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Investigation and performance analysis of MAC protocols for WBAN networks

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ABSTRACT

Recently, interest in the Wireless Body Area Network (WBAN) for patient monitoring has grown significantly. Therefore, very interesting researches are concentrating on enhancing patient monitoring systems that require quality of services provisioning at different levels and especially in communication between WBAN nodes. Therefore, the conception of an efficient MAC (Medium Access Control) protocol is required to satisfy the stringent monitoring system requirements. In this context, investigations related to the most efficient and recent WBAN MAC protocols are carried out taking in consideration the requirements of WBAN MAC protocols, and the MAC proposals classification is presented in this paper. Furthermore, to illustrate the performance of the recently drafted IEEE 802.15.6 standard, IEEE 802.15.4 (Zigbee MAC) and TMAC protocols in different working conditions, we have elaborated different scenarios to simulate these protocols using CASTALIA framework and OMNET++ network simulator. Besides that, we have also computed the end-to-end delay (E2E) in the worst case for those protocols.

1. Introduction

WBAN has become a hot topic with the increasing attention of medical applications (Damasceno et al., 2013) (Bourouis et al., 2012). The use of wireless sensor networks for healthcare has a considerable interest in the development of wireless networks around the human body to monitor body functions. Applications of wireless body area networks also include personal assistance (Ahmad and Zafar 2012), civilian (Bradai et al., 2011), military, and environmental (Valverde et al., Uriarte). A WBAN is made up of physiological, low power, miniaturized and lightweight sensor nodes that are used to monitor and perform the body functions and their environment. We cite accelerometer, gyroscope, electrocardiography (ECG), EEG, electromyography or EMG, pulse oximeter, oxygen sensor, CO_2 or carbon dioxide sensor, blood pressure, and blood sugar monitoring, that can be implanted in human bodies (implantable node) or put on the body (wearable nodes). These devices provide a scalable, unobtrusive, robust, and long-term monitoring of patient information without constraining the human activities. Before their memory fills, sensor nodes keep information and issue them to the base station, which is a Personal Digital Assistant (PDA). It is controlled by the patient and communicates with sensor nodes. The central server (CS) store samples the physiological data received at the database. The CS also keeps electronic medical documents of patients and contacts for emergencies. The three-level hierarchies' architecture (sensor nodes, a base station, and a CS) is given in Fig. 1. The sensor node and personal server protocol stacks are shown in Fig. 2. In order to reduce hospitalization and to facilitate the care of humans, especially agent people who are increasing year after year (Campbell 2013), many research groups (Keong and Yuce 2011; Beretta et al., 2012; Thotahewa et al., 2014; Sun et al., 2014; Mahalle and Ingole 2013) are focusing on the concept, design, and implementation of a body area network. WBANs invade different medical area applications (Zhang 1,* et al., Calhoun 1; Tartarisco et al., June 2012) which can be divided into wearable and implantable body area networks (BAN). Implanted BAN (Mumford 2013) is used mainly for healthcare and medical care applications whereas wearable BAN (Darwish and Ella 2011) is used for both medical and non-medical applications. Recently, this class of networks has emerged. Researches in the area of WBANs have focused on issues related to ultra low-power processing (Thotahewa et al., 2014), signal processing (Khalid Abualsaud 2012), communication protocols, and lightweight wireless sensor nodes in order to control the human body functions and healthcare monitoring systems. A major constraint is the energy-saving, in fact, WBANs consist of a limited number of batteries that are used to monitor the human body functions over long periods of time without restricting the patient's movements. WBANs bring new perspectives such as prolonging the lifetime of sensors, which depends on controlling the energy consumption of devices. To

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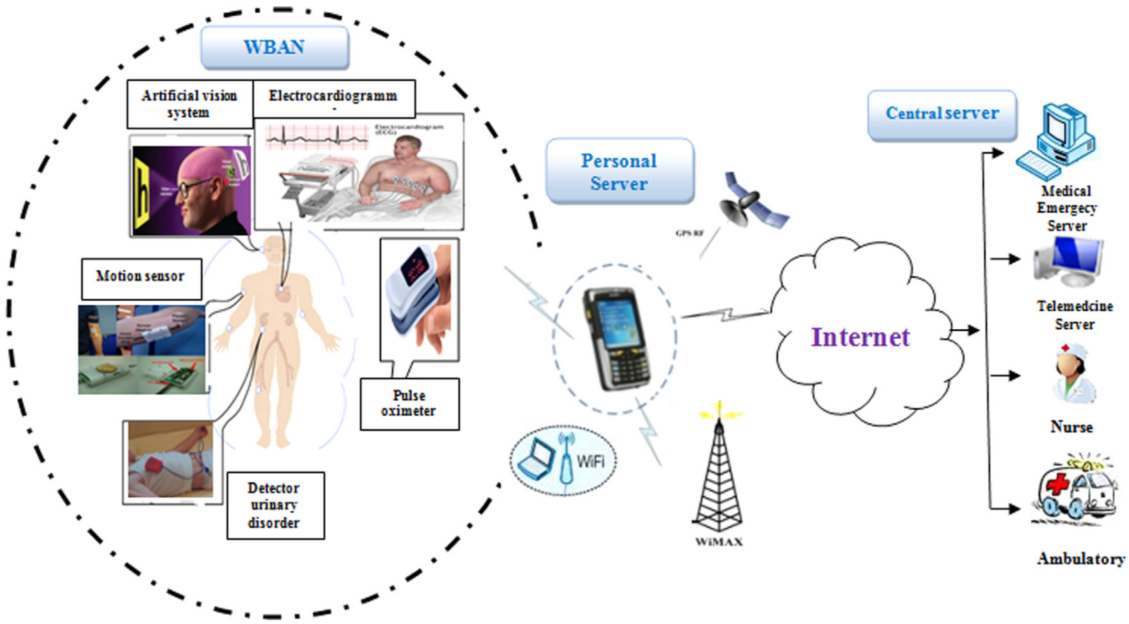

Fig. 1. WBAN architecture for healthcare applications.

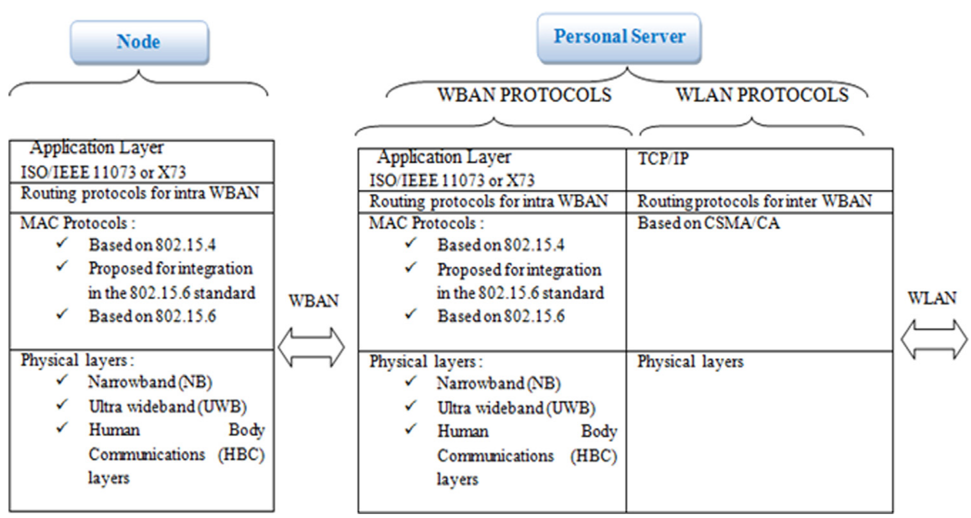

Fig. 2. WBAN nodes and personal server protocols stacks.

achieve energy efficiency, low duty cycle MAC protocols are used (Doudoua et al., 2014). The IEEE 802.15.6 task group (IEEE 2010) is developing a communication standard optimized for low power devices. It defines a medium access protocol control (MAC) layer that supports three physical layers, namely, narrowband (NB), Ultra wideband (UWB), and Human Body Communications (HBC) layers. Consequently, a performance analysis of this protocol is necessary.

In this paper, we present a deep and a comprehensive WBAN MAC protocols performance. The remainder of this paper is organized as follows. Section 2 presents MAC protocol's requirements. Section 3 recapitulates the newest WBAN MAC protocols for healthcare applications. Section 4 gives an investigation on IEEE 802.15.4 and provides an analytical analysis of the beaconless and beacon modes in the worst case. In Section 5, we provide an investigation on TMAC (Timeout MAC protocol). In Section 6, we present the basic concepts of the IEEE 802.15.6 protocol, we emphasize on their characteristics and we also give an evaluation of the end-to-end delay in the worst case. Section 7 empirically evaluates the performance of MAC protocol proposals using OMNET++ simulator with the integrated Castalia module. Simulation models are used herein in order to obtain simulation results for performance analysis. The final section concludes our work.

2. Requirements of MAC protocol for WBAN

Mostly the requirements of a MAC protocol are: energy efficiency, deployment and adaptability to changing the size, latency, the amount of flow, fairness, and network density. We detail below each requirement.

- *Energy efficiency*: With a large number of nodes powered by battery, it is very difficult to change or recharge batteries for these nodes.
- *The deployment and adaptability to changing the size*: As the networks may include many nodes, used protocols have to be able to manage change in number of nodes dynamically. These

nodes must be programmable. In fact, when new jobs arise their programs must be changed during operation.

- *Latency*: In BANs, the importance of latency depends on the application. In applications, such as monitoring nodes, BAN will be vigilant for long, but largely inactive until something is detected. During this period of vigilance, there is little data flow in the networks. We note that low latency is essential to minimize consumption.
- *The amount of flow*: Refers to the amount of data transferred from a transmitter to a receiver in a given time. Many factors affect this rate, including the effectiveness of collision avoidance, the use of channel, and latency. Like latency, the amount of flow depends on the application. The applications of body sensor networks often require a long life that accepts a long latency and low throughput.
- *Fairness:* is the ability of different users or nodes to share the channel fairly. It is an important parameter in networks, because each user wants an equal opportunity to send or receive data for his/her own applications. However, in WBANs, all nodes cooperate for a single common task. A node can have considerably more data to send to the other nodes. Rather than treating each node in the same way, success is measured by the performance of the overall application, and the equity of each node or each user becomes less and less important.
- *Network density*: Different applications have very different densities of nodes. Even within a given application, the density may vary over time and space because the nodes do not work or go into sleep mode. Similarly, the density is not homogeneous across the network (due to imperfect deployment) and the network must adapt to these changes.

Different WBAN applications have different requirements in terms of quality. Applications can be classified based on data delivery models that correspond to event-driven, query-driven, and continuous delivery models. In Table 1, we have regrouped the most QoS criterion for each data delivery model. In Table 2 (Chaari and Kamoun 2011), we have illustrated some QoS requirements for different WBAN sensor nodes and applications.

Based on Table 2, we observe that a WBAN should support data rates ranging typically from 1 Kbps to 10 Mbps in order to host a range of medical applications including images and video clips. Most of the data gathered from sensor nodes are sensitive to latency, and end-to-end delay (E2E) should be less than 250 ms. Therefore, to satisfy QoS requirements for different applications, end-to-end delay (from the sensor node to the medical service level) should be guaranteed for the data sensitive to latency. Firstly, QoS sub-modules such as classifier, scheduler, and admission control should be implemented on the coordinator node to prioritize critical data in intra-WBAN communication. Secondly, compared to intra-WBAN communications, wireless technologies for inter-WBAN communication which include: WLAN, Bluetooth, cellular and 3 G, etc., should also prioritize critical data. Thirdly, the internet is used for beyond WBAN communications to hold connection with the medical service level, so internet architecture should integrate services differentiation mechanisms such as 'INTSERV' or 'DIFFSERV' architectures (not Best Effort architecture). In Sections 4, 5 and 6, we will compute the E2E delay in intra WBAN communication in the worst case in order to extract the best MAC protocol that is suitable for WBAN networks.

3. Taxonomy of WBAN MAC proposed protocols for healthcare applications

In the past few years, many works related to WBANs access mechanisms have been proposed. The flow chart in the following (see Fig. 3) gives an idea about the classification of different proposed MAC protocols in the literature. We have three classes of MAC protocols, those based on IEEE 802.15.4, proposed for integration in IEEE 802.15.6, and those based on IEEE 802.15.6. In each class, we find three categories, namely, MAC protocols based CSMA/CA, TDMA, and hybrid mechanisms. Table 3 gives a description of the different MAC protocols for healthcare applications, QoS support, and energy efficiency.

Table 1
QOS criterion for each data delivery model.

Class	Event driven	Query driven	Continuous
End-to-end	No	No	No
Interactivity	Yes	Yes	No
Delay tolerance	No	Query specific	Yes
Criticality	Yes	Yes	Yes

4. Investigation on IEEE 802.15.4

4.1. MAC access mechanisms and frame structure

The Institute of Electrical and Electronic Engineers (IEEE) approved the formation of a working group for IEEE 802.15.4 (IEEE 2003) to draft a standard for Personal Area Network (WPAN). The 802.15.4 defines both PHY and MAC layers. The PHY layer can operate in three different bands, namely, the frequency band 2.4 to 2.4835 GHz using 16 channels, the frequency band from 902 to 928 MHz using 10 channels, and 1 channel in the frequency band 868 to 868.6 MHz. The characteristics of the MAC layer management are beacons, channel access, management of GTS (Guaranteed Time Slot), validation of the frames, etc. There are two modes of operation of the MAC layer depending on the topology used and the need for guaranteed bandwidth, namely, non-beacon mode and beacon mode. In the non-beacon mode (beaconless mode), the coordinator is the default state waiting for data. The device that wants to send data, checks if the channel is free. If so, then it sends. If not, it waits for a random period defined in the standard. When the coordinator has data to transmit to a device, it waits until the devices request for the data. The coordinator then sends an acknowledgment of reception of the request. If the data are pending, the coordinator transmits the data using the same process of CSMA/CA. If there is no data waiting, the coordinator sends a data frame empty. The non-beacon mode is typically used for sensors that have slept for most of the time (99%). When an event happens, the sensors wake-up and instantly send a frame alert. In this type of operation, the coordinator does not provide any explicit synchronization of the devices, no GTS can be reserved and only random access is adopted for medium distribution because of the absence of superframe and slot synchronization.

This solution has the advantage of optimizing the battery life of sensors and uses the channel only when it is necessary to transmit. In the beacon-enabled mode, a network operates periodically by sending a beacon in order to synchronize the devices with the coordinator. In an IEEE 802.15.4 network, all devices (including the coordinator) work independently. By consequence of communicating on the network, they must know when to wake-up to transmit. To do this, they need to synchronize the clock over the coordinator. When a beacon arrives, all devices are notified of the superframe duration (period of activity of the coordinator) and when they can transmit data. The superframe is the period of activity of the coordinator, which is 16 time slots. It is divided into two parts: the first part is CAP (Contention Access Period) which is similar to the mode beaconless where any device can transmit

Table 2
QOS requirements for different WBAN nodes.

Application	Date rate	Power consumption	QoS (Sensitive to latency)		Privacy
(Chaari and Kamoun 2011); (Jong-Tae Park et al., 2009)	(Jong-Tae Park et al., 2009); (Latré et al., 2011); (Latré et al., 2007)	(Ullah et al., 2008)	(Baozhi Chen and Pompili 2010)		(Jong-Tae Park et al., 2009)
Glucose level monitor	1.6 Kbps	Very low		< 250 ms	High
Pacemaker	Few Kbps	Low		Yes	High
Endoscope Capsule	> 2 Mbps	Low		Yes	Medium
ECG (12 leads)	288 Kbps	Low	< 10 s	< 250 ms	High
ECG (6 leads)	71 Kbps	Low			High
SpO2	32 bps	Low	< 10 s	Yes	High
Blood pressure	16 bps	High		Yes	High
Drug delivery	< 16 Kbps	-		< 250 ms	Medium
Deep brain stimulation	< 320 Kbps	-	10= > 30 s	< 250 ms	High
EEG (12 leads)	43.6 Kbps	Low		< 250 ms	High
EMG	320 Kbps	Low		< 250 ms	High
Temperature	120 bps		> 120		
Video/medical imaging	< 10 Mbps	High		< 250 ms	High
Voice	100- 50 Kbps per flow	Low		< 250 ms	Medium

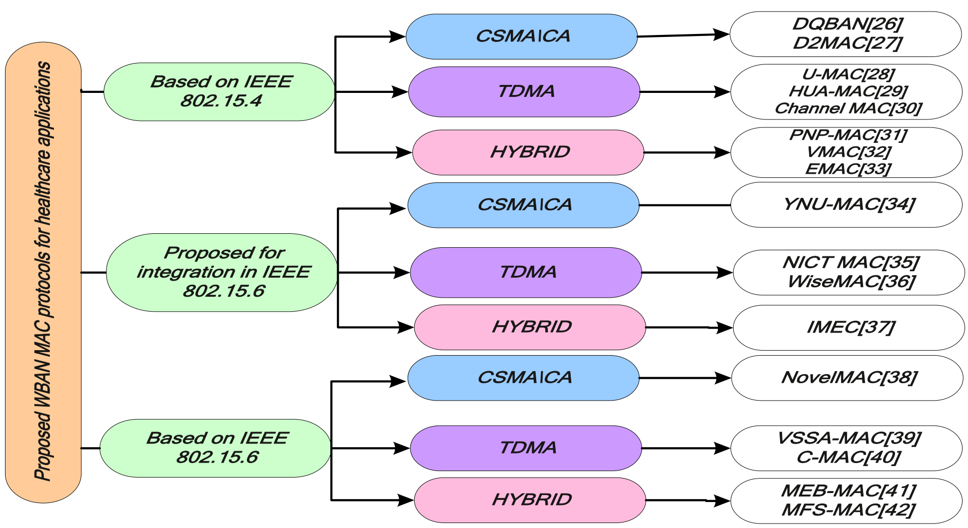

Fig. 3. Taxonomy of BAN MAC-proposed protocols for healthcare.

randomly, but within the time slot which means the transmission cannot start in the middle of a slot, and the second is the CFP (Contention Free Period) used for guarantying access to the channel to a device for a specific number of slots, called GTS. All devices wishing to communicate during the CAP are placed in competition with other devices using the mechanism of CSMA/CA. Transmission is limited by the size of the CAP, if the device could not transmit during the CAP, it must wait for the next superframe to access the channel. Similarly, if the number of slots necessary for transmission of data is more important than the number of slots remaining in the CAP, then the device will send in the next superframe. All transactions must be completed before the next beacon. The coordinator may allocate up to seven GTS. A GTS may occupy more than one slot. Nevertheless, a sufficient portion of the CAP should be reserved for predicting the arrival of new devices in the network which is defined in the IEEE 802.15.4. For applications requiring specific data bandwidth and low latency, the network coordinator may dedicate portions of the active superframe to that application. All contention-based transactions should be achieved before the start of the CFP portion. In entirety, ZigBee headers occupy 15 octets of overhead for each data frame. The complete IEEE 802.15.4 frame structure is represented in Fig. 4. The physical packet is composed of four fields, namely, the preamble which has a length of 32 bits for Symbol synchronization, the start of packet delimiter (8 bits) for frame synchronization, the physical header (8 bits) which specifies PSDU length and the PHY service Data Unit (PSDU: Payload Segment Data Unit) which has a variable length between 0 and 127 Bytes (1016 bits) for Data field.

The IEEE 802.15.4 defines three available models of transfer:

- Transfer from coordinator to node
- Transfer from node to coordinator
- Transfer between two nodes

In the case of star topology, only the first two models of transfer are possible because the exchange is made exclusively with the coordinator system's (as in Bluetooth), while in the case of a point-to-point topology the three transfer models are available.

- *Transfer to a node:* When the coordinator wishes to send a frame to a node in a network using the mechanism of superframes, it must wait until the node is synchronized, while in a network with no use of a superframe, the node sends regular frame (data request) requesting the coordinator.
- *Transfer to the coordinator:* A node desirous of contacting the coordinator using a system based on the structure of the superframe must first be synchronized using the beacon as a reference and then send a data packet during a time slot and await acknowledgment from the coordinator. In a network that

Table 3
WBAN MAC-proposed protocols.

Proposed MAC protocols	Reference	Publication year	Based concepts	Qos support	Energy efficiency
Dqban	(Otal et al., 2009)	2009	Distributed queuing body area network is an enhancement to 802.15.4. It utilizes two queues collision resolution queue (CRQ) for serving access requests and data transmission queue (DTQ) for serving data packets.	Yes	Yes
D2mac	(Mouzehkesh and Zia 2013)	2013	A fuzzy logic system is used in order to incorporate medical and non-medical applications. The authors make the backoff time produced in the IEEE 802.15.4 protocol traffic adaptive. Results show a reliable packet transmission and low latency with conservation of energy consumption level.	Yes	Yes
U-mac	(Ali et al., 2010)	2010	Urgency-based MAC is a protocol based on the IEEE 802.15.4a standard targeted for medical application. In U-MAC protocol, critical nodes packet transmissions are prioritized over non-critical through non-critical nodes packet retransmission cut-off.	Yes	Yes
Hybrid unified mac (HUA)	(Li et al., 2010)	2010	In HUA data packets are transmitted in the CFP and CAP is only used for the command and best-effort data packets. It is based on the integrated superframe structure of IEEE 802.15.4. The slotted ALOHA is employed in the contention access period (CAP) to request the slot allocation	Yes	Yes
Channel-mac	(Kunryun Cho and Cho 2014)	2014	A single-radio multi-channel TDMA MAC protocol is proposed for WBAN on IEEE 802.15.4. The advantages of the MAC protocol proposed are the low data latency, energy efficiency and high reliability. For this reason, star topology is used and the implementation of the protocol is executed.	Yes	Yes
Pnp-mac	(Yoon et al., 2010)	2010	PNP-MAC (preemptive slot allocation and non-preemptive transmission MAC) present a high reliability, low latency for periodic and continuous data, flexible configuration according to the demands from sensor nodes. PNP-MAC can flexibly handle many applications with various requirements through fast superframe adjustments.	Yes	No
Vmac	(Zhou et al., 2008)	2008	Virtual MAC (VMAC) is a hybrid access mechanism presenting an asymmetrical architecture. It is adaptable to changing conditions, such as heterogeneous traffic, reliable data communication, performance in terms of QoS, providing statistical bandwidth guarantees and adaptive resource scheduling.	Yes	No
E-mac	(Yuan et al., 2013)	2013	Enhanced MAC protocol is proposed with integration of relays in order to prolong the network lifetime adaptive topology adjustment and power control to save energy.	Yes	Yes
Ynu mac	(Kutty and Laxminarayan 2010)	2010	YNU MAC uses SIFS, DIFS and backoff in contention window and it is a cluster-based topology protocol. It presents a good channel utilization and high data throughput.	No	No
Nict mac	(Zhen et al., 2009)	2009	NICT MAC presents a star topology and it can operate in a beacon or non-beacon mode. It is scalable for the reason of using Group BAN superframe and mini slots in contention access period (CAP) and the number of GTS in superframe is configurable.	Yes	Yes
Wisemac	(John and Farserotu 2009)	2009	WiseMAC is an RF-FDMA-based concept developed by CSEM (Swiss Center for Electronics and Microtechnology) in use with optical sensor networks WiseNET. Its topology can support both star and mesh topologies and the number. of devices is scalable (traffic limited, e.g., 6 to 256).	No	Yes
Imec	(Zhang et al., 2009)	2009	IMEC MAC presents a dual duty cycling, flexibility and power efficient, enhanced slotted Aloha with QoS and a wake-up. It supports star, cluster tree, and P2P topologies and presents a slotted Aloha and TDMA-based concept.	Yes	Yes
Novel-mac	(Hur et al., 2013)	2013	Novel MAC protocol and a middleware platform are built for health monitoring on wireless USB (WUSB) over WBAN protocol.	Yes	No
Vssa-mac	(Fatehy and Kohno 2013)	2013	Variable spread slotted Aloha for IEEE 802.15.6 Standard is proposed to combine direct sequence-ultra wide band (DS-UWB) and different scenarios and channel models are tested and evaluated.	Yes	Yes
C-mac	(Wang et al., 2013)	2013	The authors introduce a cooperative medium access control protocol for mobile clusters in wireless body area networks. It combines TDMA and FDMA access mechanisms in order to avoid the interference and collision caused by the mobile cluster.	Yes	No
Meb mac	(Huq et al., 2012)	2012	Medical emergency body MAC protocol inserts listening windows dynamically within the contention-free periods. The listening window insertion occurrence is based on the minimum delay tolerance. MEB MAC protocol utilizes idle slots to insert additional listening window opportunities for emergency traffic. MEB MAC reduces channel access delay for emergency traffic particularly for long superframe durations.	Yes	Yes
Mfs-mac	(Choi and Kim 2014)	2014	An improved MAC protocol for WBAN through modified frame structure is proposed to satisfy the energy consumption rate and to overcome the problem of implantable devices. IEEE 802.15.6 MAC is used for comparison with the proposed low-power MAC in order to show that the advantage of the proposed MAC meets the expectations of the authors.	Yes	Yes

is not based on the superframe structure, the node transmits a data frame according to the CSMA/CA mechanism, when it wants.

- *Transfer point-to-point:* In the case of transferring data point-to-point, the nodes must be constantly synchronized and listen to the radio channel. The transfer mode can be CSMA/CA without time slot and with no superframe structure.

An illustration of the superframe structure in beacon mode is shown in Fig. 5 where a BaseSuperframeDuration is the number of symbols forming a superframe. The value of SO (superframe order) must satisfy $0 < SO < BO < 14$ where BO is the beacon order.

4.2. *Beaconless mode for healthcare applications under real time constraints in the worst case.*

Beaconless mode of IEEE 802.15.4 uses the unslotted CSMA/CA mechanism which is presented in Fig. 6. The unslotted CSMA/CA backoff algorithm is based on three variables that correspond to:

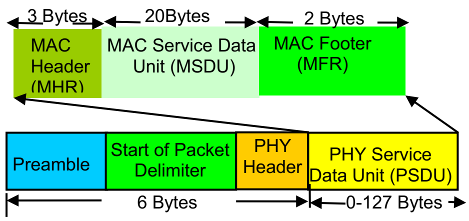

Fig. 4. IEEE 802.15.4 frame structure.

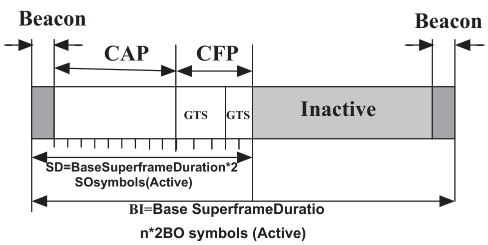

Fig. 5. The superframe in beacon mode.

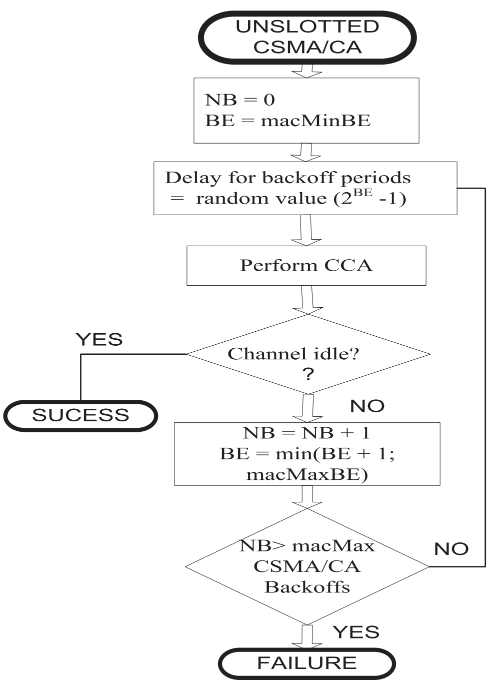

Fig. 6. Unslotted CSMA/CA algorithm.

- *Backoff Exponent (BE)* which is used to compute the backoff delay (DB). Backoff period is the time required to transmit 20 symbols, where a symbol is equivalent to 4 bits. The number of backoff periods that a device shall wait for before assessing the channel is randomly chosen between 0 and 2^{BE-1}. BE is initialized to macMinBE.
- *Number of Backoffs (NB)* which represents the number of times the CSMA/CA algorithm was required to backoff while attempting to access the channel. It is initialized to 0 before each new transmission attempt.

The IEEE 802.15.4 CSMA-CA algorithms realize energy savings by keeping the node idle during the backoff procedure. A node executes the Clear Channel Assessment (CCA) procedure. The most significant parameters in the unslotted CSMA/CA are 'macMaxFrameRetries' ($0 \le$ Maximum number of retransmissions ≤ 7), 'macMaxCSMABackoff' ($0 \le$ Maximum number of backoff stages ≤ 5), 'macMaxBE' ($3 \le \text{macMaxBE} \le 8$), and 'macMinBE' ($0 \le \text{macMinBE} \le 7$).

We focus in this sub-section on knowing the impact of the unslotted CSMA-CA algorithm, so we compute the end-to-end delay (1) in the worst case. This case is considered when the unslotted CSMA/CA parameters take their maximum values.

$$E2E_{wc} = macMaxFramretries*(BP_{wc} + T_{Frame} + T_{\tau A} + T_{Ack} + T_{LIFS}) \quad (1)$$

- BP_{wc} is the backoff period in the worst case in seconds and it is expressed as follows:

  $$BP_{wc} = macMaxCSMABackoff*(N_{BO}*T_{BOslot}) \quad (2)$$

  where N_{BO} is the maximum number of backoffs in slots and T_{BOslot} is the time for a backoff slot.

  $$N_{BO} = 2^{macMaxBE} - 1 = 2^8 - 1 = 255 \quad (3)$$

  $$T_{BOslot} = 20*T_{symbol} = \frac{20*4}{Bitrate} \quad (4)$$

  The bit rate used in (4) depends on the frequency bands. The smaller value is 20 Kbps (868.0–868.6 MHz in the BPSK modulation scheme). Hence we found $T_{BOslot} = 3.90625$ ms and $BP_{wc} = 4.98046875$ s.
- T_{Frame} is the transmission time for a frame with maximum payload length. Its expression is

  $$T_{Frame} = (133*8)/(20*1024) = 51.953125 \text{ ms}$$

- $T_{\tau A}$ is the turnaround time which represents the time between data frame and its ACK.

  $$T_{\tau A} = 12*T_{symbol} = \frac{12*4}{Bitrate} = (12*4)/(20*1024) = 2.34375 \text{ ms} \quad (5)$$

- T_{Ack} is the transmission time for an ACK and its expression is

  $$T_{Ack} = (31*8)/(20*1024) = 12.109375\text{ms}$$

- T_{LIFS} is the Inter Frame Space used when the MPDU is greater than 18 bytes. The expression of T_{LIFS} is given in the following:

  $$T_{LIFS} = 40*T_{symbol} = 7.8125 \text{ ms} \quad (6)$$

Finally we can calculate the end-to-end delay in the worst case.

$$E2E_{wc} = 7*(4.98046875 + (51.953125 + 2.34375 + 12.109375 + 7.8125)*10^{-3}) = 35.3828125 \text{ s}$$

As a conclusion, we can say that under unslotted CSMA/CA algorithm and in the worst case the$E2E_{wc}$ is equal to 35.38 s. Therefore, the unslotted CSMA-CA is not suitable for WBAN communications, especially for signs that are sensitive to latency (250 ms).

4.3. Beacon mode for healthcare applications under real time constraints in the worst case

The beacon mode of IEEE 802.15.4 uses slotted CSMA/CA mechanism which is presented in Fig. 7. After analyzing the performance of the unslotted CSMA/CA in the last sub-section, we focus now on the effect of the slotted CSMA/CA. So we also calculate the end-to-end delay (8) in the worst case (when the slotted CSMA/CA parameters take their maximum values). The difference between unslotted and slotted CSMA/CA is the addition

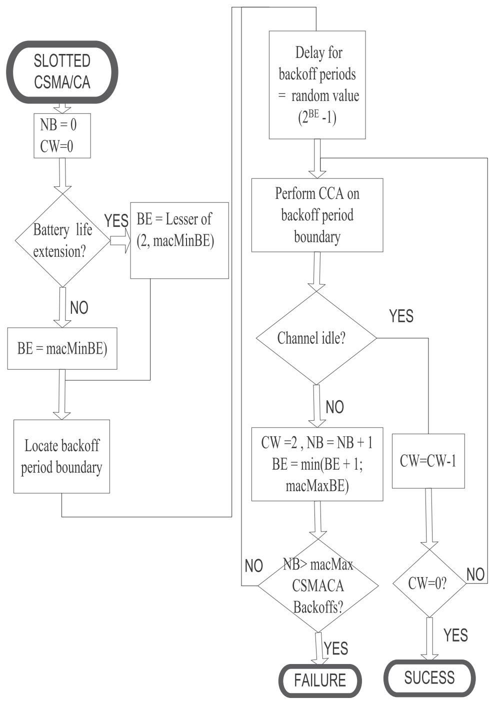

Fig. 7. Slotted CSMA/CA algorithm.

of T_{CW} which represents the backoff period in the slotted algorithm using the Contention Window (CW). CW is the number of BPs during which the channel must be sensed idle before channel access. It is used only in the slotted mode.

$$T_{cw} = cw * T_{BOslot} = 7.8125 \text{ ms} \tag{7}$$

The expression of the end-to-end delay in the worst case for the slotted CSMA/CA is

$$E2E_{wc} = T_{CAP} + T_{CFP} = macMaxFrame\text{Retries} * (T_{Frame} + T_{\tau A} + T_{Ack} + T_{LIFS} + T_{cw}) + 16 * T_{BOslot} \tag{8}$$

The $E2E_{wc}$ is equal to 609.337495 ms. We can conclude that under slotted CSMA/CA algorithm, the end-to-end delay is lower than the unslotted CSMA/CA in the worst case, however, it is still not suitable for WBAN communications.

5. Investigation on Timeout Mac Protocol (T-Mac)

5.1. Overview

In T-MAC (vanDam and Langendoen 2003), each node wakes up periodically to communicate with its neighbors. The nodes communicate with each other using a mechanism RTS/CTS for avoiding collisions and the hidden station problem. A node listens to the radio channel and can send data while it is in its active period. An active period ends when no activation event occurs during a time TA (minimum time for idle listening per frame). An activation event is identified by

- Beginning of a timer frame;
- Reception of data on radio;
- Detection of communication on the radio channel due to a signal strength indicator on the radio;
- Acknowledgment of its own packages and
- Knowledge by listening before issuing RTS and CTS that the transmission of data from a neighbor ended.

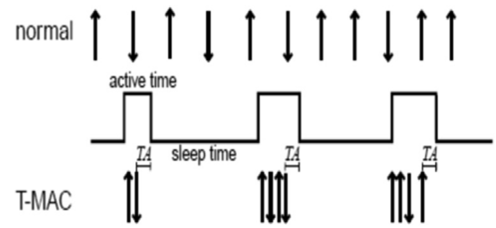

Fig. 8. The basic T-MAC protocol scheme.

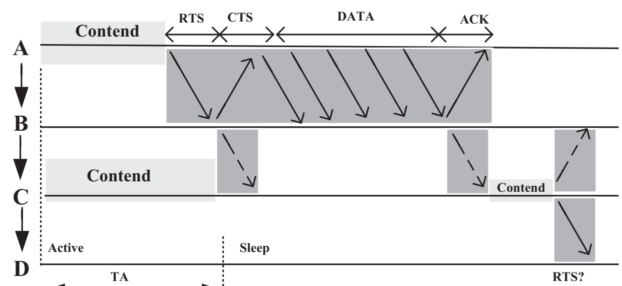

Fig. 9. The problem of falling asleep early.

The illustration of the basic T-MAC protocol scheme, with adaptive active times is shown in Fig. 8.

5.2. Timing

When a node wakes up, it begins by listening. If it doesn't hear anything for a while, it simply selects a scheduling frame and transmits it through a SYNC packet that contains the time until the beginning of the next frame. If at startup the node receives a SYNC packet from another node, it follows the scheduling defined in this packet and transmits its own SYNC accordingly. Nodes retransmit their SYNC from time to time. If a node has adopted a scheduling and receives a SYNC packet from another node with another scheduling, then it must adopt both schedules. It must also send a SYNC packet to the other node so that it learns the presence of another scheduling. Adopting these two scheduling means that the node will have an activation event at the beginning of each two frames. Nodes should begin data transmission at the beginning of their active period. At that time, neighbors which have the same scheduling are adopted the more awakened. TA should be long enough to consider pending before issuing the SYNC packet and time of receipt of a possible RTS packet.

5.3. Frts

In T-MAC, there is a problem when traffic is essentially unidirectional in the case when the sensors send their information to a collection information station. For example (see Fig. 9), we assume node A is sending data to node D via nodes B and C. Consider node C is waiting to send data packets. Node C can lose contention due to node B, that means by receiving a packet RTS from B or because of A, that means by receiving a CTS packet from B response to an RTS packet that B has received from A. Consider the second case, where C having received the CTS from B, it must remain silent and therefore D does not receive anything. Therefore, it returns to sleep. When node A has finished transmitting data, B sends an ACK that all its neighbors receive and then C. Node C can expect to obtain contention to transmit its packets to D but it is sleeping; it cannot receive the RTS packet from node C. One solution is the introduction of future request-to-send (FRTS). In the previous example, when node C receives the CTS from B, C

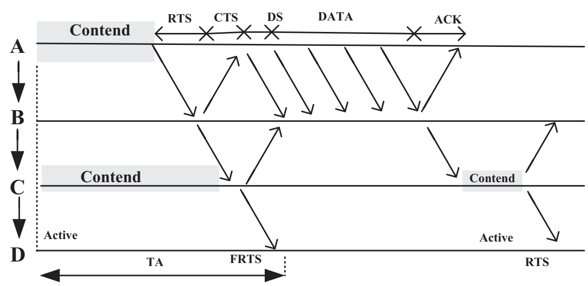

Fig. 10. FRTS mechanism.

sends a packet FRTS to D (B hears this package) that contains the length of the data communication blocking. Thus, the node can then define that it will be the recipient of an RTS packet and not be asleep when the package arrives. It should take into account the time of a possible package reception (FRTS) for calculating TA. The addition of the mechanism FRTS adds a packet Data Send (DS) before the packet transmission data. Indeed, since C sends the FRTS packet after receiving the CTS packet from B, A sends a packet DS which has the same size as a packet FRTS, after receiving the CTS packet. So, it will not lose any contention and the data it needs to send to B doesn't collide with the package FRTS that B receives. FRTS mechanism which is illustrated in Fig. 10 should be used only under certain traffic conditions; otherwise, it adds an energy that can be avoided.

5.4. E2E delay analysis for healthcare applications under real time constraints in the worst case

We focalize now on the effect of the TMAC protocol, so we calculate also the end-to-end delay presented in (9) in the worst case (when TMAC protocol parameters take their maximum values). We set the macMaxFrameRetries to 7 in order to stay in the same terms.

$$E2E_{wc} = macMaxFrameRetries * (T_c + T_{RTS} + T_{CTS} + T_{DS} + T_{Frame} + T_{Ack}) \quad (9)$$

T_c is the contended interval and it is equal to the addition of the minimum time for idle listening per frame and the FRTS time so its expression is

$$T_{cw} = cw * T_{BOslot} = 7.8125 \text{ ms} \quad (10)$$

- T_{RTS} is the time required for sending an RTS packet in second.
- T_{CTS} is the time required for sending a CTS packet in second.
- T_{DS} is the time required for sending a DS packet in second.
- T_{Frame} is the transmission time for a DATA packet with maximum payload length.
- T_{ACK} is the time required for sending a ACK packet in second.

Finally the $E2E_{wc} = 4.368s$

We can see that TMAC protocol in the worst case is better than unslotted CSMA/CA algorithm because it presents fewer end-to-end delays but it is still not appropriate for WBAN communications.

6. Investigation on IEEE 802.15.6

6.1. Frame structure of IEEE 802.15.6

The IEEE 802.15.6 (IEEE 2010) is a standard for WBANs, which operate in and around the human body. It appears to focus on functioning at relatively low frequencies, less than one megahertz, and short-range use, low cost, reliable wireless communication and especially an ultra low power. In this section, we try to present the medium access protocol described in the last draft standard. This draft specifies a medium access with different access modes and their access phases. In WBAN, the channel is separated into superframe structures. The superframe is of fixed length bounded by network beacons period of equal length. The hub has many functions, such as selecting the boundaries of the beacon period, transmitting a beacon frame in each beacon period except in inactive superframes and shifting its beacon transmission time by including a beacon shifting sequence field in its beacons and it shouldn't be a beacon sequence which is used by its neighbor hubs, in order to provide or to support time referenced allocations. When the hub is not sensed for providing and supporting time referenced allocation in a BAN, it can operate without considering neither superframe nor time base and it is not necessary to transmit a beacon at all. Finally, we can say that the IEEE 802.15.6 MAC layer can support three modes of operations, which are beacon mode with beacon period superframe boundaries, non-beacon mode with superframe boundaries, and non-beacon mode without superframe boundaries. In this paper we will consider the beacon mode with beacon period superframe boundaries. In this mode, the hub transmits a beacon frame in each beacon period, except in inactive superframe, it has sensed to provide time referenced allocation and should divide the beacon access mode in access phases supported in beacon mode as it is shown in Fig. 11. The superframe is constructed of nine access phases, which are beacon, Exclusive Access Phase 1 (EAP1), Random Access Phase 1 (RAP1), Managed Access phase 1, Exclusive Access Phase 2 (EAP 2), Random Access Phase 2 (RAP 2), Managed Access phase 2, beacon 2 and a Contention Access Phase (CAP).

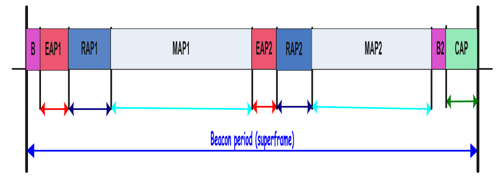

Fig. 11. IEEE 802.15.6 superframe structure.

- *Beacon:* Beacons initialize a superframe. They are sent in the first slot of each superframe. They identify the coordinator, allow power management and device synchronization.
- *EAP1 and EAP2:* These access phases are used for an emergency traffic where failure of delivery in a certain delay may affect the health of a person and his life so that they present the highest priority.
- *RAP1, RAP2 and CAP:* These kinds of access are dedicated for normal traffic where the data traffic is in its normal conditions without the critical time.
- *Managed access phase:* This access phase is used for uplink, downlink and bilink allocation intervals.
- *Beacon 2:* It is dedicated for indicating the beginning and the end of the CAP phase, grouping acknowledgment, coexistence information and fast reservation or adaptation.

6.2. MAC acess mechanisms

The access mechanisms used for each access phase of the superframe are: random access, improved and unscheduled access and scheduled access and variants. Random, improved and unscheduled access are both connectionless contention-free access, whereas scheduled access and variants are connection-oriented contention-free access. The allocations in exclusive access phases (EAP1, EAP2), random access phases (RAP1, RAP2) and the contention access phase (CAP) may only be contended so that the access methods for obtaining the contended allocations in these access phases are CSMA/CA and slotted aloha access.

- *CSMA*/CA*:* Uses a backoff counter and a contention window in order to obtain a new contended allocation. Here, we explain the CSMA/CA procedure in IEEE 802.15.6 standard. A node shall initialize its counter to a random integer value between one and CW where CW belong to CWmin and CWmax, depending to the user priority (Table 2). Then the counter decremented when an idle CSMA slot is equal to 'pCSMASlotLength' and data is transmitted when the counter is equal to zero. The node locks its backoff when the channel is busy and the CW is doubled in this case until it reaches CWmax.
- *Slotted Aloha access:* Uses a contention probability and a node shall maintain this probability in order to guess if it obtains a new contended allocation in an Aloha slot. A node can also start, use, modify, abort and end a contended allocation.

6.3. E2E delay analysis for healthcare applications under real time constraints in the worst case

We calculate the end-to-end delay of the protocol IEEE 802.15.6 (11) in the worst case (when IEEE 802.15.6 MAC protocol parameters take their maximum values) in order to compare its performance with the IEEE 802.15.4 and TMAC. The CSMA/CA mechanism of the IEEE 802.15.6 is illustrated in Fig. 12 (R is the retransmissions retry and it is set equal to macMaxFrameRetries of the IEEE802.15.4 MAC protocol).

$$E2E_{wc} = macMaxFramretries*(T_{cw} + T_{Frame} + T_{\tau A} + T_{Ack}) \quad (11)$$

- T_{cw} is the contended period in the worst case in seconds and it is expressed as follows:

$$T_{cw} = cw*T_{pCSMASlotLength} \quad (12)$$

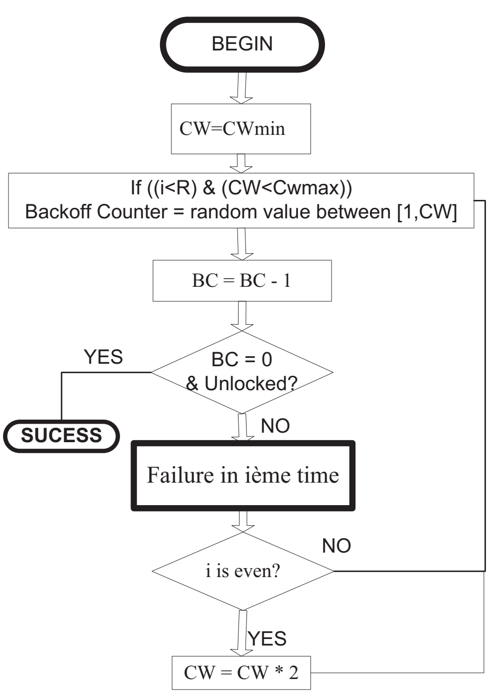

Fig. 12. CSMA/CA mechanism of the IEEE 802.15.6.

$$TpCSMASlotLength = pCCATime + pCSMAMACPHYTime \quad (13)$$

where

$pCSMAMACPHYTime = 40\ \mu s$ and $pCCATime = (63/\text{Data Rate})$

We note that data rate depends on the frequency bands. The smaller value is 75.9 Kbps (402–405 MHz and the modulation scheme is DBPSK) (IEEE 2010). We found $T_{cw} = 5.4144$ ms.

- T_{Frame} is the transmission time for a frame with maximum payload length. Its expression is

  $T_{Frame} = ((264*8)+31)/(75.9*1024) = 27.5727$ ms

- $T_{\tau A}$ (14) is the turnaround time which represents the time elapsed from the end of the received frame to the start of the transmitted frame. The turnaround time should be between pSIFS (short interframe spacing) and pSIFS+pExtraIFS. Hence, in the worst case we found

$$T_{\tau A} = pSIFS + pExtraIFS = 85\ \mu s \quad (14)$$

- T_{Ack} is the transmission time for an ACK and its expression is

$$T_{Ack} = ((9*8)+31)/(75.9*1024) = 1.325 \text{ ms} \quad (15)$$

Finally, we can calculate now the end-to-end delay in the worst case:

$E2E_{wc} = 240.7797$ ms

As a conclusion, the IEEE 802.15.6 algorithm is suitable for WBAN communications especially for signs that are sensitive to latency (250 ms). Finally, the IEEE 802.15.6 protocol is the best in terms of end-to-end delay in the worst case. Furthermore, IEEE 802.15.6 matches better in real time application and it is more suitable for WBAN networks communication. Table 4.

7. Simulation results

The simulator used in this paper is the open source Castalia 3.2 ($author1$ et al., Castalia Simulator). In our scenarios, we have used the throughput test application which is integrated under the OMNET++ simulator. All nodes send packets to the hub, which is the node number zero. We have evaluated the performance of the three MAC protocols: IEEE 802.15.4, IEEE 802.15.6, and TMAC. The simulation uses the physical layer of Medwin proposal described in Davenport et al. (2009). The parameters of the physical radio model are summarized below: the data rate used is 1024 Kbps, the receiver (Rx) sensitivity is -87 dBm, and the transmitter power is varying from -10 to -25 dBm. For our simulation, we considered a

Table 4
Contention window bounds for CSMA/CA and contention probability thresholds for slotted Aloha access.

User Priority	CSMA/CA		Slotted Aloha access	
	CWmin	*CWmax*	*CPmax*	*CPmin*
0	16	64	1/8	1/16
1	16	32	1/8	3/32
2	8	32	1/4	3/32
3	8	16	1/4	1/8
4	4	16	3/8	1/8
5	4	8	3/8	3/16
6	2	8	1/2	3/16
7	1	4	1	1/4

Table 5
Simulation parameters.

Parameters	Value
Number of nodes	6
Deployment	Random
Initial energy	18720j
MAC	TMAC,IEEE 802.15.6, IEEE 802.15.4
Channel Model	Log Shadowing Wireless Model
Path loss exponent	2.4
Simulation time	50 s
Simulation area	4*3 m

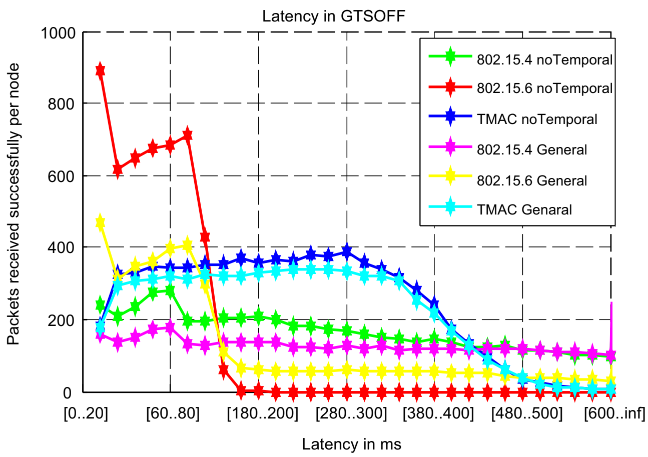

Fig. 13. GTS OFF latency.

star topology network. The simulation parameters are listed in Table 5.

In this paper, in order to evaluate the effectiveness of the three MAC protocols and to take a decision about the better access mechanism to be used in WBAN networks, we run several simulations varying different parameters each time and observing different performance metrics such as packet delivery ratio (PDR) and latency. In fact, two scenarios are discussed. The first one is the latency which is equal to the arrived message time minus the message creation time and the second is the PDR which is the mean number of data packets delivered successfully to the destination per node divided per total number of transmitted data packets per node. We have evaluated these two metrics in GTS ON configuration (taking in consideration the CSMA/CA and the TDMA access mechanisms) and GTS OFF configuration (taking into account only the CSMA/CA mechanism). This analysis will give us an idea about the nature of the best MAC protocol suitable for WBAN networks.

7.1. Scenario1: latency analysis

In this scenario, we focus on the performance of running the three protocols depending on GTS functionality (turned ON or OFF). We analyzed the effect of the no temporal channel (no temporal configuration) vs. the temporal channel (general configuration taking into account the temporal variability).

Figs.13 and 14 represent the latency of all the packets received by the MACs of all nodes. If a packet is received successfully but after certain latency, we can conclude that it is useless in case of emergency packet. According to Figs.13 and 14, the three MAC protocols perform better when the GTS is turned ON. Therefore, the TDMA-based concept is more efficient and has no interference compared with the GTS OFF. Using the GTS lets also the Baseline

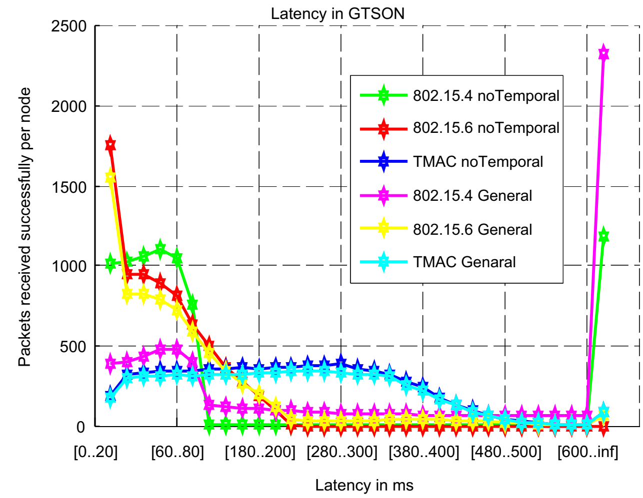

Fig. 14. GTS ON latency.

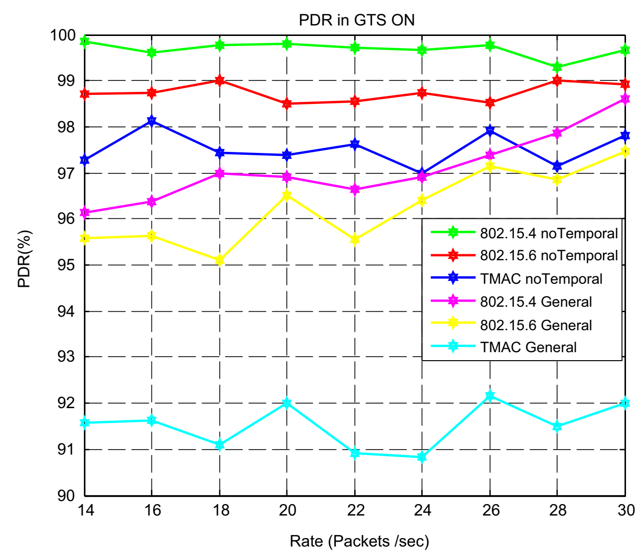

Fig. 15. PDR in GTSOFF.

MAC (IEEE 802.15.6) have lower latency compared with the Zigbee MAC and TMAC protocols. The no temporal variation introduces more latency in sending packets compared with the temporal variation.

In this first scenario, we concluded that the MAC protocols based on CSMA/CA and TDMA mechanisms perform better than others based only on CSMA/CA.

7.2. Scenario2: packet delivery ratio analysis

In this scenario, we have evaluated the packet delivery ratio for GTSOFF and GTSON modes. Simulation results are illustrated, respectively, by Figs.15 and 16. The y-axis is the PDR and the x-axis is the sending rate of several nodes measured in packets/sec. Generally, MAC protocol performs better when its GTS is ON. As it is clear in Figs.15 and 16, the TMAC present the same PDR when their GTS is turned ON and OFF; because it uses the RTS/CTS mechanism so it does not take into account the GTS effect, whereas the Zigbee MAC and IEEE 802.15.6 perform better when their GTS is turned ON. We notice that the TDMA concept lets the MAC protocol be more efficient.

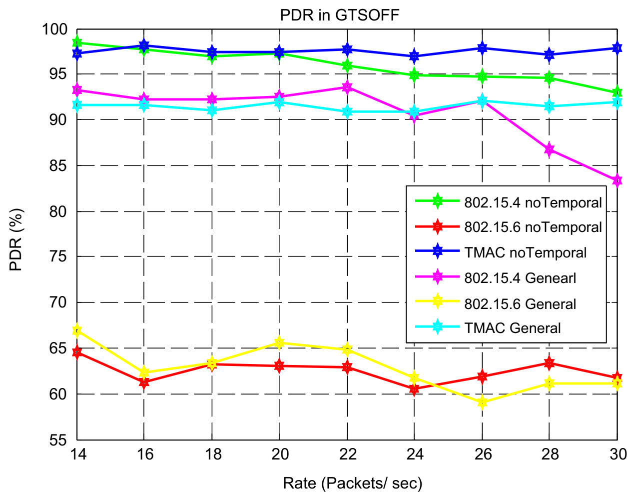

Fig. 16. PDR in GTSON.

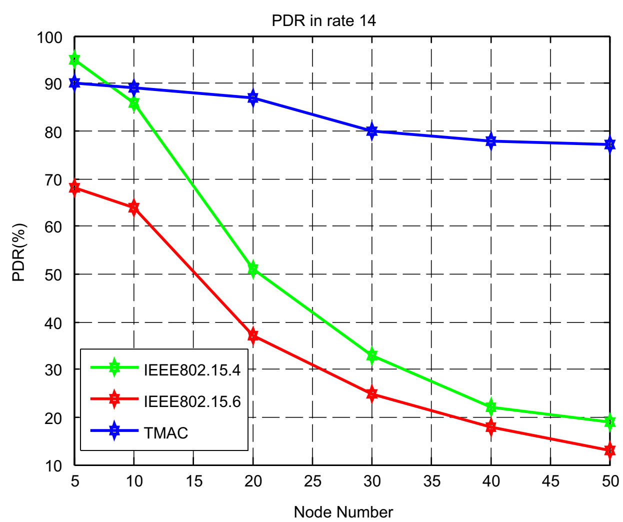

Fig. 17. PDR in rate 14.

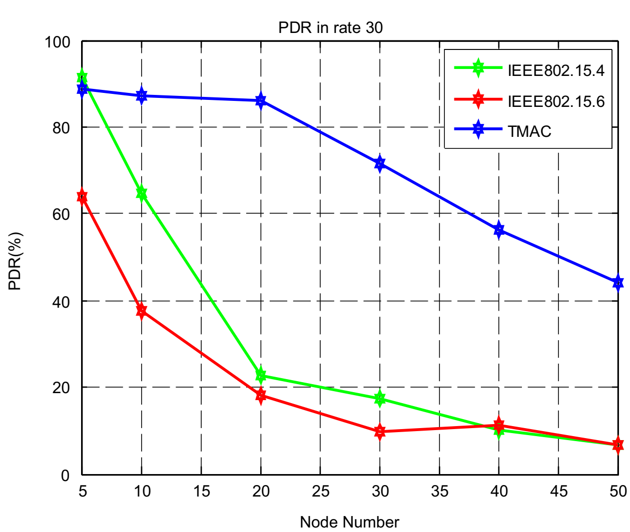

Fig. 18. PDR in rate 30.

Hence, in this scenario we can say that the hybrid protocols (CSMA/CA and TDMA-based protocols) are more performing in terms of PDR.

Now, we fix the rate at 14 and we vary the number of nodes. Fig.17 describes the average PDR. We note that the more we increase the number of nodes, the more the PDR decreases. The TMAC protocol presents the performing result because it receives more packets than BaselineMAC and ZigbeeMAC. The PDR obtained for the various protocols appears to be deteriorating with the increase in the number of nodes. This result is obtained because in the three MAC protocols, the nodes have to send data using access mechanisms. Thus, with increase in the number of nodes, the PDR decreases.

We change the rate to 30 and we repeat the same simulation with the same configuration. We constant the same conclusion concerning the PDR. Results of the simulations are presented in Fig. 18.

7.3. Results and discussion

According to the results of the two scenarios, it is clear that the MAC protocols based CSMA/CA and TDMA access mechanisms (GTS ON configuration) give better performance compared with MAC protocols-based CSMA/CA mechanisms (GTS OFF configuration). Consequently, hybrid protocols are the most suitable for WBAN networks.

8. Conclusion

WBAN is paving the way for the deployment of a variety of medical and non-medical applications. WBANs bring out a new set of requirements and specifications, which are necessary for developing a WBAN MAC protocol. These requirements are highlighted in this paper. Furthermore, we have overviewed the existing MAC protocols, namely, IEEE 802.15.4, IEEE 80.2.15.6, and TMAC to compare them in order to find the appropriate one that respects the needs and scopes of WBANs. Our comparative study has been elaborated at three levels: at the first level, we deeply discussed and presented the MAC access mechanisms and frame structure for each proposed MAC protocol. At the second level, we evaluated the end-to-end delay in the worst case of the three WBAN MAC protocols. The results show that the IEEE 802.15.6 matches better in real time application and it is more suitable for WBAN networks communication. At the third level, we have elaborated different scenarios to evaluate the performance (latency and PDR) of the IEEE 802.15.6 MAC protocol and compare it to TMAC and IEEE 802.15.4 using OMNET++ with Castalia as simulating tools. We notice that the three MAC protocols perform better (low latency and more packet received successfully (PDR)) with GTS ON and temporal variation so we can say that hybrid protocols are the best for WBAN networks. In our future work, we will propose a hybrid MAC protocol that takes into consideration the requirements of WBANs networks.

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