2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP) | 979-8-3503-4874-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/CSNDSP60683.2024.10636608

Investigation of Suitable MAC Protocols for Optical Wireless Body-Area Networks

1st Christos Giachoudis
Aix-Marseille University, CNRS
Centrale Med, Fresnel Institute
Marseille, France
christos.giachoudis@fresnel.fr

2nd Mohammad Ali Khalighi
Aix-Marseille University, CNRS
Centrale Med, Fresnel Institute
Marseille, France
Ali.Khalighi@fresnel.fr

3rd Stanislav Zvanovec
Faculty of Electrical Engineering,
Czech Technical University in Prague,
Prague, Czech Republic
xzvanove@fel.cvut.cz

4th Vasilis K. Papanikolaou
Erlangen-Nuremberg University (FAU)
Erlangen, Germany
vasilis.papanikolaou@fau.de

5th Sotiris A. Tegos
Aristotle University of Thessaloniki
Thessaloniki, Greece
tegosoti@auth.gr

6th George K. Karagiannidis
Aristotle University of Thessaloniki
Thessaloniki, Greece
Lebanese American University (LAU)
Beirut, Lebanon
geokarag@auth.gr

***Abstract*—We consider the use of optical wireless data transmission from the medical nodes in wireless body-area networks (WBANs) for monitoring a patient's vital signs. To investigate efficient medium-access control (MAC) protocols, we contrast the two developed standards of IEEE 802.15.6 and IEEE 802.15.7 from the points of view of energy efficiency and latency. The first standard was originally developed for radio-frequency signal transmission, whereas the latter is based on the optical wireless technology. The comparison of the two protocols is made using the Castalia simulator and realistic optical WBAN channel models from previous work. This study also offers valuable insights into the performance of the latest IEEE 802.15.13 standard, designed for optical WBANs.**

***Index Terms*—Wireless body-area networks; optical wireless communications; patient monitoring; IEEE 802.15.6; IEEE 802.15.7; IEEE 802.15.13; Castalia simulator.**

I. INTRODUCTION

Wireless body-area networks (WBANs) have emerged recently as an efficient way for remotely monitoring patients or elderly people either inside or outside hospitals and healthcare centers [1]. In a typical WBAN, a few wearable medical sensor nodes (SNs) transmit the acquired vital signs to a central coordinator node (CN), placed on the patient's body, what is usually referred to as intra-WBAN connectivity. The CN, then sends the collected data to an access point via a so-called extra-WBAN link, which are finally forwarded to a remote location via an external network.

A number of prototypes and proofs-of-concept have been realized so far, mostly based on radio-frequency (RF) signal transmission. The majority of these studies have been based on Zigbee and Bluetooth technologies [2]. The use of optical wireless technology for signal transmission has become subject of interest more recently, as it has the potential to provide enhanced security (due to the confinement of optical signals in indoor spaces) and robustness against RF interference. It also alleviates concerns about the health impact for individuals exposed to electromagnetic radiation and the interference with highly sensitive sensors designed to detect very weak signals [2]–[5]. Previous research on optical WBANs concerned mainly the channel characterization and modeling for intra- and extra-WBANs, and signal transmission with a focus on the design of suitable and efficient multiple-access techniques in the physical (PHY) layer for both cases [6]–[11]. However, as the number of SNs or users (that share the same indoor space) increases, more efficient multiple-access (MA) management can be done in the medium-access control (MAC) layer. For instance, in a recent work [11], we studied the performance of the simple Slotted-ALOHA scheme for optical WBANs and further proposed optimizing the network energy efficiency using particle swarm optimization.

In terms of standardization, IEEE 802.15.6 was developed in 2012 for RF-based WBANs for applications that are more demanding in terms of data rate, as compared to the basic IEEE 802.15.4 standard [12], [13]. Also, IEEE released the IEEE 802.15.7 standard in 2011 for optical WBANs [14], [15], which was revised later in 2018. The 802.15.6 and 802.15.7 standards have tried to address the requirements in terms of quality-of-service (QoS), energy efficiency, and security. Recently, IEEE released a new standard, IEEE 802.15.13 [15], which incorporates numerous features from the 802.15.4 and 802.15.7 standards and enhances the data rate and communication range. Specifically, in the MAC layer, it follows the design guidelines of 802.15.4, and utilizes a streamlined version of the 802.15.7 MAC protocol, while incorporating new functionalities.

This work was supported by the European Union's Horizon Europe Program in the frame of Marie Skłodowska-Curie Actions Doctoral Networks (MSCA-DN) project OWIN6G (Optical and wireless sensors networks for 6G scenarios) under Agreement No. 101119624. It was also based upon work from COST Action CA19111 (European Network on Future Generation Optical Wireless Communication Technologies, NEWFOCUS), supported by COST (European Cooperation in Science and Technology). The authors would like also to thank Dr. Oussama Haddad from University of Versailles Saint-Quentin, France, for the fruitful discussions on WBAN channel modelling and his help on using the Castalia simulator.

Our aim in this paper is to investigate the MAC protocols of the IEEE 802.15.6 and 802.15.7 standards with the purpose of designing efficient MAC protocols for use in optical WBANs. More specifically, we want to compare them in terms of both energy consumption and transmission latency when they are used for an optical WBAN. This comparison is done using the Castalia simulator, which is based on the OMNeT++ platform and is a convenient tool for simulating a realistic wireless channel and nodes' behavior in order to investigate the efficiency of the communication protocols. To use this simulator, we have first inserted the WBAN optical channel model, extensively explored in [7], in order to include the specificity of optical signal propagation in a typical indoor environment. Then, considering a few typical examples of medical sensors, we compare the energy consumption and the latency of the network when using the MAC protocols of IEEE 802.15.6 and 802.15.7 standards. To the best of our knowledge, no previous work has compared the energy efficiency of the aforementioned protocols in detail.

The remainder of this paper is structured as follows. First, some general connectivity requirements in WBANs are described in Section II. Then, Section III reviews the existing communication IEEE standards of 802.15.4, 802.15.6, and 802.15.7. In fact, the reason behind presenting 802.15.4 is that 802.15.7 has been built upon the foundation of this standard. Afterwards, in Section IV, the performances of the two latter protocols are compared using the Castalia simulator. Lastly, Section V concludes the paper.

II. CONNECTIVITY AND MAC-LAYER PROTOCOLS

As mentioned before, MA management can be done at either PHY or MAC layers. For medical sensors, which send (mostly) a limited volume of data and in a rather sporadic way, efficient MA can be done in the MAC layer, especially for a relatively large number of nodes or users. This approach can also offer reduced computational and hardware complexity and improved energy efficiency. Indeed, energy efficiency is a crucial point in medical WBANs in order to maximize the battery lifetime of the medical sensors. For this reason, special attention should be devoted to reducing the network energy consumption in the MAC layer design. In fact, the main reasons for energy wastage related to the MAC layer are [16]:

- Packet Collisions: when two or more nodes try to access the communication medium simultaneously;
- Idle Listening: when the nodes are always on standby, waiting possible signal transmissions;
- Overhearing: when a node receives a packet addressed to another node;
- Packet Overhead: when the message overhead has a non-negligible size compared to the main message.

Therefore, the designed MAC protocols generally use energy-efficient mechanisms to reduce energy consumption, such as:

- Low-power listening (LPL): where nodes wake up for a short duration to check the channel activity; if the channel is idle, nodes go into sleep mode, otherwise they stay on to receive/send the data;
- Time-division MA (TDMA): where the nodes follow a time schedule for signal transmission;
- Scheduled-contention mechanisms: where nodes use both TDMA and contention techniques such as ALOHA or carrier-sense MA with collision avoidance (CSMA/CA) to manage both periodic and random transmissions.

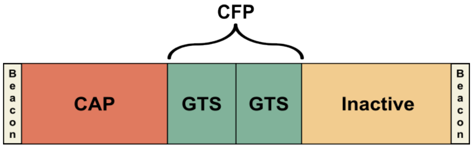

Fig. 1. The IEEE 802.15.4 / 802.15.7 superframe structure [13]. In this example, the CFP is divided into two GTS intervals for two transmitting nodes with different data rate requirements.

As mentioned before, our aim in this paper is to compare the efficiency of MAC protocols in the available standards for WBANs, i.e., IEEE 802.15.6 (RF-based) and IEEE 802.15.7 (optical-based). For this, we use the Castalia simulator in which both standards have been implemented. As a matter of fact, we have not actually implemented the latter standard, but have considered instead the IEEE 802.15.4 protocol, which uses almost the same MAC protocol design as 802.15.7 [13], [14].

III. OVERVIEW OF STANDARDS

Before presenting the performance comparison, we provide a brief overview of the three above-mentioned standards and their MAC protocols.

A. *IEEE 802.15.4*

This standard, which is in fact the basis of Zigbee, defines the PHY and MAC layer specifications for low data rate wireless connectivity among relatively simple devices, typically operating within a range of 10 meters or less, while ensuring low power consumption. It is based on using the license-free industrial scientific medical (ISM) frequency bands, with typical data rates of 250 kbps in the 2.4 GHz band, 40 kbps in the 915 MHz band and 20 kbps in the 868 MHz band [13], [17]. The frame structure of this standard is shown in Fig. 1, where it is separated into: the contention access period (CAP), where devices contend via a slotted random access mechanism; the contention free period (CFP), that provides guaranteed time slots (GTS) for low latency for specific nodes with more critical data to transmit; and the inactive period, where nodes switch off to save energy [17]. Lastly, frames are bounded by beacon periods of equal length.

B. *IEEE 802.15.6*

This standard defines three PHY layers of narrow-band (NB), ultra-wideband (UWB), and human body communications (HBC), in order to cover the broad range of applications. Originally, compared to 802.15.4, this standard was designed

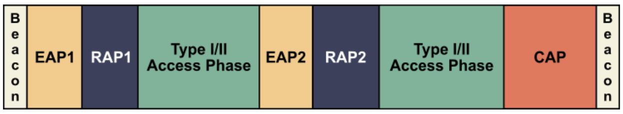

Fig. 2. IEEE 802.15.6 superframe structure [12].

to address applications that are more demanding in terms of data rate (up to 10 Mbps) [12], [18].

Figure 2 shows the frame structure of the IEEE 802.15.6, which is divided into exclusive access phase 1 (EAP1), random access phase 1 (RAP1), Type I/II phase, EAP2, RAP2, Type I/II phase, and a CAP interval. In EAP, RAP and CAP periods, nodes contend for resource allocation using either CSMA/CA or Slotted-ALOHA. RAP1, RAP2, and CAP are used for regular traffic, whereas the EAP1 and EAP2 intervals are envisioned for highest priority traffic such as reporting emergency events. Type I/II phases are used for uplink, downlink, bilink (bidirectional link), and delay bilink allocation intervals during which, polling is used for resource allocation. Depending on the application, any of these periods can be disabled by setting its duration to zero.

C. IEEE 802.15.7

This standard specifies six different PHY, each one operating at a different data rate depending on the application [14], [19]:

- PHY I: low data rates: tens to hundreds of kbps for outdoor applications;
- PHY II: moderate connection rates: tens of Mbps for indoor applications;
- PHY III: data rates of tens of Mbps based on color-shift keying;
- PHY IV: data rates of up to 22 kbps for discrete light sources;
- PHY V: data rates of up to 5.71 kbps for use with scattered ambient sources of light;
- PHY VI: data rates of ∼kbps for digital displays operating at broadband speeds.

It also defines four random access methods: non-beacon-enabled un-slotted random access, beacon-enabled slotted random access, non-beacon-enabled un-slotted random access with CSMA/CA, and beacon-enabled random access slotted with CSMA/CA [20]. In the beacon-enabled mode, the time axis is divided into superframes, each one being bounded by beacons and divided into equally sized time slots. As shown in Fig. 1, the frame can optionally be divided into active (comprising of CAP and CFP periods) and inactive portions, as described above for IEEE 802.15.4.

IV. PERFORMANCE COMPARISON

A. System setup

TABLE I
CONSIDERED SNs AND THEIR SPECIFICATIONS

Node #	Bit Rate	Packet Rate	Sensor Type	Position
SN1	32 kbps	38.08 pps	Pulse oximetry	Earlobe
SN2	3 kbps	3.57 pps	Heart rate	Lower arm
SN3	0.02 kbps	0.02 pps	Temperature	Shoulder
SN4	2 kbps	2.38 pps	Glucose level	Thigh
SN5	0.01 kbps	0.01 pps	Blood pressure	Upper arm

TABLE II
CHANNEL PATH LOSS CORRESPONDING TO THE DIFFERENT SNs

Node #	Path loss
SN1	-58.2 dB
SN2	-55.5 dB
SN3	-55.6 dB
SN4	-53.0 dB
SN5	-57.0 dB

We consider a WBAN consisting of six nodes in a star topology, with one node serving as CN, which has the role of MAC control and data collection from five sensor nodes (SN). Optical transmission is done in the infrared band. Table I shows the considered sensors, their typical placement on the human body, and their data generation rates, used in our simulations [1]. The shown packet rates are used for Castalia simulations given that the corresponding packet size used is 105 bytes. In addition, the considered channel path losses between the CN and the SNs are shown in Table II. These data are taken from [7, Table 4], and correspond to the infrared channel loss for the case where the CN is located on the hip of the user of 1.7 m height, who is in a stationary position (i.e., without movement) for the sake of simplicity, in the middle of a $(5 \times 5 \times 3)$ room and the LEDs used for signal transmission are at 850 nm wavelength and of Lambertian order 1 (see [7] for more details on the simulation parameters).

To use the Castalia simulator, we managed to match the simulations with the optical equivalents for IEEE 802.15.4 and 802.15.6 protocols in order to investigate the two MAC protocols in an optical communication scenario. We have presented in Table III the parameters that we have modified in the Castalia simulator.[1] The considered battery energy for both CN and SNs is 27000 joules, which corresponds to two AA batteries. For the 802.15.7 protocol the CFP is activated by turning on the GTS, by using the corresponding command in the terminal. For the 802.15.7 standard, we have considered the PHY II case with data rates of tens to hundreds of kbps, which matched well the considered WBAN scenarios. Also, the relevant random access method for our case is the beacon-enabled random access slotted with CSMA/CA (see Subsection III-C). For 802.15.6, the choice of the PHY layer scheme (see Subsection III-B) does not influence the results as

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[1] Parameter modification can be done in the Castalia C++ or .ned files. For some specific parameters, like the output power, one has also to change the acceptable values in the corresponding configuration file. Using a terminal and some specific commands explained in the available manual, the results were saved into text files before being analyzed. Concerning the simulator installation, it is worth mentioning that the simulator is rather old and has been developed using specific versions of libraries and software. For this reason, one has to install first the right Ubuntu distribution, the correct library versions and some adjustments in the python files used for script execution.

TABLE III
SIMULATION PARAMETERS USED IN CASTALIA

Simulation time	5001 sec
Channel temporal variance	None
Tx output optical power	12 dBm
PHY data rate	2250 kbps
Rx sensitivity	-57 dBm
Rx power consumption	1.62 mW
Initial (battery) energy	27000 joules

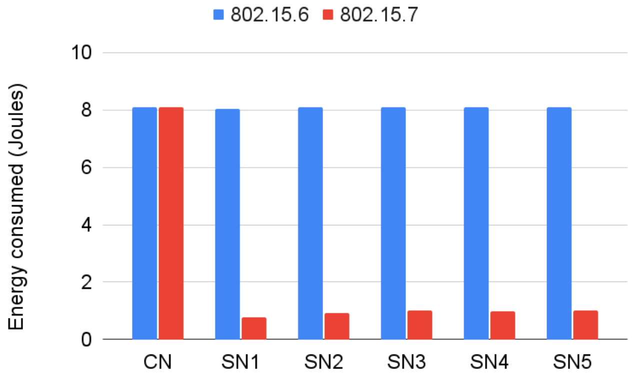

Fig. 3. Comparison of total energy consumption per node (in Joules) during the simulations for IEEE 802.15.6 and 802.15.7 standards.

we only use the MAC layer protocol here, which is the same for the three supported PHY schemes [21].

B. Numerical results

1) Energy consumption: In Fig. 3, we have presented the energy consumption per node during a simulation time of 5001 sec. At first glance, we notice the superiority of the 802.15.7 standard which achieves much less energy consumption for all SNs. Meanwhile, the energy consumptions of the CNs are almost identical, and very close to those of SNs for 802.15.6. If we define the network lifetime as the time period until one of the nodes runs out of energy, the two protocols perform almost in the same way; the estimated network lifetime by Castalia is about 193 days.

To understand better the relatively high energy consumption by SNs in the case of the 802.15.6 protocol, we should notice that it consists of contention periods, during which collisions occur, which in turn, necessitate re-transmissions, thus, the increased energy consumption. In contrast, the 802.15.7 has a hybrid MAC protocol, consisting of contention and contention-free periods, which results in less collisions, thus, a lower energy consumption of the SNs (as we will show later at the end of this section).

2) QoS: The QoS here is considered based on both network latency and packet reception probability. Figure 4 compares the latency for the transmitted packets for the two protocols, where the y-axis indicates the number of packet transmissions which have been delayed for the corresponding time period on the x-axis. We notice that 802.15.7 performs better as most of the packets are received within a relatively shorter delay.

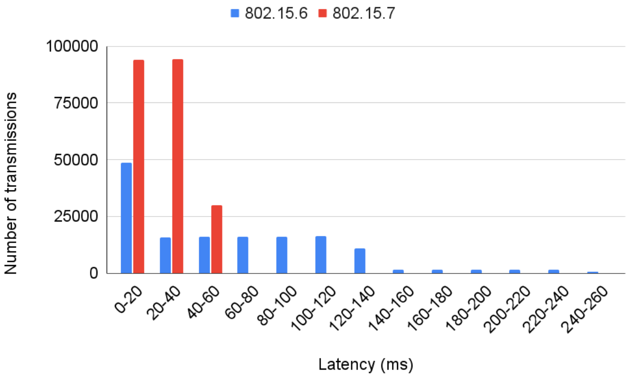

Fig. 4. Comparison of application-level latency (in ms). The y-axis represents the number of packets. (There are still a few packets received with longer delays, which are negligible and therefore not shown in the figure for the sake of illustration clarity.)

TABLE IV
NUMBER OF PACKETS SENT FROM SNS TO THE CN.

	SN1	SN2	SN3	SN4	SN5
802.15.6	124186	17880	102	10017	51
802.15.7	190910	18199	102	10201	52

In order to compare the packet reception probability (PRP) for the considered protocols, we have shown in Tables IV and V, the corresponding numbers of packets sent from the SNs to the CN, and those effectively received at the CN, respectively. Note that the data rates are the same for both protocols, as specified in Table I. Also, the same simulation time was set with Castalia (5000 seconds). It is worth mentioning that the difference between the numbers of effectively sent packets in Table IV is due to the difference in the superframe structures, see Figs. 1 and 2, and the fact that 802.15.6 uses contention slots with CSMA, whereas 802.15.7 uses CSMA only in the CAP periods (see Section III). As a result, the former protocol incorporates longer waiting times, resulting in a lower number of transmissions.

Based on these results, the PRP corresponding to i^{th} SN is calculated as:

$$\text{PRP}_i = P_{r,i}/P_{t,i}, \tag{1}$$

where $P_{r,i}$ is the number of effectively received packets by the CN and $P_{t,i}$ is the number of packets sent by the i^{th} SN during the simulation interval. We have compared in Fig. 5 the PRP for different SNs, where we notice the advantage of

TABLE V
NUMBER OF PACKETS RECEIVED BY THE CN FROM SNS.

	SN1	SN2	SN3	SN4	SN5
802.15.6	122880	16641	83	9175	40
802.15.7	190396	17848	99	9999	49

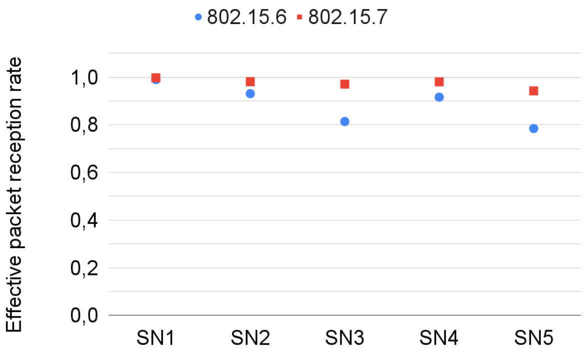

Fig. 5. Comparison of packet reception probability per node.

TABLE VI
NUMBER OF PACKETS SENT FROM SNS TO THE CN DURING CAP AND CFP SUPERFRAME PERIODS FOR IEEE 802.15.7.

	SN1	SN2	SN3	SN4	SN5
Contention	20440	3317	61	1746	2
Contention-free	170470	14882	41	8455	50

802.15.7 over 802.15.6. Indeed, the latter protocol does not manage to handle packet reception as efficiently as 802.15.7 and, consequently, experiences more packet loss due to experiencing greater interference issues. For instance, for 802.15.6 the total number of packets that fail to arrive at the CN because of collisions is 3417 compared with 1073 for 802.15.7.

One can get more insight into packet reception using further output from Castalia simulations. For instance, there is a small loss of 11 packets because of synchronization problems for 802.15.6, which is not the case for 802.15.7. Furthermore, for both protocols, a number of acknowledgement (ACK) messages from the CN do not arrive at the SNs, either because the actual message does not arrive at the destination or the ACK message faces a collision itself. For example, SN1 fails to receive 32 control and ACK messages when using 802.15.7, compared with 789 control and ACK messages when using 802.15.6, based on the Castalia results.

To further explain these results, we should note that, as stated in Subsection III-B, 802.15.6 relies on contention for the channel access, and as a result, packet collisions result in degraded QoS and increased energy consumption. However, the 802.15.7 protocol is more robust in terms of interference management, due to the use of CFP periods in the MAC superframes in addition to CAP interval, see Fig. 1. To illustrate this in more detail, we have presented in Table VI the numbers of transmitted packets from the SNs to the CN for the case of 802.15.7 during CAP (contention) and CFP (contention-free) periods, where we can see that most packets are sent during the CFP periods. Note, for 802.15.6 all transmissions happen in the contention mode.

V. CONCLUSION AND DISCUSSIONS

In this paper we presented a comparative study in order to evaluate the suitability of the MAC protocols of two IEEE standards, namely 802.15.6 and 802.15.7, for managing MA in a medical WBAN. We focused on the two main criteria of energy efficiency and QoS in terms of network latency and effective packet reception rate, which were investigated using the Castalia simulator, with parameters adapted to the case of optical wireless connectivity. Although the estimated network lifetime is roughly the same for both protocols, 802.15.7 performs better in terms of energy efficiency of SNs, which are the most difficult to replace. In terms of QoS on the other hand, although 802.15.6 promises shorter latency, 802.15.7 manages contention in a better way. Given that the MAC layer of the 802.15.13 is similar to 802.15.7, the same robustness against packet collisions is expected, making it a promising candidate for the new generations of optical WBANs.

Our future work will consider the implementation of these protocols and their further optimization to improve both energy efficiency and QoS for an optical WBAN, and study the trade-off between complexity, energy consumption, and QoS.

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