

## Chapter 2

# MAC Protocols for UWB-Based WBAN Applications

**Abstract** Wireless Body Area Network (WBAN) is a networking concept that has evolved with the idea of monitoring vital physiological signals from low-power and miniaturized in-body or on-body sensors. In a WBAN, data collected from the sensor nodes are transferred to a remote node via a wireless medium, where the data is forwarded to a higher layer application to be interpreted. A WBAN system might require both real time and periodic data transfer. Since WBAN sensor nodes are battery powered, they should be low-power devices. The sensor tier communication of a WBAN involves the co-existence of WBAN hardware and Medium Access Control (MAC) protocol that enable the efficient communication of sensor data. The main focus of this chapter is to investigate key aspects of MAC protocols used in WBAN systems focusing on UWB as the wireless technology. This chapter also discusses the wireless technologies used for WBAN applications, paying attention to their ability to cater to the need of high data rate while operating at a low power. Key advantages of Ultra-wide band (UWB) over the other wireless technologies for WBAN applications are highlighted herein.

**Keywords** UWB • MAC • Algorithm • Packet formats • IEEE 802. 15. 6 • IEEE 802. 15. 4a • Transmit-only UWB • Dual-band

## 2.1 Introduction

The basic requirement of wireless healthcare monitoring systems is to send physiological signals acquired from implantable or on-body sensor nodes to a remote location. Low-power consumption is required for wireless healthcare monitoring systems since most medical sensor nodes are battery powered. The emergence of new technologies in measuring physiological signals has increased the demand for high data rate transmission systems. UWB is a suitable wireless technology to achieve high data rates while keeping power consumption and form factors small. The main drawback of the UWB technology is its receiver

complexity. Due to the short pulse width and low power level of the transmitted signal, the front-end circuitry of an UWB receiver is complex in design and has high power consumption [1]. Synchronization of the IR-UWB pulses at receive stage using low power front end circuitry is one of the major problems that restricts the use of IR-UWB receivers for implant applications.

MAC protocols for UWB systems govern the multiple access of the UWB channel. The MAC protocols for UWB systems have to be designed in a way such that they enhance the advantages provided by the UWB signals and overcome the drawbacks such as high receiver complexity [2]. In general, MAC protocols based on carrier sensing and Clear Channel Assessment (CCA) are not appropriate for UWB based MAC protocols, because it is extremely difficult to assess the channel condition of a wideband UWB channel that uses narrow pulses to transmit data. CCA for IR-UWB cannot be implemented using a peak detector, matched filter or correlation method [3]. A frequency domain method to implement CCA for IR-UWB signal is proposed in [3]. This method requires a large number of narrow-band filters and energy detectors. The proposed circuit is designed for the detection of IR-UWB signals spread across the entire 7.5 GHz band. It is not suitable for channelized UWB systems where only a sub-band of UWB is utilised. In a channelized UWB system, the typical transmission bandwidth is between 500 MHz to 1 GHz. Most of the energy detectors in the CCA circuit will register a false reading when a strong narrowband interferer is present.

The MAC protocols for UWB systems may preferably use a random medium access method or a transmit-only MAC protocol for the multiple access of the UWB channel. This chapter intends to give a critical analysis of the recently published work on UWB MAC protocols that has the potential usage for WBAN applications.

## 2.2 The IEEE 802.15.6 Standard

The IEEE 802.15.6 standard [4] is the first standard that defines the MAC architecture for in-body and on-body wireless communications. The standard defines the physical layer communication using UWB and other narrow band technologies. The standard recommends the star topology to form a network for the wireless nodes in a WBAN. Multiple access is achieved in the time domain with the aid of a super frame structure. The super frame is divided into equal length time slots, which are allocated to the contending sensor nodes by a central coordinator, which controls the shared access to the wireless medium.

The IEEE 802.15.6 standard supports three communication modes [4]:

1. Beacon mode with super frame boundaries:

The super frame structure is divided by beacons transmitted in the downlink by the coordinator in this communication mode. Several medium access mechanisms

are supported for sensor nodes communicating using this mode: Exclusive access, Managed access, Random access and Contention access. Exclusive access and Managed access periods in the super frame are used to provide guaranteed data transfer for sensor nodes with high priority while other two methods provide data transfer for less priority sensor nodes.

## 2. Non-beacon mode with super frame boundaries:

This communication mode does not use a downlink beacon in order to indicate the super frame boundaries to the sensor nodes. Instead it uses the scheduling of data communication through techniques, such as polling. The coordinator schedules the data transmission of each individual sensor node through polling, such that the data communication from the sensor nodes falls within a super frame structure. This communication mode falls within the Managed access.

## 3. Non-beacon mode without super frame boundaries:

In this communication mode a pre-defined super frame structure is not used. The data communication occurs through polling or posted allocation where a certain amount of timeslots are allocated by the coordinator node, which can be accessed by any sensor node waiting for data transmission.

The access to the shared medium is provided using various mechanisms [4]:

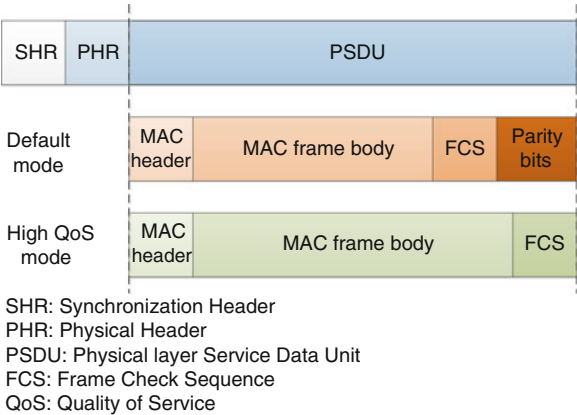
1. Random access using slotted ALOHA and CSMA/CA.
2. Improvised and unscheduled access mechanism, where the coordinator node send polling and posting commands without pre-reservation or pre-scheduling in a random manner.
3. Scheduled access using polling.

The UWB physical layer (PHY) specifications in the IEEE 802.15.6 standard is used to provide high data rate and low power consuming data transfer using UWB signals. The UWB spectrum in the range of 3.1–10 GHz is divided into eleven channels with a channel bandwidth of 499.2 MHz for each channel. The PHY specifications support both IR-UWB and Frequency Modulation-UWB (FM-UWB). This section will only discuss the specifications for IR-UWB, as it is better suited for WBAN applications because of the possibility of implementing low complexity hardware for IR-UWB transmitters.

The IEEE 802.15.6 standard supports three different modulation schemes for IR-UWB: On-Off Keying (OOK), Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK). The Physical layer Protocol Data Unit (PPDU) for the IR-UWB based data communication is shown in Fig. 2.1.

The Synchronisation Header (SHR) provides a preamble bit pattern (*Kasami* sequence with a length of 63) which is essential part in the narrow pulse based UWB data transmission. The PHY Header (PHR) provides 24 data fields which are used to indicate communication parameters such as data rate, MAC frame body

**Fig. 2.1** The IEEE 802.15.6 standard physical layer protocol data unit (PPDU) for IR-UWB PHY specifications



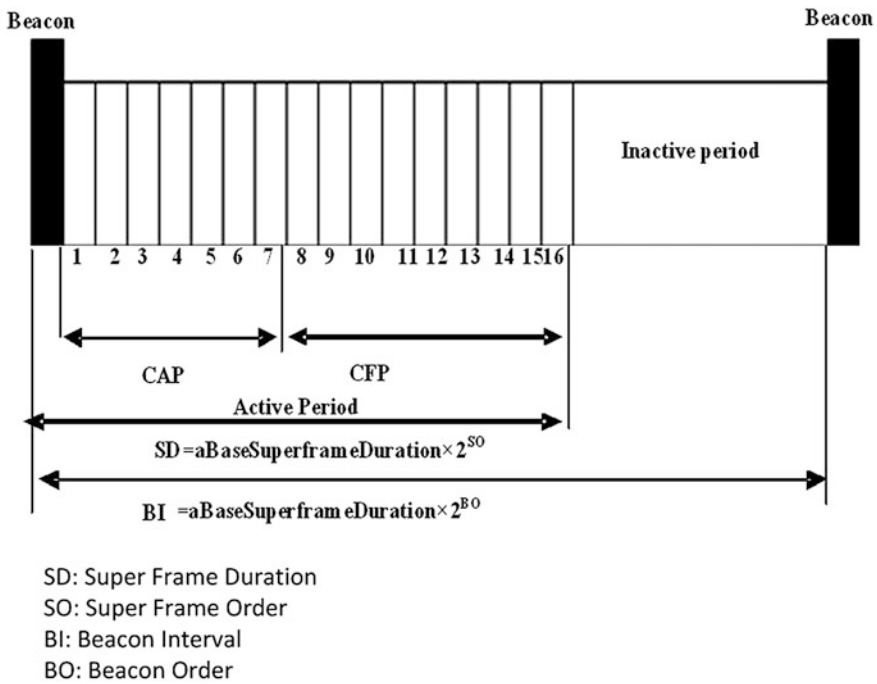
length, pulse type (chirp pulse, chaotic pulse and short pulse) and modulation mode. The IEEE 802.15.6 standard supports also bit interleaving using a modulus interleaver in order to provide robust data transmission by avoiding large sequences of consecutive ones and zeros. Because of the difficulty in CCA for UWB, a random access mechanism based on the slotted ALOHA or a polling based medium access mechanism is recommended for UWB based WBANS in the IEEE 802.15.6 standard.

*Drawbacks:* although the IEEE 802.15.6 standard defines a robust standard for WBAN applications, it has several drawbacks when it comes to using UWB for WBAN applications. It ignores several key limitations in the implementation of the UWB transceivers. The MAC protocol defined by the IEEE 802.15.6 standard utilises a UWB receiver at the sensor node end. Although the UWB transmitters are relatively less complex, the implementation of the UWB receiver requires power hungry complex circuit design. In addition, the MAC protocol defined in the standard ignores the optimisation of the UWB transmit power control through duty cycling and gated pulse transmission techniques [5, 6], which can be used to optimise the power consumption of the transmitter node while controlling the transmit power of the sensor nodes according to the FCC regulations for UWB transmission [7].

### 2.3 The IEEE 802.15.4a Standard

The IEEE 802.15.4a standard [8] is currently the most discussed and adopted standard for UWB applications in the literature. The IEEE 802.15.4a standard has been the inspiration for many UWB based MAC implementations found in the literature.

The main application of IEEE 802.15.4a is for low data rate UWB applications and ranging applications. Similar to the IEEE 802.15.6 standard, the IEEE



**Fig. 2.2** The IEEE 802.15.4a standard super frame structure

802.15.4a standard also uses a beacon enabled super frame structure for UWB PHY layer communication. The maximum number of timeslots is limited to 16. The super frame is divided into a Contention Access Period (CAP) and a Contention Free Period (CFP). The CAP supports random access using ALOHA, while the CFP offers Guaranteed Time Slots (GTS) for high priority data traffic. The IEEE 802.15.4a standard super frame structure is shown in Fig. 2.2.

The performance of the IEEE 802.15.4a standard for WBAN applications has been intensively studied in [9, 10]. MAC layer for the IEEE 802.15.4a standard is almost identical to that of IEEE 802.15.4. The main difference is that mandatory channel access mechanism is changed to ALOHA or slotted ALOHA rather than CSMA/CA. This amendment is necessary, as it is difficult to perform CCA on the low power UWB signal.

In [9], the delay performance of the IEEE 802.15.4a standard for WBAN applications is evaluated based on two categories of physiological signals: continuous and routine signals. Physiological data such as Electrocardiography (ECG) and Electroencephalography (EEG) require continuous monitoring: hence, they are considered as continuous signals. The routine signals include body temperature and blood pressure, which are monitored periodically. The time delay is analysed based on the performance of ALOHA and slotted ALOHA channel access mechanisms on these two types of signals. The results show that the worst-case

delay performance for Slotted ALOHA is better than that for the ALOHA when continuous signal data is transmitted. The performance further improves for slotted ALOHA when the number of GTS increases. The results show that when the number of GTS for slotted ALOHA is increased from 7 to 12, worst case delay drops from 75 to 25 ms. However, ALOHA has better delay performance as compared to slotted ALOHA for routine data. The results also show that the performance of slotted ALOHA degrades for routine signal as the number of GTS increases. In terms of delay, slotted ALOHA performs better for continuous signal monitoring, but not for routine signal monitoring.

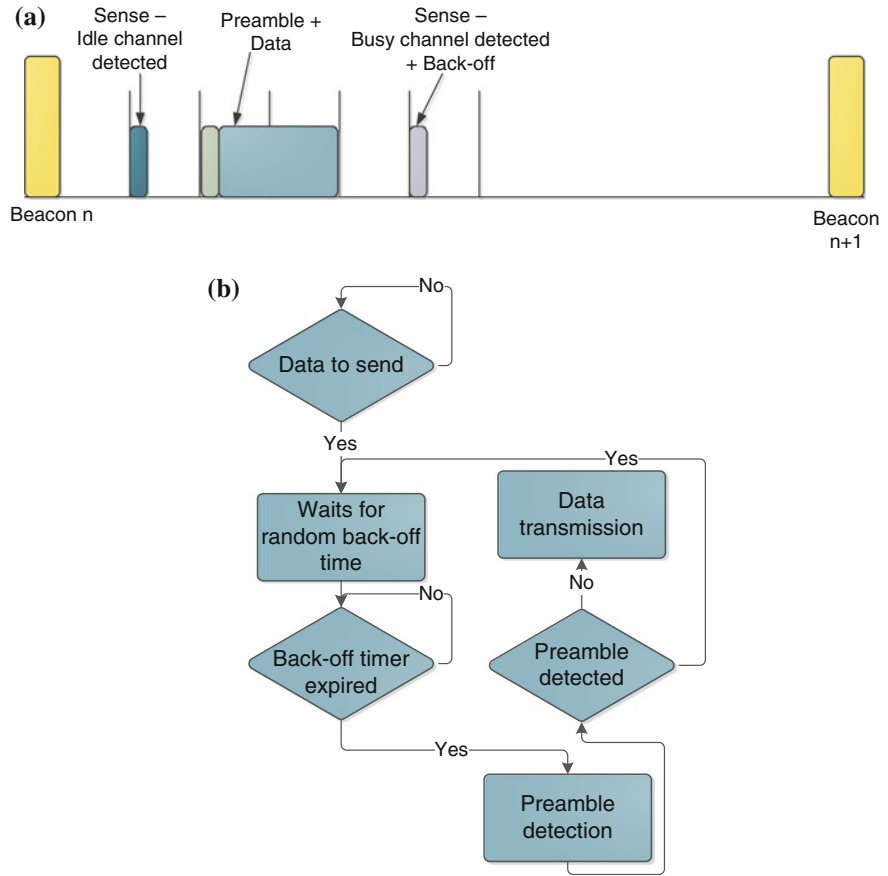
Bit Error Rate (BER) analysis for on-body WBAN sensor nodes that communicate using IEEE 802.15.4a is analysed in [10]. The results show that the BER increases significantly as the number of on-body sensor nodes increases. The analysis shows that in order to maintain an acceptable BER of  $10^{-3}$ , the maximum number of attached on-body sensor nodes has to be limited to six. The analysis is carried out based on a single user scenario where all the sensor nodes are attached to a single patient. The performance of the WBAN system will significantly degrade if there are other users in the same vicinity.

*Drawbacks:* The IEEE 802.15.4a standard has similar drawbacks as the IEEE 802.15.6 standard, such as the frequent use of a UWB receiver at the sensor nodes and disregarding the dynamic power control capability achievable through UWB physical layer manipulations. In addition, it does not support high data rate communication; hence restricts the extraction of the benefits provided by the UWB communications.

## 2.4 PSMA-Based MAC

The work presented in [11, 12] analyses the performance of an IR-UWB MAC protocol for medical data monitoring in terms throughput and power consumption. It presents a MAC protocol based on a medium access protocol called Preamble Sense Multiple Access (PSMA), where the WBAN sensor nodes sense a preamble in order to detect a busy channel or an idle channel condition. Every sensor node attaches a preamble sequence at the beginning of a data packet. The presence of this preamble code in the channel indicates a busy channel condition. The objective of using a preamble sequence is to minimize the false alarms and miss detections that can occur in traditional energy or feature based CCA methods [13]. The suggested MAC protocols in [11, 12] also uses a beacon enabled super frame structure inspired by the IEEE 802.15.4a standard. The operation of the proposed medium access method is depicted in Fig. 2.3.

The throughput and energy consumption analysis presented in [11] compares the performance of the PSMA based MAC with the slotted ALOHA based IEEE 802.15.4a standard. The comparison shows that the suggested MAC protocol performs better in terms of throughput and energy consumption for WBAN s consisting of large number of sensor nodes.



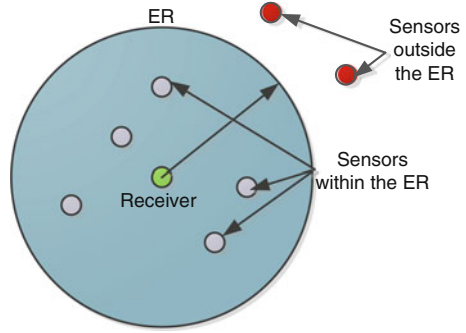
**Fig. 2.3** PSMA based medium access proposed in [12], **a** data transmission using a super frame structure; **b** channel access mechanism

*Drawbacks:* The major drawback of this MAC protocol is that it assumes the presence of an IR-UWB based receiver at the sensor node end in order to sense the channel using PSMA mechanism. Hence, it ignores all the complexities that involve in using an IR-UWB receiver at WBAN sensor nodes that are mentioned above. It also does not provide a solution for the case where two or more sensor nodes perform preamble sense simultaneously, which leads to an eminent collision scenario.

## 2.5 MAC Protocol Based on Exclusion Regions

A MAC protocol developed based on transmit and receive antenna patterns and the antenna directionality is proposed in [14]. An Exclusion Region (ER) is defined as an area surrounding a receiver, such that the transmitter sensor nodes within an ER

**Fig. 2.4** ER based UWB communication



cause interference to each other. However, the transmitter sensor nodes that are not located inside an ER do not cause interference at the targeted receiver. In this MAC protocol, the data communication of sensor nodes within the same ER is resolved temporally using Time Hopping codes (TH-codes), while the sensor nodes in different ERs are allowed to transmit data concurrently. All the sensor nodes transmit data asynchronously. The main objective of this MAC protocol is to minimize the interference that can occur in a multiple UWB transmission environment, while optimizing the throughput using concurrent transmissions in mutually exclusive ERs. Figure 2.4 depicts the sensor communication using the ERs.

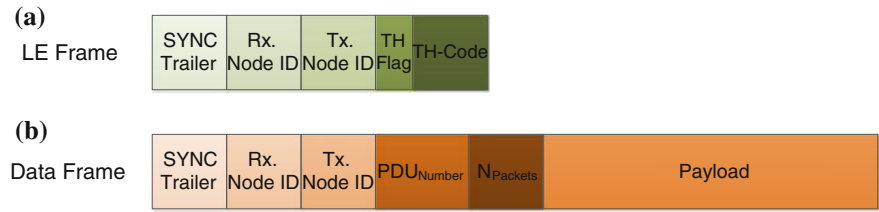
*Drawbacks:* Although this MAC protocol addresses the issue of interference mitigation in UWB multiple access, it does not investigate the efficiency of important factors such as pulse synchronization and multiple access for sensor nodes within the same ER. It also assumes that a sensor node can determine whether it is within the range of a certain ER by accurate ranging capabilities.

## 2.6 UWB<sup>2</sup>

The Uncoordinated Wireless Baseborn Access for UWB Networks (UWB<sup>2</sup>) protocol [15, 16] utilizes orthogonal time hopping codes in order to achieve multiple access in a shared medium. In this protocol, each node is identified using a unique TH-code, which is generated using the method provided in [17]. A common TH-code is used in order to communicate control messages and sensor initialization.

At initialization, a sensor node sends a Link Establishment (LE) frame shown in Fig. 2.5a, using the common TH-code. In this LE frame, the sensor node proposes a TH-code to be used for communication between the sensor and the coordinator. The coordinator node then replies with a Link Control (LC) message and listens to the TH-code allocated for the sensor node. The sensor initialization is followed by the data communication using the suggested TH-code and the data frame format shown in Fig. 2.5b. The UWB<sup>2</sup> MAC protocol supports both acknowledged and un-acknowledged data communication. The main advantage of this MAC





**Fig. 2.5** a LE frame format used for sensor initialisation. b Data frame format

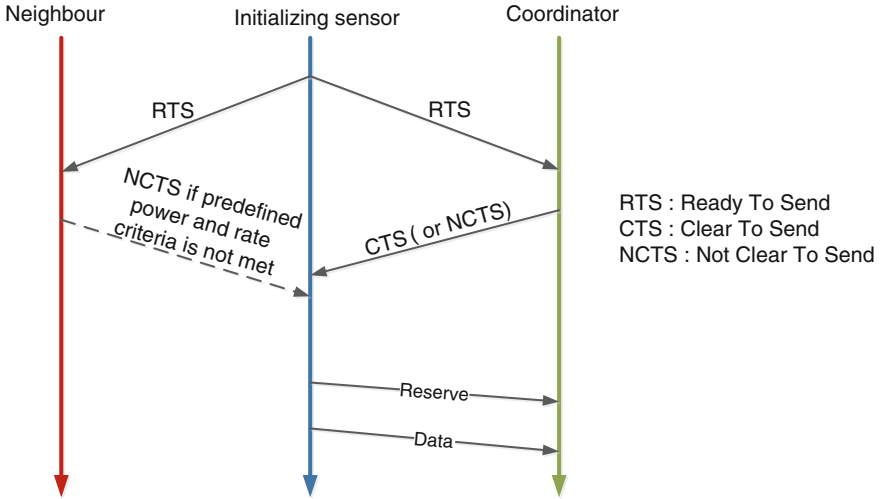
protocol is that, it has avoided the requirement for CCA by using orthogonal TH-codes. Although this MAC protocol assumes the use of a UWB receiver at the sensor node end in order to receive LC messages from the coordinator, a considerable energy saving can be achieved by avoiding the CCA. Reduced energy consumption makes it more suitable for WBAN applications.

*Drawbacks:* This MAC protocol does not provide a method to re-initialize the data transmission in the case of a lost LC frame. In the case of a lost LC frame, the data transmission from the sensor nodes can be inhibited permanently. In addition, collisions can occur while using the common TH-code for control messages. The MAC protocol does not suggest a method to avoid or minimize such collisions.

2.7 U-MAC

The U-MAC protocol described in [18] suggests the use of an adaptable pro-active approach for a UWB MAC design instead of a re-active approach. It is adaptable and pro-active in the sense that it suggests the dynamic allocation of transmit power and data rate at the UWB sensor nodes using *hello* messages that are used by the sensor nodes in order to advertise their local state. These messages are sent at a fixed power level, which is known to all the sensor nodes. At the reception of a *hello* message, a sensor node can determine the ranging information of the neighboring sensor nodes. This information can be used to dynamically adjust the transmit power levels of the sensor nodes. This MAC protocol suggests a more sensor centric network organization approach compared to the coordinator centric approach used in other UWB based MAC protocols. This MAC protocol also supports a prioritized delivery mechanism depending on the QoS requirement of the sensor data. Similar to the UWB<sup>2</sup> protocol, U-MAC also uses unique TH-codes in order to provide multiple access to the shared medium, while control messages are sent using a common TH-code. Figure 2.6 demonstrates the sensor initialization procedure suggested in the MAC protocol.

On the reception of a Ready To Send (RTS) message, the neighboring sensor nodes will determine whether a new sensor node is transmitting at an admissible data rate and transmit power criteria, which are determined by the interference level and Signal to Noise Ratio (SNR) at the neighboring node. A Not Clear To



**Fig. 2.6** Sensor initialization in U-MAC

Send (NCTS) message will be sent if a neighboring sensor node or a coordinator node disagrees with the parameters of the new sensor. The reception of a NCTS means that the new sensor node has to reduce its transmit power or the data rate. If the new sensor parameters are admissible, the coordinator node will reply with a Clear To Send (CTS) message while the neighboring sensor nodes refrain from sending any messages. The data transmission occurs after the initialization. The link parameters can be dynamically adjusted during the data transmission using the *hello* messages according to the requirement of the sensor nodes.

*Drawbacks:* While this MAC protocol allows more dynamic usage of the UWB channel resources, it allocates significant processing load to the sensor nodes. In the context of WBANs, it is advisable to minimize the processing at the sensor node end in order to reduce power consumption. Similar to the UWB<sup>2</sup> MAC protocol, the U-MAC uses a UWB receiver at the sensor node end in order to receive *hello* messages and other control messages, which leads into increased power consumption and complex hardware implementation.

## 2.8 DCC-MAC

The DCC-MAC presented in [19, 20] uses Dynamic Channel Coding (DCC) technique in order to mitigate the multiple access interference. This MAC protocol assumes that all the sensor nodes transmit at maximum allowable transmit power in contrast to the power control mechanisms used in Sects. 2.3 and 2.6. A cross layer technique is suggested in this MAC protocol in order to mitigate the multiple access interference at the PHY layer level. The received UWB pulse amplitude is

compared against a pre-defined threshold at the coordinator end. Since all the sensor nodes transmit using a pre-defined transmit power, the expected receive power for a particular sensor node can be determined by the coordinator using UWB ranging techniques. If received pulse amplitude exceeds the threshold level, it indicates a collision at the coordinator. This concept is used in the DCC-MAC in order to identify and eliminate erroneous data at the coordinator end.

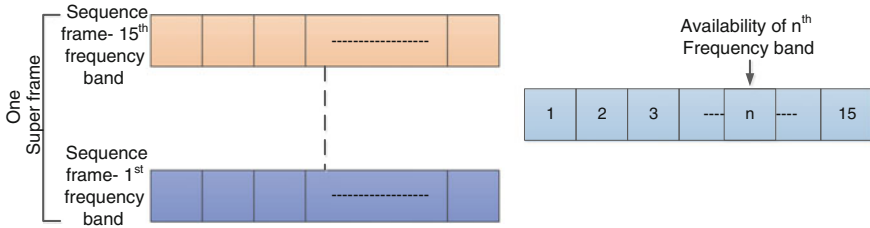
Rate Compatible Punctured Convolution (RCPC) [19] codes are used in order to achieve dynamic channel coding. The multiple access to the shared medium is achieved through TH-codes as in the case of UWB<sup>2</sup> and U-MAC. The TH-codes are generated locally at the sensor node using a random number generator.

*Drawbacks:* This MAC protocol has the same drawbacks as UWB<sup>2</sup> and U-MAC when it comes to the use of a UWB receiver at the sensor node end. Additionally, it tries to mitigate the interference at the expense of physical layer complexity. In addition, an extensive amount of processing is allocated to the sensor nodes, which leads to an increased power consumption. It also assumes that the sensor nodes always transmit at the maximum allowable transmit power. Although this has some advantages when it comes to interference mitigation and optimizing the throughput [21], a power controlling approach might be well suited for power stringent WBAN applications of UWB. It also assumes the presence of resynchronization per every data packet, which results in increased overhead. Instead, synchronization per session is recommended for WBAN applications.

## 2.9 Multiband MAC for IR-UWB

Multiple access through allocation of a unique frequency band per each sensor-coordinator data communication link is suggested in [22]. A common control channel, which is assigned with a unique frequency band, is used for sensor initialization and control message transfer in this MAC protocol. Both control and data communication bands are allocated with a 500 MHz bandwidth. TH-codes are used in the common control channel in order to share it with multiple users. The main advantage of this MAC protocol is that it can be used for concurrent data transmissions from multiple numbers of sensor nodes, because of the use of different frequency bands. This assists in reducing the probability of collision, hence increases the throughput and results in low latencies, which are ideal properties for high data rate WBAN applications.

A super frame structure is used for data and control message transfer. A super frame is divided into 15 sequence frames. Each sequence is used for data transmission in each band. An *availability frame* is used between two super frames in order to indicate the availability of a particular band for data transmissions. If a sensor node intends to continue data transmission in a particular band, it has to send consecutive UWB pulses in the relevant slot allocated to indicate the occupancy of that frequency band. By sensing those UWB pulses within the corresponding time slots of the *availability frame*, other sensor nodes can determine the



**Fig. 2.7** Super frame structure used in multiband MAC

availability or occupancy of a particular band for data transmission. This super frame structure is shown in Fig. 2.7.

*Drawbacks:* This MAC protocol requires the sensor nodes to operate in multiple frequency modes in order to transmit data in different frequency bands. This method increases the hardware complexity of the sensor nodes, which is disadvantageous in WBAN applications. In addition, it adds the complexity of modulating the data signals into TH-codes in order to access the common control channel. The sensor nodes have to sense the narrow UWB pulses during the *availability frame*. This implies the use of a UWB receiver at the sensor node, and energy consuming pulse-sensing procedures. Broustis et al. [22] has not specified how the node synchronization is achieved in this MAC protocol.

## 2.10 Pulsers

The PULSERS project [23] uses an altered format of the IEEE 802.15.4a standard super frame structure in order to provide high guarantee of delivery for sensor nodes with high QoS requirements. It uses an extended CFP that facilitates GTS for priority traffic in the IEEE 802.15.4a standard. The CAP is limited to two time slots, where initialization messages and control messages are exchanged. When a sensor node wants to transmit data, it requests the allocation of a GTS in the CFP in the next super frame using the one of the time slots available in CAP. Hence, this MAC protocol follows a Time Division Multiple Access (TDMA) based approach in providing multiple access to the shared UWB channel.

This MAC protocol is well suited for WBAN applications with high data rate requirements. It also proposes a peer-to-peer relay mechanism using a static routing table, which is known to all the sensor nodes during the initialization. This mechanism helps in decentralizing the control of the network, hence reduces the latency. The sensor nodes can be put into inactive mode between the data transmission slots used in the MAC protocol; hence, the power consumption can be reduced.

*Drawbacks:* This MAC protocol possesses all the drawbacks in the IEEE 802.15.4a standard MAC protocol when it comes to WBAN applications. The

TDMA based multiple access mechanism relies on precise synchronization in timing. However, a synchronization mechanism has not been proposed for the MAC protocol.

## 2.11 Transmit-only MAC

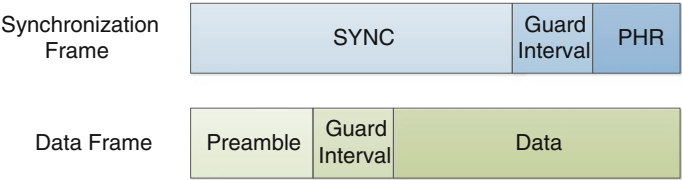
Most of the MAC protocols discussed above have limitations when it comes to UWB based WBAN applications. Many MAC protocol designs have not paid their attention towards the practical constraints that occur in hardware design. Even though IR-UWB transmitters consume low power, IR-UWB receiver needs to detect pulses with low-power level. This leads to a complex and high power consuming receiver architecture. For example, the CMOS IR-UWB transmitter discussed in [24] has a power consumption of 2 mW while the IR-UWB receivers consumes up to 32 mW of power [25]. Addition of an IR-UWB receiver in the sensor node will increase its power consumption as well as the design complexity. Implantable or wearable sensor nodes are battery powered. Hence, power consumption in sensor nodes is a critical factor that determines the efficiency of a MAC protocol. The transmit-only MAC protocol suggested in [5, 26] enables the use of a transmit-only hardware design at the sensor node end.

The suggested transmit-only MAC protocol is of asynchronous nature; hence, it faces several challenges when it comes to collision avoidance and synchronization at the receiver end. It has been designed with following characteristics in order to overcome the challenges;

- Data packets are transmitted at a much higher data rate than the required data rate so that it is possible to get an optimum sleep time for sensor nodes while it waits for the next set of data.
- Each sensor transmits at a pre allocated unique transmission slot in order to minimise the occurrence of collisions.
- A unique pulse rate is assigned for each WBAN in the same region.
- Sensor nodes transmit without prior knowledge of the channel condition.
- There is no feedback in the network.

The frame structure for this WBAN system is shown in Fig. 2.8.

When a sensor node is first connected to the network, synchronizing frame structure is used in order to assist the self-synchronization at the gateway node. A guard interval follows immediately after the initial synchronization process to allow the receiver to prepare for the reception of information in the Physical Header (PHR). The PHR contains information on the chirp rate, symbol rate, and the timing of the next transmission window. After establishing initial communication with the gateway node, the data frame will then be used in the successive transmissions. The data frame has a short preamble, which helps the receiver achieve fine synchronization followed by a guard interval to prepare the receiver



**Fig. 2.8** Frame structure for Transmit-only MAC protocol for WBAN

for data reception. The data frame overhead is kept to a minimum in order to keep the transmission period short and thus reducing the chances of collision.

*Drawbacks:* Although the transmit-only MAC protocol addresses the problem of high power consumption, which arises due to the use of UWB receiver at the WBAN sensor node, it has several drawbacks.

- When the network traffic increases, the number of collisions, which occur due to asynchronous transmission of pulses, adversely affect the data delivery capability in the network.
- There is no feedback path to dynamically adjust the transmit power in accordance with the changing channel conditions.
- Rescheduling of the network requires manual intervention with the sensor nodes.

This MAC protocol can be further improved by the use of a narrow band receiver in order to eliminate the issues regarding the network reconfigurations and network expansion while achieving low power consumption in the sensor nodes. Such a MAC protocol is suggested in [27]. The MAC protocol described in [27] uses a narrow band receiver at the sensor node to receive feedback on properties, such as receive BER. This MAC protocol will be discussed further in [Chap. 3](#).

### 2.12 Comparison of UWB-Based MAC Protocols for WBAN Applications

The MAC protocols discussed above have advantages in different areas when they are used in WBAN applications. A summary of the selected MAC schemes discussed in this section is tabulated in [Table 2.1](#) based on their performance attributes described below.

- **Energy efficiency**—Factors affecting the energy efficiency of a MAC scheme are energy wastage due to protocol overhead, idle listening, collisions, over-emitting and overhearing.
- **QoS**—Quality of Service (QoS) is crucial in a WBAN system due to the sensitivity of the data collected by sensor nodes. If the QoS is poor and the data

Table 2.1 Comparison of MAC protocols

Performance attributes	IEEE 802.15.6 [4]	IEEE 802.15.4 a [8]	PSMA based MAC [11, 12]	ER based MAC [14]	UWB <sup>2</sup> [15, 16]	U-MAC [18]	DCC-MAC [19, 20]	Multiband MAC [22]	PULSERS [23]	Transmit-only MAC [5, 26]	UWB-Tx and NB-Rx MAC [27]
Energy efficiency	X	X	X	X	✓	✓	X	X	X	✓	✓
Qos	✓	X	X	X	X	✓	X	X	✓	X	✓
Priority traffic	✓	✓	✓	X	X	X	X	X	✓	X	✓
Scalability	✓	X	X	✓	X	✓	X	X	X	✓	✓
Latency	X	X	X	✓	X	X	X	✓	X	✓	X
Interference mitigation	X	X	✓	✓	✓	✓	✓	✓	X	X	✓
Channel access	Random – ALOHA	Random – ALOHA	Random – PSMA	TH-code with spatial reuse	TH-code	TH-code with power management	TH-code	Frequency division	Time division	Random – Rate division	Random + TDMA

reliability is low, this could lead to a wrong diagnosis and it can be life threatening.

- **Priority traffic**—In a WBAN system, the MAC should be able to support on demand traffic and provide a method for critical data to be transmitted reliably with minimum latency.
- **Scalability**—Data rates for WBAN ranges from a few kilobytes to tens of megabytes. The number of nodes in a WBAN system can vary from a single node to tens of nodes. Therefore, scalability is an important factor to be considered in a WBAN MAC scheme.
- **Latency**—WBAN contains time critical data, therefore latency is another important factor to be considered in a WBAN MAC protocol.
- **Interference mitigation**—As the WBAN nodes are mobile, the channel condition is constantly changing. The channel condition deteriorates significantly in areas densely populated with other WBAN users. The MAC scheme should be resilient to multiple network interference.
- **Channel Access**—A WBAN constitutes of both implantable and on-body nodes. When selecting a channel access scheme, type of the nodes and the physical layer characteristics should be taken into consideration in order to ensure the reliability of the system.

## 2.13 Conclusion

An UWB WBAN system should be considered as a combination of a MAC protocol and the UWB hardware platform. The MAC protocols for UWB systems should be designed in a way such that it enhances the advantages provided by UWB signals and overcomes the drawbacks, specially the high complexity of a receiver. MAC protocols mentioned in this chapter have not considered manipulation of the physical layer properties of the UWB systems such as number of pulses per data bit, and transmit duty cycle, which can be incorporated with the MAC algorithm in order to make the system more dynamic in terms of data rate and QoS. These studies consider UWB for both up-link and down-link communication; hence they do not consider the complexities introduced by UWB receivers. Although the transmit-only MAC protocol suggested in [5, 24] addresses the problem of high power consumption, which arises due to the use of UWB receiver at the WBAN sensor node, it has several drawbacks. When the network traffic increases, collisions that occur due to asynchronous transmission of UWB pulses adversely affect the data delivery capability of the network. There is no feedback path to dynamically adjust the transmit signal in accordance with the changing channel conditions. Rescheduling of the network requires manual intervention with the sensor nodes. It also has to occupy different receiver nodes for each patient, since different pulse repetitive frequencies are being used to identify different users.



To avoid the use of power hungry UWB receivers and to increase the reliability of data delivery, a MAC protocol that uses a narrow band feedback path in order to communicate control messages to the sensor nodes is described in Chap. 3. With the introduction of the narrowband feedback system, it is possible to achieve a more dynamic power reduction scheme that involves cross layer designs. The use of a narrow band receiver at the sensor node end leads to simplicity of circuit design by reducing the computational complexity at the sensor node end. A dual band sensor node provides the opportunity to communicate simultaneously in the up-link and down-link reducing the communication delay. By using a narrow band receiver, in combination with a suitable MAC protocol, it is possible to achieve more dynamic network configurations; hence enable the employment of higher number of sensor nodes as well as dynamic transmit power configurations to compensate for the varying channel conditions. A narrow band receiver also provides the opportunity to manipulate various physical layer properties of UWB, such as number of IR-UWB pulses sent per data bit and duty cycle of data transmission at the sensor node; hence provide a power efficient way of controlling the performance of the network.

## References

1. M.R. Yuce, T.N. Dissanayake, H.C.Keong, Wideband technology for medical detection and monitoring, recent advances in biomedical engineering. ed. by G.R Naik, ISBN: 978-953-307-004-9, InTech, 2009
2. K.M.S. Thotahewa, J.-M. Redoute, M.R. Yuce, Medium access control (MAC) protocols for ultra-wideband (UWB) based wireless body area networks (WBAN), ultra-wideband and 60 GHz communications for biomedical applications (Springer, 2013) ISBN: 978-1-4614-8895-8
3. N.J. August, H.J. Lee, D.S. Ha, Enabling distributed medium access control for impulse-based ultrawideband radios. *IEEE Trans. Veh. Technol.* **56**, 1064–1075 (2007)
4. <http://www.ieee802.org/15/pub/TG6.html> (2014)
5. H.C. Keong, M.R. Yuce, Analysis of a multi-access scheme and asynchronous transmit-only UWB for wireless body area networks. In: *31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC'09)*, pp. 6906–6909 (2009)
6. R.J. Fontana, E.A. Richley, Observations on low data rate, short pulse UWB systems. In: *IEEE International Conference on Ultra-Wideband*, pp. 334–338 (2007)
7. FCC 02-48 (First report and order) (2002)
8. IEEE-802.15.4a-2007. Part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area Networks (LR-WPANs): amendment to add alternate PHY. Standard, IEEE (2014)
9. K. Takizawa, L. Huan-Bang, K. Hamaguchi, R. Kohno, wireless patient monitoring using IEEE 802.15.4a WPAN. In: *IEEE International Conference on Ultra-Wideband*, pp. 235–240 (2007)
10. D. Domenicali, M.G. Di Benedetto, Performance analysis for a body area network composed of IEEE 802.15.4a devices. In: *4th Workshop on Positioning, Navigation and Communication*, pp. 273–276 (2007)

11. L. Kynsijarvi, L. Goratti, R. Tesi, J. Iinatti, M. Hamalainen, Design and performance of contention based MAC protocols in WBAN for medical ICT using IR-UWB. In :*IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops*, pp.107–111, 26–30 Sept 2010
12. J. Haapola, A. Rabbachin, L. Goratti, C. Pomalaza-Raez, I. Oppermann, Effect of impulse radio-ultrawideband based on energy collection on MAC protocol performance. *IEEE Trans. Veh. Technol.* **58**, 4491–4506 (2009)
13. B. Zhen, H.-B. Li, S. Hara, R. Kohno, “Clear channel assessment in integrated medical environments. *EURASIP J. Wireless Commun. Netw.* **8**(3), 1–8 (2008)
14. L.X. Cai, X. Shen, J. Mark, Efficient MAC protocol for ultra-wideband networks. *IEEE Commun. Mag.* **47**(6), 179–185 (2009)
15. M.-G.D. Benedetto, L.D. Nardis, G. Giancola, D. Domenicali, The aloha access (UWB)<sup>2</sup> protocol revisited for IEEE 802.15.4a. *ST J. Res* **4**(1), 131–141 (2006)
16. M.-G.D. Benedetto, L.D. Nardis, M. Junk, G. Giancola, (UWB)<sup>2</sup>: uncoordinated, wireless, baseborn medium access for UWB communication networks. *Mob. Netw. Appl.* **10**(5), 663–674 (2005)
17. R. Merz, J. Widmer, J.-Y.L. Boudec, B. Radunovi’c, A joint PHY/MAC architecture for low-radiated power TH-UWB wireless ad hoc networks. *Wireless Commun. Mob Comput. J.* **5**(5), 567–580 (2005)
18. R. Jurdak, P. Baldi, C.V. Lopes, U-MAC: a proactive and adaptive UWB medium access control protocol. *Wireless Commun. Mob Comput. J.* **5**(5), 551–566 (2005)
19. J.Y.L. Boudec, R. Merz, B. Radunovic, J. Widmer, DCC-MAC: a decentralized MAC protocol for 802.15.4a-like UWB mobile ad-hoc networks based on dynamic channel coding. In: *1st International Conference on Broadband Networks*, pp. 396–405, Oct 2004
20. M. Iacobucci, M.D. Benedetto, Computer method for pseudorandom codes generation. National Italian Patent RM2001A000592, Sept 2001
21. B. Radunovic, J.Y.L. Boudec, Optimal power control, scheduling, and routing in UWB networks. *IEEE J. Sel. Areas Commun.* **22**(7), 1252–1270 (2004)
22. I. Broustis, S.V. Krishnamurthy, M. Faloutsos, M. Molle, J.R. Foerster, Multiband media access control in impulse-based UWB Ad Hoc networks. *IEEE Trans. Mob. Comput.* **6**(4), 351–366 (2007)
23. I. Bucaille, A. Tonnerre, L. Ouvry, B. Denis, MAC layer design for UWB LDR systems: PULSERS proposal. In: *4th Workshop in Positioning, Navigation and Communication*, pp. 277–283, March 2007
24. J. Ryckaert, C. Desset, A. Fort, M. Badaroglu, V. De Heyn, P. Wambacq, G. Van der Plas, S. Donnay, B. Van Poucke, B. Gyselinckx, Ultra-wide-band transmitter for low-power wireless body area networks: design and evaluation. *IEEE Trans. Circuits Syst.* **52**, 2515–2525 (2005)
25. G. Yuan, Z. Yuanjin, H. Chun-Huat, Low-power CMOS RF front-end for non-coherent IR-UWB receiver. In: *European Solid-State Circuits Conference*, pp. 386–389 (2008)
26. H.C. Keong, K.M.S. Thothahewa, M.R. Yuce, Transmit-only ultra wide band body sensors and collision analysis. *IEEE Sens. J.* **13**(5), 1949–1958 (2013)
27. K. Thothahewa, J. Khan, M. Yuce, Power efficient ultra wide band based wireless body area networks with narrowband feedback path. *IEEE Trans. Mobile Comput.* **PP**, 1–1 (2013) (in pre-print version)

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