T4PW: TSCH in WBAN for Real-Time Monitoring of Pregnant Women

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Abstract. Most developing countries are face to a deficit of doctors and qualified medical staff. This situation poses a real problem for population, especially pregnant women who are at a much greater risk. The use of biosensors can be an alternative solution to overcome these deficiencies. This article presents a new protocol called T4PW (TSCH For Pregnant Woman). T4PW uses the Wireless Body Area Networks (WBANs) and is based on 802.15.4e TSCH standard. Our new protocol aims to provide a real-time remote monitoring to pregnant woman during the pregnancy period and at childbirth. The woman health state is determined from the values measured by the biosensors. Several slotframe templates are proposed according to the health status and the 802.15.4e default timeslot length is reduced.

Keywords: Network · Biosensors · Health · T4PW · 802.15.4e · TSCH · QoS · WBAN

1 Introduction

Most developing countries fall below the WHO (World Health Organization) standards for the minimal threshold of doctors, midwives and nurses per population. Countries below this threshold struggle to provide required healthcare to their population. In addition to that, the distribution of the health staff often reveals significant disparities between regions. Furthermore, most health structures do not have an adequate technical platform and often staff have limited expertise and skills to properly analyze and diagnose some medical conditions.

This deficit of health workers causes many problems to the population, especially pregnant women. Often, pregnant women residing in some areas must make displacement (sometimes long distances) to regions to receive healthcare services. WHO recommends [1] women to consult their health providers at least 8 times during pregnancy to identify potential problems, manage them and reduce the risk of death or neonatal death. Frequent and quality consultations for all women during pregnancy [2] will facilitate the application of preventive measures and the early detection of risks, avoid complications as much as possible, and help to overcome health inequalities. Unfortunately, most

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pregnant women are not able to comply with these recommendations due to the issues mentioned above.

Another problem arises during childbirth, where midwives do not always have all the physiological information about the woman. For example, childbirth often causes bleeding and unfortunately most women don't know their blood type. Unfortunately, the time required for a blood test and a laboratory analysis to determine the blood type is often quite long, which usually leads to loss of life.

To provide a solution to the problems mentioned above and ensure a continuous real-time monitoring of pregnant women (during pregnancy period and at childbirth), we propose a new protocol called T4PW (TSCH for Pregnant Woman). T4PW is based on the IEEE 802.15.4e TSCH (Time Slotted Channel Hopping) standard. TSCH is an amendment of IEEE 802.15.4e and uses a mechanism of channel hopping that permit access for multiple devices and avoid the cross-technology interference, which can decrease the network reliability. Our protocol T4PW uses a Wireless Body Area Network (WBAN) which [3] is a kind of wireless network composed of biosensors worn by the patient to collect his/her health information such as vital signs.

In IEEE 802.15.4e TSCH network [14], all nodes are synchronized. The time is subdivided into equal interval called timeslot and a succession of timeslot represents a slotframe.

The medical data transmission, required time constraints. The data must be transmitted with low latency times. Also, WBAN networks use a wireless link and can be subject to interference that can affect the performance.

Taking these constraints into consideration, T4PW inherits all the advantages of TSCH, while adding several improvements. To achieve this, several health states are defined for the measurements taken by the biosensors. Then, in order to provides the appropriate medical information, T4PW can dedicate a number of slotframes depending on the health status of the pregnant woman. To reduce the transmission latency, T4PW shortens the timeslot length of the IEEE 802.15.4e TSCH standard by eliminating individual acknowledgments which are to be replaced by cumulative acknowledgment.

The rest of the document structured as follows: Sect. 2 described in detail the IEEE 802.15.4e TSCH standard. Section 3 discusses some related works. Section 4 presents the detailed operation of T4PW. And, finally, the document ends with simulation results and a conclusion.

2 Overview of 802.15.4e TSCH

The IEEE 802.15.4e TSCH, published [4, 5] in 2012, was design to improve the IEEE 802.15.4 standard (2011) Medium Access Control (MAC) protocol. The main objective of the new design was to to improve the IEEE 802.15.4 standard performance in two main fronts: latency and reliability. It does this by operating multiple channels simultaneously. In the TSCH design, IEEE 802.15.4 nodes are allowed to support many applications including industrial ones. TSCH integrates a technique that uses time synchronization and channel hopping to ensure low-power operation, reliability robustness, reliability, availability and security. This integration of frequency hopping and the uses of Time Division Multiple Access (TDMA) [4, 6] makes the network robustness against effects such as noise, interference, and multipath fading.

2.1 TimeSlot

In TSCH, time is divided into [7] fixed periods that are called timeslots. The timeslot, [8, 12] typically 10 ms long, is a sufficient interval of time needs to ensure the following functionalities: the transmission of a data frame from the sender to the recipient, the reception of an acknowledgment to inform the sender that the frame has been successfully received, the operations required for security and the turning the radio to on or off. Each frame is [13] composed by application data (the payload) and information needed to identify it in the network. The maximum size is 127 bytes. TSCH network defines a default a Timeslot Template Structure that is illustrated in Fig. 1.

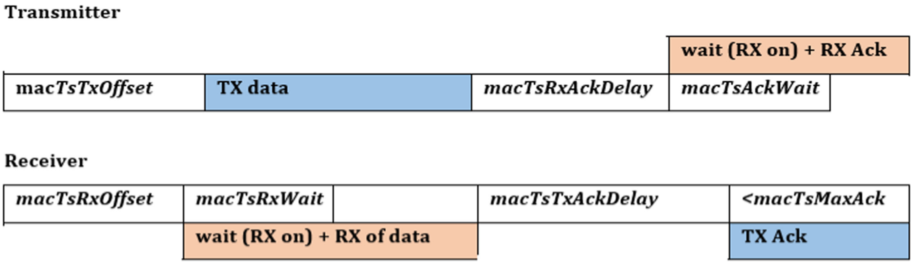

Fig. 1. Default timeslot template

By default, for all transmitted data, acknowledgment is expected. In a timeslot, data is transmitted by the transmitter after macTsTxOffset from the beginning of the timeslot. The receiver waits macTsRxOffset and then goes into receive mode, and starts listening for incoming data for macTsRxWait. If no data has not received from the transmitter after macTsRxWait, the receiver may turn off its radio. After transmitting the data, the transmitter waits macTsRxAckDelay and then enables the receiver mode to await the acknowledgment from the receiver. Once the data has been received, the receiver waits macTsTxAckDelay and then sends an acknowledgment to tell that the packet is successfully received.

2.2 SlotFrame

A slotframe [8] is a succession of timeslots that automatically and periodically repeats over the time. Each node knows the necessary information about the network by receiving the EB (Enhanced Beacon) message sent by the coordinator. The message contains all the required information for a device to be synchronize with the network. This information specially concerns the channel hopping and the timeslot structure. TSCH does not require [4] a fixed length for slotframe. This length must be adapted according to the needs of the application. The slotframe size [5, 8] depends on the application needs.

2.3 TSCH Node Scheduling

Communication between the nodes [8] is done according to a scheduling strategy that is composed by several cells in the form of a mathematical matrix. The number of timeslots represents the rows and the columns are determined by the number of the channelOffset. During a timeslot a node can transmit, receive, or sleep as details below:

- transmit: for this, the device checks on its buffer if a matching corresponding to the scheduling is found. If yes the device sends the data. Otherwise, the device turns off its radio (sleep) to save power.
- receive: the device puts itself into listening mode and waits for incoming data. If a packet is received, the device generates an ACK to confirm the success reception. Otherwise, it turns off his radio (sleep) as before.

We have different types of cell communication with TSCH [8, 9]:

- Dedicated: 2 nodes (transmitter/receiver) can exchange information without collisions. Nodes that are not affected may turn off they radio.
- Shared: the same timeslot can be used by one or several devices to send data. With this mode, collisions can occur.
- Free: any node is assigned to a free cell: it is an available resource for scheduling.
- Advertisement: cells are dedicated for sending synchronization frames or Enhanced Beacons. The broadcast Transmissions is use.

2.4 Channel Hoping

TSCH standard [8, 9] uses 16 channels for communication numbered from 0 to 15 that defines the channelOffset. A communicating between devices is represented by a combination of slotOffset and channelOffset. The frequency is determined as follow (1).

$$f = F[(ASN + channelOffset)\%Nchannels] \tag{1}$$

where, NChannels and ChannelOffset represent respectively the available channels and the channelOffset; ASN (Absolute Slot Number) defines the timeslot counter executed since the network is set up (when network is launched for the first time, the ASN is fixed to 0. After each timeslot, the value is incremented by 1. The de-vices obtain the current value through the EB message); and F defines the available channels that can be use.

Figure 2 descripts an example of SlotFrame with 28 timeslots length.

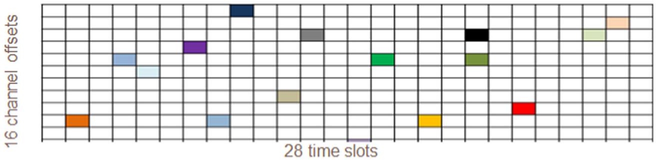

Fig. 2. Example of SlotFrame

3 Related Works

Despite its recent publication, IEEE 802.15.4e TSCH has been subject of many research studies recently.

Rasool Tavakoli et al. [7] presented a new template of timeslot named hybrid timeslot. With their solution, each timeslot is dedicated to one node and at the same time shared by other nodes. Before using the channel, the none-owner nodes must wait Δt to be sure that the dedicated node is not sending or receiving. If the dedicated node is active (sending or receiving), none-owners cancel their planned transmission. Otherwise, they can use the channel. As a consequence, the hybrid timeslot has a length greater than the default length of TSCH.

In Ref. [10] the authors worked on the use of a heart rate sensor for monitoring patients. They consider that the amount of generated data is determined by the health status of the patient to be monitored. The more the patient health status becomes critical, the more the quantity of generated data increases. To manage this variation of data, they improve the use of TSCH by proposing a dynamic allocution for timeslot. When data increase, they allocate additional timeslots to the concerned node. When the status returns to normal, the coordinator recovers the additional allocated timeslots.

After arguing that the existing planning approaches in IoT sensor systems fail to satisfied the different requirements, the authors of [10] propose an adaptive scheduling algorithm (PASA) for quality of service (QoS) of heterogeneous applications. The service cycle (ST) of each node is managed adaptively according to several criteria like priority traffic (RP) that is calculated based on data throughput and delay requirements. As the priority becomes high, so does the corresponding ST.

This article in [11] presents a slotframe partitioning-based cell scheduling (SPCS) planning procedure. SPCS is based on the IEEE 802.15.4 TSCH standard. It subdivides a slotframe into several subframes of different sizes and the allocation of these partitions is determined by the depth of a node and the number of slotOffsets required for each partition. SPCS uses a network information table (NIT) containing all the routing information for all sensor nodes allowing the root to have all the information concerning the network.

In Ref. [6] the authors made a detailed study of several communication protocols used in WBAN network. They also explain the importance of using the standard TSCH technology in WBANs due to its operation based on TDMA and channel hopping, in addition of inheriting of basic advantages offered by the 802.15.4 standard such as resilience low noise. WBANs uses wireless communication and operate on the same frequency band (2.4 GHz) as many other devices. With this constraint, working with a protocol using a single frequency channel can cause interference. This situation can lead to a loss of synchronization for biosensors and can impact on the performance of application and increase energy consumption and latency time with packet retransmissions. The use of several channels is a solution to avoid interference. The results of its simulations show good performance for TSCH in WBAN networks.

4 T4PW Operation

T4PW is based on the 802.15.4e TSCH standard. T4PW provides a regular monitoring to pregnant woman by providing a real-time communication between the biosensors and the coordinator. In T4PW, our Wireless Body Area Network (WBAN) uses 6 biosensors (blood pressure, blood glucose, blood type, oxygen saturation, temperature, pulse). The biosensor for blood group will not be permanently worn by the woman. Since it's a factor with a static value. Each biosensor measures a physiological parameter and processes the data for use by the medical staff. The data measured by the biosensors are transmitted to the coordinator. The coordinator collects all the data coming from the different biosensors and acts as a gateway for outside.

Figure 3 shows the woman with the biosensors and the coordinator.

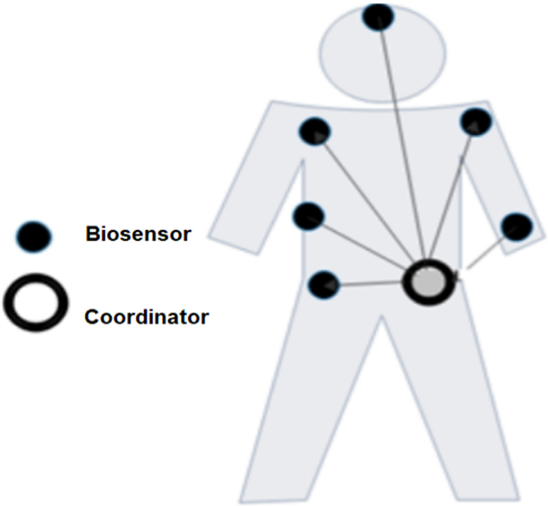

Fig. 3. Woman with biosensors

4.1 Data Classification

For each biosensor, in collaboration with a doctor, a range of values is defined to indicate the health status of the pregnant woman.

The following Table 1 shows the thresholds set for each class:

The class 1 corresponds to the normal thresholds. The class 2 refers to weakly critical data. The class 3 shows critical data. The class 4 corresponds to very critical data. This classification is used to determine the health status of the pregnant woman.

The normal status refers to the situation in which all values are in class 1. Therefore, the status health of the woman presents no abnormality.

The weakly critical status: at least one measured value belongs to class 2 and no value belongs to classes 3 and 4.

Table 1. Data classification

Type	Class 1	Class 2	Class 3	Class 4
Blood pressure	$7 \leq D \leq 8$ and $12 \leq S \leq 13$	$6 \leq D < 7$ or $13 < S \leq 14$	$5 \leq D < 6$ or $14 < S \leq 15$	$5 < D$ or $S > 15$
Blood glucose (G) g/l	$0{,}7 \leq G \leq 1$	$1 < G \leq 1{,}1$	$1 < G \leq 1{,}25$	$G > 1{,}25$ or $G < 0{,}7$
Pulse (P) beats/min	$80 \leq P \leq 120$	$120 < P \leq 140$	$140 < P \leq 160$	$P > 160$
Temperature	$37.6^\circ \leq T \leq 38$	$38 < T \leq 39$	$39 < T \leq 40$	$T > 40$
Oxygen saturation (SO2)	$94 < SO2 \leq 99\%$	$94 < SO2 \leq 92$	$92 < SO2 \leq 90$	$SO2 < 90\%$

The critical status: at least one measured value belongs to class 3 and no value corresponds to class 4. This situation requires the intervention of the medical staff.

The very critical status: at least one measured value belongs to class 4. In such situation, an urgent intervention must be do.

4.2 Measuring Frequency

For each state, a measuring periodicity validated by a doctor is predefined. This periodicity indicates the interval time between 2 successive measuring for each biosensor. The following Table 2 shows the measuring frequency used for each state.

Table 2. Measuring frequency

Status	Interval between 2 measures
Normal status	F1 every 15 min
Weakly critical status	F2 every les 5 min
Critical status	F3 every minute
Very critical status	F4 every 30 s

We have a measuring sequence every 30 s when the woman's health status is very critical. At childbirth, the frequency F4 will be retained. The care during childbirth meets very precise monitoring criteria and requires careful monitoring of the woman.

4.3 T4PW Detail

Medical applications require real-time, availability and guarantees. A delay in intervention can lead to a loss of life. Medical staff must have all the required information, especially in urgent situations. Taking into account all these important factors, T4PW proposes to reduce the length of the timeslot which is by default equal to 10ms and SlotFrames with a duration of 15 min which corresponds to the maximum time interval between two consecutive measurements. The SlotFrame template is determined by the status health according to the measuring frequencies defined for each state. T4WP opted for dedicated timeslot to avoid collisions, so for a given timeslot only the dedicated biosensor can transmit.

T4PW TimeSlot Template

Since T4PW uses a network whose composition is determined beforehand, the number of nodes is known in advance, in other words for each measurement sequence, we know the number of packets that the coordinator must receive. So instead of sending an acknowledgment to each biosensor during its timeslot, the coordinator waits to receive all the data from the biosensors before responding to all of them with a broadcast message. Therefore, to reduce the transmission latency, T4PW eliminates the acknowledgment generation by the receiver. Consequently, the coordinator after receiving the data measured by a biosensor, will not send an acknowledgment and the transmitter which corresponds to the biosensor may idle the radio after sending its data, it does not wait for the reception of an acknowledgment. From the timeslot template, we can see that the time Δack required for the receiver to prepare and transmit an acknowledgment can be calculated as follows:

$$\Delta\text{ack} = \text{ macTsTxAckDelay } + \text{ macTsMaxAck}. \tag{2}$$

The corresponding values [15] are respectively 1 ms and 2,4 ms. Then we can deduce that

$$\Delta\text{ack} = 1\,\text{ms} + 2,4\,\text{ms} = 3,4\,\text{ms}. \tag{3}$$

Therefore, the T4PW timeslot length is obtained by:
IEEE 802.15.4e default length timeslot

$$\Delta\text{ack} \ = 10\,\text{ms} - 3,4\,\text{ms} = 6,6\,\text{ms} \tag{4}$$

T4PW SlotFrame Templates

After any measuring, the coordinator dedicates a timeslot TS with the length 6,6 ms to each biosensor for transmission of his data. In total 5 timeslot are granted. For a given timeslot, the biosensors that are not concerned turn off their radio to save energy. The first timeslot is reserved for sending the EB (Enable Beacon) by the coordinator to biosensors. After receiving the EB, each biosensor has information about when to transmit, receive or sleep.

After having received all the data from the biosensors, the coordinator generates and sends a broadcast message EB + to all the biosensors. The 7th timeslot will be used for sending this EB + broadcast message. So all the biosensors must wake up on the 7th timeslot to receive the EB + and check if their transmission during their dedicated timeslot was successful. Each biosensor that the coordinator has not received its package during its dedicated timeslot, will be allocated another TS + (timeslot +) for the retransmission of its package. A biosensor that has not benefited a TS + will know that its transmission was successful.

The retransmission is proved to improve the performance of T4PW by reducing packet error rates. This makes T4PW more stable.

The EB + is also used by the coordinator to inform the biosensors about the time of the next measuring. This can help to intervene more quickly in critical situation. For example, a very critical status can occur suddenly after a normal. With the sending of EB +, biosensors will be informed that the next measuring must be taken in 30 s. To ensure the permutation between the different SlotFrames templates, after each measuring sequence, the coordinator checks if the health status has changed. If yes, the template corresponding to the new state is loaded otherwise the coordinator continues with the template of the current SlotFrame.

To represent the different templates defined for SlotFrames, we consider the following parameters:

- Biosensors are numerated from S1 to S5.
- C defines the coordinator.
- T means that the biosensor is in transmission mode.
- R means that the biosensor is on receiving mode.
- Seq represents a measuring sequence.

Normal Status

In this status only one measuring is taken by the biosensors throughout the duration of the SlotFrame (Fig. 4).

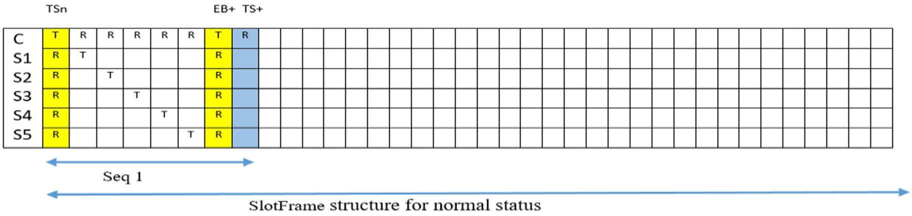

Fig. 4. SlotFrame template for normal status

Weakly Critical Status

In this state, the biosensors can take 3 successive measuring at regular intervals of 5 min during the SlotFrame (Fig. 5).

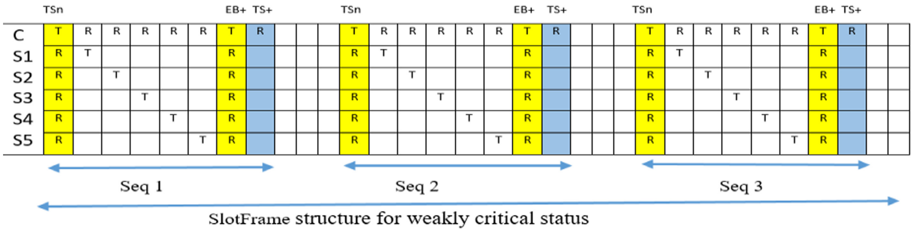

Fig. 5. SlotFrame template for weakly critical status

Critical Status

Measuring should be done every minute. SlotFrame can support 15 measuring sequences numbered from Seq1 to Seq15 (Fig. 6).

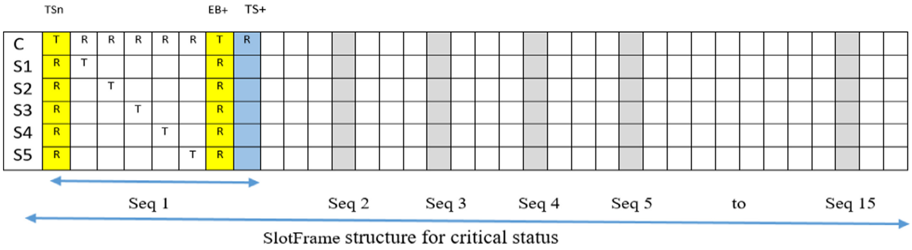

Fig. 6. SlotFrame template for critical status

Very Critical Status

Measuring become more frequent. The coordinator must allocate timeslots every 30 s. This allows to get 30 measuring sequences numbered from Seq1 to Seq30 (Fig. 7).

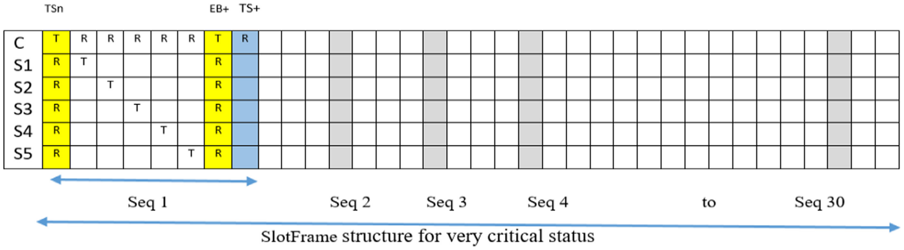

Fig. 7. SlotFrame template for very critical status

5 Performance Evaluation

This section presents the performance of the T4PW protocol in comparison with the traditional IEEE 802.15.4e TSCH.

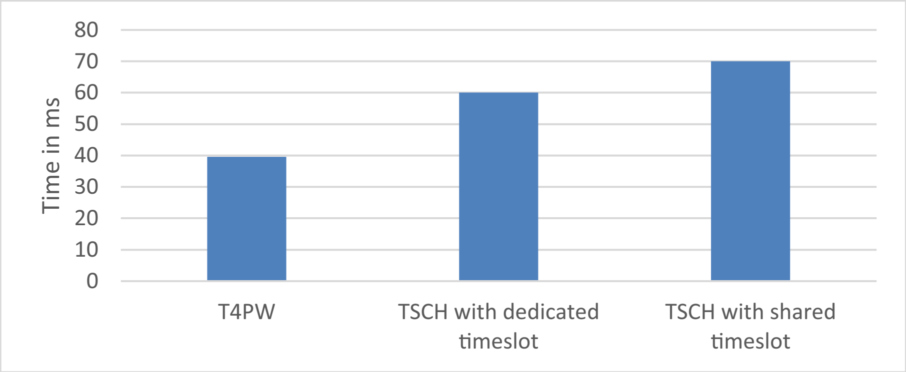

Fig. 8. Time use by each protocol for 1 sequence

This Fig. 8 compares the time used by each protocol for 1 sequence, to allow all biosensors to transmit their packet. We observe that the time uses by T4PW is less than the 802.15.4e TSCH time.

This Fig. 9 illustrates the average time required for retransmission in situation where packet loss has occurred. By default, in TSCH, for dedicated timeslot, retransmission of packet waits until the next assigned transmit timeslot occurs. For shared timeslot, a sender waits for the arrival of the first shared link to retransmit. For our case, we suppose that the dedicated TSCH timeslot uses an EB + which informs a biosensor when to retransmit.

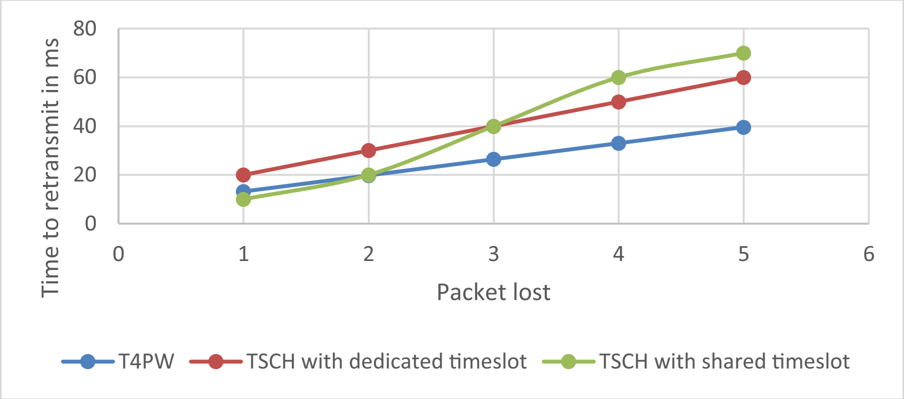

Fig. 9. Time average to retransmit packet loss

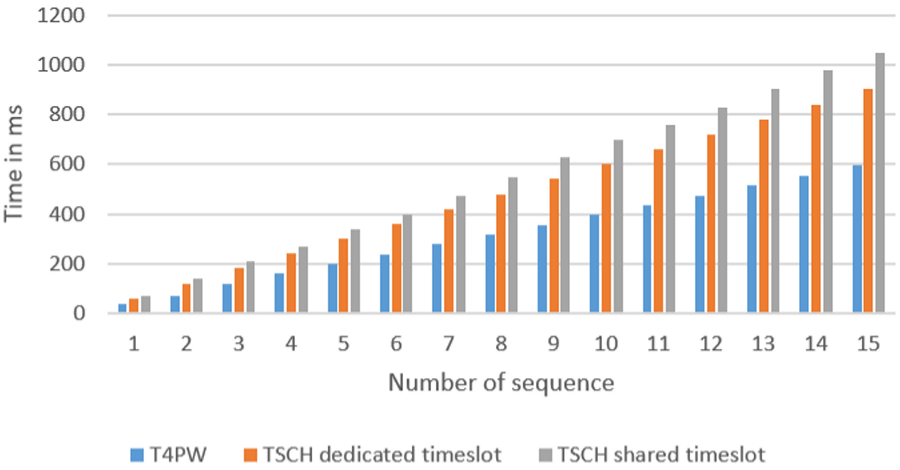

Fig. 10. Average time to send respectively 15 measurements sequences

In this Fig. 10, we have the evolution of the average time required to send respectively the 15 measurement sequences corresponding to the critical state. Through this figure, we can observe that the average delay for the proposed protocol T4PW is far less than that the 802.15.4e TSCH.

Technology grows so fast, T4PW takes account the scalability. Thus with T4PW, the coordinator can allocate additional timeslots in situation where other biosensors need to be integrated. This graph shows the evolution according to the number of deployed biosensors (Fig. 11).

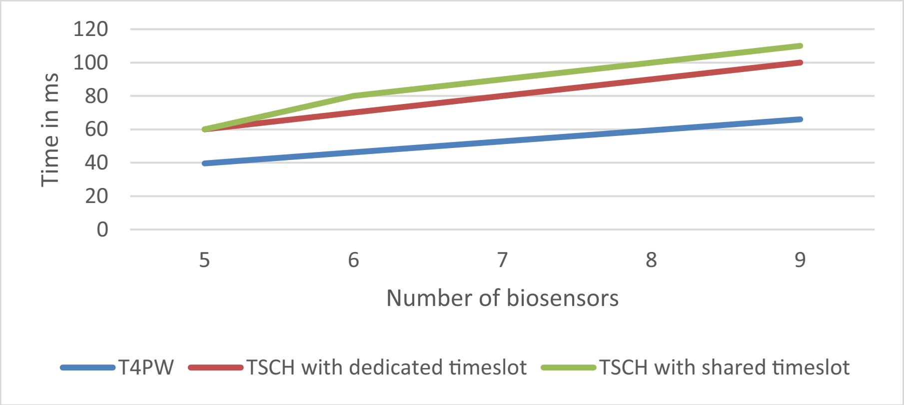

Fig. 11. Evolution time transmission according to the scalability of number of biosensors

6 Conclusion

The effective use of biosensors can participate to the development, by providing quality care to pregnant women. In this paper, we proposed a new protocol called T4PW. This protocol is based on the 802.15.4e TSCH standard and provides SlotFrames whose templates are determined by the health status of the pregnant woman to be monitored. To reduce the transmission delays, the default timeslot length proposed by the 802.15.4e TSCH standard has been reduced. Simulations results show that T4PW offers lower latency times than 802.15.4e TSCH.

References

1. OMS, Santé de la mère et des enfants: 10 moyens d'améliorer la qualité des soins. 17 février 2017
2. OMS, Les femmes enceintes doivent pouvoir bénéficier de soins adaptés au bon moment, 7 novembre 2016
3. Pushpan, S., Velusamy, B.: Fuzzy-Based Dynamic Time Slot Allocation for Wireless Body Area Networks, 7 May 2019
4. Hissein, M.H.S.: Etude et prototypage d'une nouvelle méthode d'accés aléatoire multi-canal multi-saut pour les réseaux locaux sans fil, 12 juillet 2017
5. Watteyne, T., Palattella, M., Grieco, L.: Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement, Internet Engineering Task Force (IETF), May 2015
6. Veisi, F., Nabiy, M., Said, H.: An Empirical Study of the Performance of IEEE 802.15.4e TSCH for Wireless Body Area Networks
7. Tavakoli, R., Nabi, M., Basten, T., Goossens, K.: Hybrid Timeslot Design for IEEE 802.15.4 TSCH to Support Heterogeneous WSNs
8. Hammoudi, S., Aliouat, Z., Harous, S., Louail, L.: Time slotted channel hopping with collision avoidance. Int. J. Ad Hoc Ubiquitous Comput. (2018)
9. Morin, E.: Interopérabilité de protocole de communication adaptatifs basse-consommation pour des réseaux de capteurs, HAL Id: tel-01903194 (2018)
10. Ngo, M.V., La, Q.D., Leong, D., Quek, T.Q.S.: User Behavior Driven MAC Scheduling for Body Sensor Networks
11. Kwon, J.-H., Kim, E.-J., Kim, D.: Slotframe partitioning-based cell scheduling for IEEE 802.15.4 time slotted channel hopping. Sens. Mater. **31**(5) (2019)
12. Duquennoy, S., Nahas, B.A., Elsts, A., GOikonomou, A.: TSCH and 6TiSCH for Contiki: Challenges, Design and Evaluation (2017)
13. Gaillard, G.: Opérer les réseaux de l'Internet des Objets à l'aide de contrats de qualité de service (Service Level Agreements) (2016)
14. Shi, K., Zhang, L., Qi, Z., Tong, K., Chen, H.: Transmission scheduling of periodic real-time traffic in IEEE 802.15.4e TSCH-Based Industrial Mesh Networks, September 2019
15. IEEE-SA Standards Board, IEEE Standard for Low-Rate Wireless Networks (2015)