Chapter 2
MAC Protocols

Abstract Resource efficiency is one of the most important factors that should be considered when developing a MAC protocol for CPS like WBAN. This chapter presents the critical literature review of different approaches used to design MAC protocols to minimize energy consumption. Control packet overhead of communication, idle listening of nodes to receive expected data packets, overhearing, and collision of data packets are the major sources of energy dissipation in WBANs. A versatile MAC protocol should have the capabilities to minimize energy dissipation in aforementioned situations. An introduction of typical MAC protocols (which are not based on IEEE 802.15.4) for WBAN is presented in this chapter with focus on their strengths and weaknesses.

Keywords Medium access · Multiple access · Communication overhead · Overhearing · Contention

2.1 Introduction

MAC is a sublayer of data link layer commonly known as layer 2 of Open Systems Interconnection (OSI) model. MAC sublayer is responsible for a number of functions including addressing and channel access controlling mechanism. For multiple nodes in a network to communicate through shared medium, MAC sublayer provides channel access control mechanism known as multiple access protocol. For short-range wireless communications in CPS (e.g., WSN, WSAN, and WBAN), MAC protocols often use Time Division Multiple Access (TDMA) or Carries Sense Multiple Access with Collision Avoidance (CSMA/CA) for fair access of shared medium. Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) are not supposed to be suitable mechanisms to access the shared medium in CPS like WBAN due to hardware complexity and high power consumption. In case WBANs are not dynamic by nature, CSMA/CA will not be a suitable choice. On the other hand, TDMA-based approaches consume extra energy for synchronization. Design of MAC protocols varies according to the applications' requirements. This chapter, which is based on our paper published in the seventh International

F. Xia and A. Rahim, *MAC Protocols for Cyber-Physical Systems*,
SpringerBriefs in Computer Science, DOI 10.1007/978-3-662-46361-1_2

Table 2.1 CSMA/CA and TDMA comparison

Feature	CSMA/CA	TDMA
Power consumption	High	Low
Traffic level support	Low	High
Bandwidth utilization	Low	Maximum
Synchronization	N/A	Necessary
Mobility (Dynamic)	Good	Poor

Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA 2012) [1], provides in-depth analysis of different existing approaches used to design MAC protocols that are not based on IEEE 802.15.4. MAC protocols that explore IEEE 802.15.4 will be covered in the following chapters. Table 2.1 presents the comparison of CSMA/CA and TDMA approaches.

It is worth noting that IEEE 802.15.4a is a low data rate standard which defines PHY and MAC layer specifications [2]. This standard is adopted for many applications [3, 4]. Another related standard is IEEE 802.15.6 [5], which defines the PHY and MAC layer specification to be used for in-body or on-body sensor nodes communication via UWB. This standard operates in three modes: beacon-enabled mode with superframe boundaries, nonbeacon-enabled with superframe boundaries, and nonbeacon-enabled without superframe boundaries. Due to the required complex and power demanding transceiver at sensor node, this standard does not suit WBANs investigated in this book.

2.2 Classification of MAC Protocols

MAC protocols for CPS like WBAN can be categorized into three categories based on the underlying channel access mechanism: contention-based, contention-free, and low power listening (LPL) or polling. The following subsections will provide details with their pros and cons.

2.2.1 Contention-Based MAC Protocols

Sensor nodes contend for shared medium using contention-based channel access mechanism to communicate with other nodes or coordinator. Unavailability of predefined schedule for communication results in variable latency and packet loss. CSMA is a contention-based mechanism to access available shared medium for data transmission. CSMA/CA is a modification of CSMA algorithm to avoid packet collision. Ready to send (RTS) and clear to send (CTS) are used in CSMA before packet transmission; however, in CSMA/CA without RTS/CTS exchange, before transmission

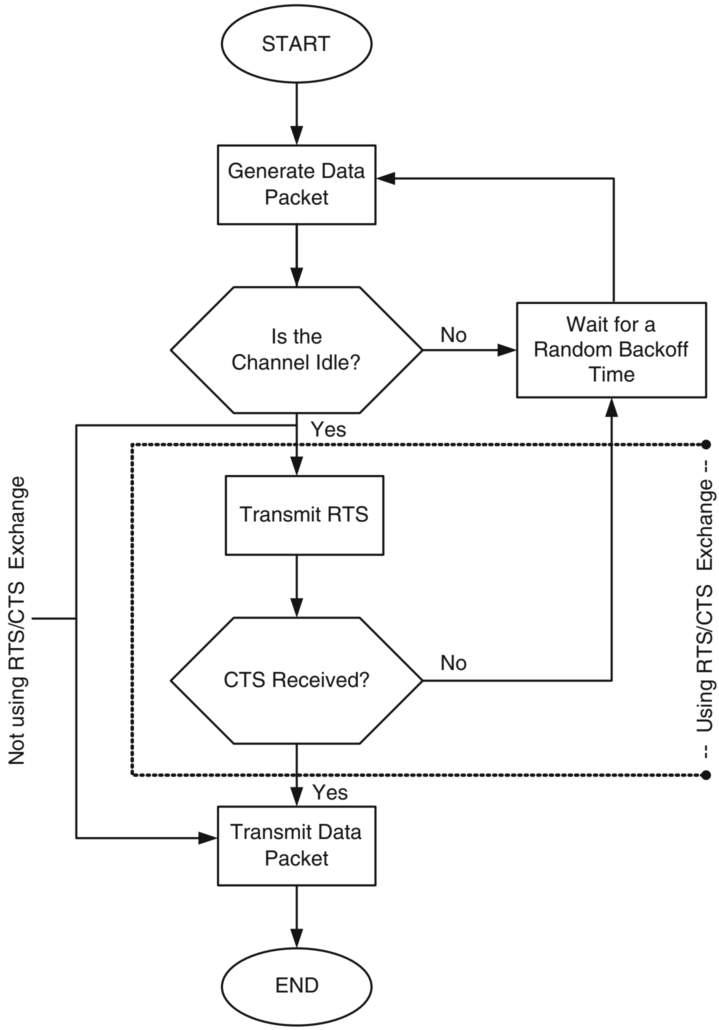

Fig. 2.1 CSMA/CA algorithm

of data packets, nodes listen to shared medium/channel to find out whether shared channel is idle or not. In case of idle situation, node starts transmission of data packets. However, if channel is sensed busy, transmission is rescheduled for a random period of time. Figure 2.1 shows CSMA/CA simplified algorithm.

To ensure reliable and collision-free communication, a common schedule is used with contention called as scheduled contention. In some cases, we need a schedule-based contention channel access mechanisms called as scheduled contention. A common schedule is used for data communication to ensure reliability and collision avoidance. Scheduled-contention mechanisms required periodic synchronization. To maintain synchronization, schedules are exchanged on regular basis which leads to extra energy consumption. Synchronization of nodes is highly sensitive to clock drift. Periodic sleep of nodes in this mechanism reduces idle listening and overhearing to improve power efficiency.

Contention-based mechanisms are well suited in dynamic and scalable networks. However, in WBANs such mechanisms do not provide reliable and efficient communication due to high energy consumption for CCA and poor handling capabilities for emergency and on-demand traffic.

2.2.2 Contention-Free MAC Protocols

In contention-free MAC protocols, sensor nodes are assigned guaranteed time slots (GTS) for data communication. These protocols provide deterministic delay with no packet loss due to communication in guaranteed time slots without contention period. TDMA is a contention-free channel access mechanism where the channel is divided into multiple time slots of fixed or variable length, see Fig. 2.2. These time slots are allocated to end nodes for communication. Multiple time slots can also be assigned to a single node depending upon requirements and data volume. Predefined and dedicated time slots in TDMA provide a collision-free environment for data communication. Synchronization is the key issue in TDMA-based MAC protocols. In general, TDMA-based MAC protocols are more efficient than CSMA/CA-based protocols in terms of energy efficiency and bandwidth utilization.

TDMA is a suitable option for limited number of sensor nodes in WBANs with fixed data rate. Sensor nodes only wake up in specified time slots for communication; otherwise, they remain in sleep mode to avoid idle listening and overhearing. Assigning time slots to sensor nodes with different data rates, nonperiodic data, and scalability are the key issues in implementing TDMA in WBANs.

2.2.3 Low Power Listening (LPL) MAC Protocols

In LPL mechanism, sensor nodes periodically listen to the channel. Nodes go into sleep mode if the channel is sensed idle; otherwise, keep the transceiver in active mode to receive data packets. This mechanism is also known as "Polling." In polling-

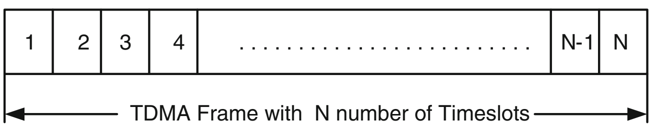

Fig. 2.2 TDMA frame structure

based MAC protocol, time interval is divided into an idle interval and wakeup interval. During the idle interval, ordinary nodes sleep to avoid extra power consumption due to idle listening [6].

Once the idle interval ends, all nodes wake up to listen the long preamble transmitted by the network coordinator. The preamble contains the address of the polled node. Once the node receives the preamble with its address, either it transmits the data packet or the null packet indicating that the buffer of the node is empty. LPL mechanisms avoid idle listening and overhearing. Synchronization is not required here. Due to hardware complexity and listening of long preamble, LPL mechanisms are not well suited to WBANs. LPL mechanisms support simplex communication. However, WBANs require duplex channel communication to accommodate periodic, on-demand, and emergency traffic.

2.3 MAC Protocols for WBAN

Many researchers have proposed various MAC protocols for WBAN. Some of them have been submitted to Task Group 6, which was formed in 2007 to address the problems/issues of WBAN and to define relevant standards. Due to the similarity of WBAN and WPAN, most proposed protocols are based on superframe structure of IEEE 802.15.4. However, time-critical communication and high QoS requirements are needed for WBAN, for which IEEE 802.15.4 falls in short. To achieve the QoS requirements for time-critical application of WBANs, a number of protocols that are not based on IEEE 802.15.4 have been proposed so far [7–15]. This section covers the pros and cons of some of these prominent MAC protocols proposed for WBANs. The protocols are introduced with emphasis on energy consumption and how they tackle energy inefficiency caused by collision, overhearing, idle listening, and control packet overhead.

2.3.1 Battery-Aware TDMA Protocol

Battery-aware TDMA protocol [7] is one of the protocols designed for WBANs to maximize the lifespan of the network using cross-layer approach. A number of parameters are considered to design this protocol, which include: time-varying wireless fading channel, electrochemical properties of battery, and packet queuing characteristics. Periodic beacons are transmitted by the coordinator just as IEEE 802.15.4 does. The time axis is divided into three time slots: (1) active time slot, (2) inactive period, and (3) beacon slot. Figure 2.3 shows the frame structure of this protocol.

To support different applications of WBANs, the frame structure is adaptive and can be changed. Periodic wakeup mechanism is introduced to avoid idle listening of nodes. A dedicated time slot T_s is assigned to each node, where data is transmitted by end node when it receives beacon from the coordinator. Dedicated GTS assigned

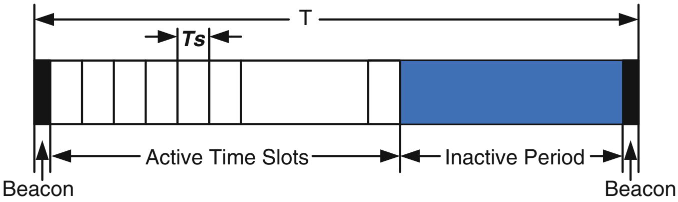

Fig. 2.3 Frame structure of battery-aware TDMA protocol

to each node improves reliability and timely delivery of packets. End nodes remain in sleep mode for the inactive period of time to avoid extra consumption of energy. However, the lack of mechanism to accommodate emergency data and holding of data packets in buffer for long intervals are the two drawbacks of this proposed solution. In addition, packet buffering might result in high packet delay and packet drop rate.

2.3.2 Priority-Guaranteed MAC Protocol

Superframe structure plays an important role in the design of MAC protocols. A new superframe structure is introduced for the priority-guaranteed MAC protocol [8], as shown in Fig. 2.4. Time axis is divided into two main portions: active and inactive periods. Active time period is further divided into five parts to accommodate various kinds of data flow. Control Channel AC1 and Control Channel AC2 are used for uplink control of life-critical medical applications and consumer electronics applications, respectively. Two different times slots are reserved for period and burst data known as Time Slot Reserved for Periodic traffic (TSRP) and Time Slot Reserved for Burst traffic (TSRB), respectively. Beacon is used for synchronization on nodes. For uplink control, randomized ALOHA is used by AC1 and AC2. However, TDMA is used to assign GTS to end nodes for data communication in the two data channels. The performance of this mechanism is better than IEEE 802.15.4 in terms of energy consumption. Unadaptability to emergency data traffic and complexity of superframe are the major shortcomings.

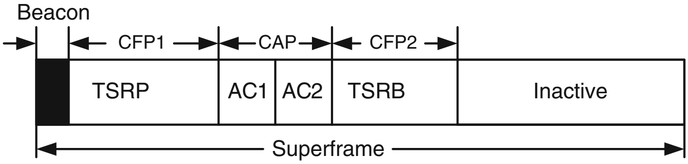

Fig. 2.4 Superframe structure of priority-guaranteed MAC

2.3.3 Energy-Efficient Low Duty Cycle MAC Protocol

Energy-efficient Low Duty Cycle (ELDC) is one of the TDMA-based protocols proposed to accommodate streaming of large amount of data [9]. Network life is maximized with efficient utilization of TDMA approach for medium access. In the proposed network topology, master node (MN) is responsible for on-body network coordination and synchronization. The time axis is divided into multiple time slots, as shown in Fig. 2.5. End nodes are assigned dedicated time slots S1 to Sn. To facilitate the communication of emergency/on-demand traffic, time slots RS1 and RS2 are reserved. Acceptable packet drop, packet error rate, and number of sensor nodes are the parameters used to decide the number of reserved channels for on-demand traffic.

Guard band time slots are inserted between two consecutive time slots to avoid overlapping/collision of data transmission caused by clock drifts. To facilitate simultaneous data communications from end nodes and to MS (monitoring station), MN uses two transceivers with different physical layer communication models. ELDC performs better in terms of energy efficiency, high data rate, and accommodation of short burst of data. However, period synchronization will cause extra energy consumption.

Two types of communication models can be employed in this context. First, MN has one transceiver. In this case, enough time is reserved for communication of MN with MS. In the second case, where the MN has two transceivers, simultaneous communication of MN with MS and sensor nodes is possible. The communication uses different physical layer communication models for transparency. Due to features of pure TDMA and fixed frame structure, the protocol fails to accommodate on-demand traffic.

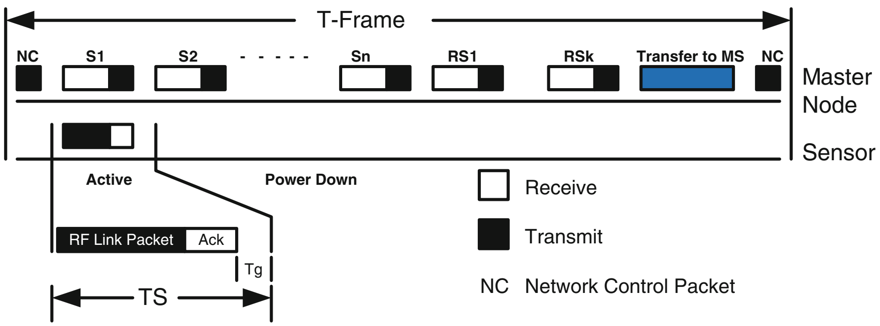

Fig. 2.5 Frame structure of ELDC

2.3.4 A Power-Efficient MAC Protocol for WBANs

In [10] researchers have proposed a power-efficient MAC Protocol to accommodate the normal, on-demand, and emergency traffic in WBANs. Two wakeup mechanisms are introduced to improve the network performance for not only normal traffic but also for on-demand and emergency data traffic. The data traffic generated by routine monitoring of physiological is categorized as normal traffic. In life-critical applications, some of the in/on or around the human body sensor nodes initiate emergency traffic. End nodes are requested by coordinator for on-demand traffic to acquire information if needed. To accommodate all these three types of communication patterns, the time axis in superframe is divided into three parts: a beacon message, a configurable contention access Period (CCAP) to accommodate short burst of data where slotted ALOHA is used for channel access, and a contention-free period (CFP) where GTS are assigned to end nodes for collision-free communication. The newly defined superframe structure is shown in Fig. 2.6.

Traffic-based wakeup table is maintained by the coordinator for different applications. Unnecessary energy dissipation is controlled by periodic sleep/wakeup mechanism. Sensor nodes wake up in advance for time interval of $T_K = 2\theta T_W$ in order to compensate clock drift either at coordinator or end node; T_W is the beacon period. Wakeup radio signals are sent from end node to coordinator and coordinator to end node for emergency and on-demand traffic, respectively. This protocol performs better than WiseMAC [11]. However, low power listening is not an optimal solution for improved efficiency in on-body or implanted sensor nodes.

2.3.5 Energy-Efficient Medium Access Protocol

The Energy-efficient Medium Access Protocol (EMAP) is a prominent protocol designed for WBANs to maximize energy efficiency [12]. Central control mechanism is used for periodic sleep and wakeup scheduling. Cross-layer optimization is being utilized to reduce power dissipation caused by control packet overhead. Star network topology with a single coordinator (i.e., master node) is considered to coordinate with eight on-body/implanted sensor nodes. Master nodes are responsible for most of the activities and processes.

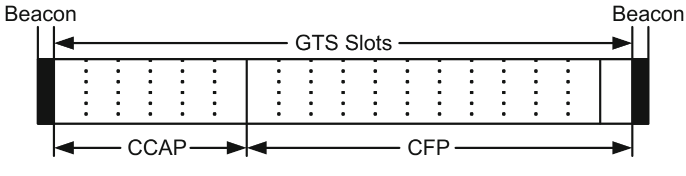

Fig. 2.6 Superfame structure of power-efficient MAC protocol

The operation is based on three processes: link establishment, sleep/wakeup scheduling, and exception process. Link establishment occurs when a node wants to join the cluster. Nodes are assigned unique scheduling for sleep and wakeup periods to communicate with master node. This procedure helps to avoid extra energy consumption due to idle listening and overhearing. Exception process is initiated to facilitate communication of emergency data. Wakeup Fallback Time (WFT) is introduced to make the communication guaranteed and reliable. In case of data communication failure in specific wakeup interval, the sensor node enters a sleep interval defined by WFT. This mechanism helps to avoid overlapping of time slots.

It is observed from the simulation results of different physiological signs that the power consumption depends upon the number of retransmissions and sleep intervals. Centrally-controlled idle listening and overhearing reduce energy consumption efficiently. However, there are some limitations in implementation which include, e.g., complexity, limited number of nodes in a cluster, lack of mechanism for on-demand data, and link establishment process where only one node can establish a link at a time.

2.3.6 BodyMAC

TDMA is one of the most reliable and widely used channel access mechanism for WBANs. BodyMAC utilizes the TDMA channel access mechanism to define uplink and downlink subframes to improve power efficiency [13]. End nodes use periodic sleep scheduling when they have no data to communicate. *Burst Bandwidth procedure, Periodic Bandwidth procedure, and Adjust Bandwidth procedure* are the three procedures used to accommodate different data streaming. Improved network stability and control packet transmission are achieved with this flexible and efficient bandwidth management.

As shown in Fig. 2.7, MAC frame is divided into three parts: beacon, downlink, and uplink. Beacons are used for periodic synchronization whereas downlink is used for communication from coordinator to end node for on-demand traffic. The uplink frame is divided into Contention Access Period (CAP) and CFP for different kind of

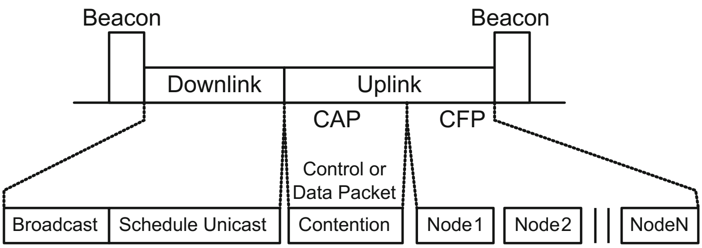

Fig. 2.7 Superframe structure for BodyMAC

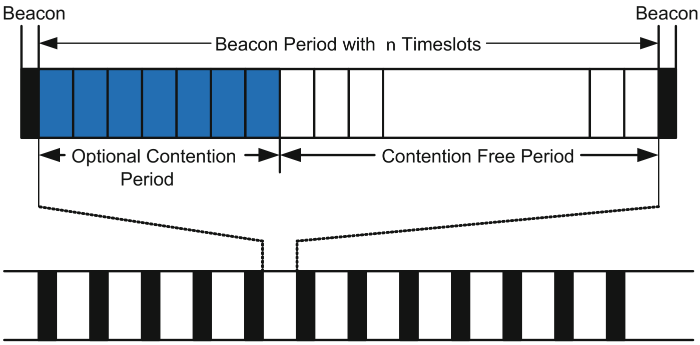

Fig. 2.8 Superframe with *m* Beacons for MedMAC

services. Communication in CAP is based on CSMA/CA where small data packets and control requests for guaranteed time slots are sent to coordinator. Sensor nodes are assigned guaranteed time slots for communication in CFP, which improve the performance in terms of energy consumption. However, CCA and packet collision in CAP result in high energy consumption.

2.3.7 MedMAC

MedMAC [14] is one of the TDMA-based proposed protocols for WBANs to improve power efficiency and channel access. This protocol utilizes the TDMA approach to assign GTS to end nodes. However, the GTS assigned by this protocol are of variable length and depend on the applications. A novel mechanism with multisuperframe is used for periodic synchronization, as show in Fig. 2.8. An optimum contention period is used for network initialization, emergency traffic, and low data streaming.

Timestamp scavenging with Adaptive Guard Band Algorithm (AGBA) is introduced by MedMAC to maintain clock synchronization of coordinator and end nodes. Packet collision is avoided with unique GTS assignment and synchronization of nodes using AGBA. A guard band time defined by AGBA is inserted between two consecutive time slots. The value of guard band time depends upon clock drift of nodes. Drift Adjustment Factor (DAF) is used to avoid wastage of bandwidth assigned for extra guard bands.

Simulations are performed using OPNET[1] to compare the performance of MedMAC with that of IEEE 802.15.4 in terms of energy dissipation. From simulation results in [13], it is observed that MedMAC outperforms IEEE 802.15.4 in terms of energy consumption. GTS are assigned for collision-free communication of data. However, MedMAC takes low-data traffic applications into consideration, which is

[1]OPNET is a simulation tool used for performance analysis of computer networks and applications. Details can be found at https://www.opnet.com/.

not always applicable in WBANs where data rates for in/on or around the human body sensor nodes may be high.

2.3.8 Heartbeat-Driven MAC Protocol

Heartbeat-Driven is a TDMA-based protocol which utilizes heartbeat rhythm for synchronization [15]. Like some of the previously mentioned protocols, this protocol uses a star network topology with GTS allocation for collision-free data communication. heartbeat rhythm is used instead of periodic control messages for network synchronization required by TDMA mechanism. Information of heartbeat rhythm are extracted from sensory data by each biosensor node for synchronization. The coordinator is responsible to assign time slots to individual nodes and calculate the number of frame cycles for synchronization.

Idle listening and overhearing are controlled with synchronized communication in dedicated time slots. Utilizing heartbeat rhythm for synchronization reduces the power consumption. However, heartbeat rhythm cannot be available to all in/on or around the human body sensor nodes. In such cases, it is difficult to synchronize with the system. On the other hand, complexity increases if the sensor nodes without heartbeat rhythm information are integrated with other sensor nodes.

2.4 Discussion

Energy efficiency is one the most important goals to be achieved in CPS like WBAN. Healthcare applications over WBAN include data streaming of critical and noncritical physiological signs sensed by in/on or around the human body sensor nodes. It has been the focus of researchers to improve the performance of WBAN in terms of reliability and energy efficiency at the MAC layer. However, other techniques including, e.g., cross-layer approach, antenna design, and RF communication and propagation models also affect the performance of WBAN. Mobility, transparency, interoperability, security, and high QoS are the other main issues to be considered by researchers for improved and high-quality healthcare services outside as well as inside the hospitals.

Multiple medium access techniques have been used at MAC layer for shared medium access. The prominent four techniques are CSMA, TDMA, FDMA, and CDMA. Selection of medium access technique depends upon application and hardware compatibility. CDMA is the best option for channel access where packet collision is not acceptable. This is not a suitable choice in WBAN due to limited computational and power capabilities of sensor nodes. Similarly, hardware complexity required for FDMA to avoid collision in WBAN makes it an inappropriate choice for channel access. For dynamic networks like WBAN, CSMA outperforms in terms of reliable communication and low delay. However, protocol overhead and extra energy consumption for channel assessment are the major shortcomings of CSMA. TDMA is the best approach for guaranteed communication, but this approach also faces some issues, including, e.g., synchronization, nonadaptability, and scalability. Based on limited numbers of sensor nodes in WBANs, TDMA could be considered the suitable channel access approach. A number of MAC protocols, based on these observations, have been proposed so far to improve reliability and power efficiency in WBANs. However, efforts are still needed to develop protocols to avoid energy dissipation due to collision, overhearing, and idle listening with reduced control packet overhead and implementation complexities. Other design objectives include high bandwidth utilization, fairness at MAC layer, minimum delay, reliable communication, and reduced synchronization cost. Furthermore, the protocols should also have the capabilities to accommodate communication of normal, emergency, and on-demand traffic generated by different in/on or around human body sensor nodes.

2.5 Summary

In this chapter, existing MAC protocols for CPS like WBAN are introduced with emphasis on energy minimization. These protocols have been developed to prolong lifespan of the system, reliable communication, flexibility, fair management, and QoS. MAC protocols based on random access and LPL are unable to accommodate emergency and on-demand traffic. On the other hand, TDMA-based protocols can potentially improve the performance of WBANs. Consequently, the majority of existing MAC protocols for WBANs are based on TDMA approach. Each of them have some advantages and disadvantages. Due to diverse application requirements and hardware constrains, none of them has been accepted as a standard. New protocols need to be developed to address requirements of WBANs like energy efficiency, scalability, fairness, reduced implementation complexity, support for diverse applications, interoperability, reduced synchronization overhead, and QoS.

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http://www.springer.com/978-3-662-46360-4

MAC Protocols for Cyber-Physical Systems
Xia, F.; Rahim, A.
2015, XII, 89 p. 57 illus., Softcover
ISBN: 978-3-662-46360-4