the whole sensor field. Moreover, the depth of the intensity region is also computed and maintained by the sink node. By using TDMA in a localized manner, and putting more management on the sink, the scalable problem is solved for the deployment of TDMA in a sensor network. The experimental results show that the funneling MAC effectively alleviates the funneling effect, improves throughput, loss, and energy efficiency, and more importantly significantly outperforms other representative protocols, for example, B-MAC [38], a default protocol in TinyOS [41], and more recent hybrid MAC protocols, for example, Z-MAC.

3.5 SUMMARY AND FUTURE DIRECTIONS

Medium access control plays an important role in improving energy efficiency and network performance of WSNs. This chapter introduced the fundamental concepts on MAC, discussed the major challenges in MAC design, and presented a survey of MAC protocols for WSNs. Although a variety of MAC protocols have been proposed for sensor networks, no protocol has been standardized yet. The primary reason is that sensor networks are application specific and thus a MAC protocol is usually application dependent. Basically, TDMA and CSMA are the most common underlying MAC protocols that are used for sensor networks. The major advantage of TDMA is its collision-free nature, which can significantly improve energy efficiency under high traffic load. However, it has higher delay and lower throughput under low traffic load due to idle timeslots. Moreover, TDMA requires strict time synchronization between different sensor nodes, and has limited scalability and adaptability to network changes. In contrast, CSMA are contention based, which results in lower energy efficiency and higher delay under high traffic load, but can reduce delay and has higher throughput under low traffic load. Depending on specific applications, a MAC protocol can incorporate TDMA or/and CSMA with other techniques to meet different performance requirements. Due to the limitation of space, there are many other MAC protocols not included in this chapter. The reader is referred to Refs. [42–52] for further readings. To further improve the network performance, there is a trend to take into account the effects across multiple protocol layers in the design of MAC protocols, which provides many research opportunities in the future.

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