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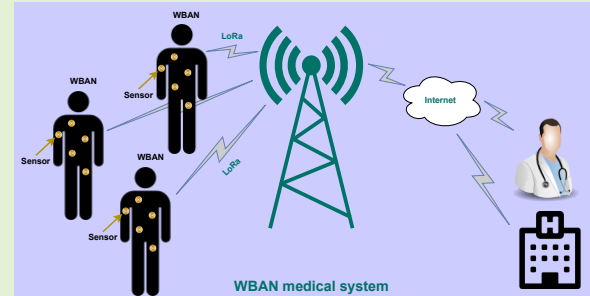


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# Energy consumption improvement of a healthcare monitoring system: application to LoRaWAN

H. Taleb, A. Nasser, G. Andrieux, N. Charara, E. Motta Cruz

**Abstract**—Recent advances in wireless communication technologies are having a great impact on people’s life, especially in the field of healthcare industry that provides a remote monitoring enabling medical staff to follow up the patient and diagnose his disease. LoRa wireless technology is becoming one of the most energetic effective solutions for Wireless Body Area Networks (WBANs) communications. In this work, we propose a LoRa-based low power healthcare WBAN platform called *HeaLoRa* for an adaptive patient monitoring process. Physicians can remotely monitor patient’s temperature, oxygen saturation level, blood pressure and heart rate to prevent any abnormality. Moreover, data acquisition and transmission are controlled based on a power consumption optimization strategy aiming to reduce redundant data. Based on the Early Warning Score (EWS), the system configuration is dynamically adapted, using a Fuzzy logic controller that makes the decision about the system sleep mode duration and the sent data rate. Furthermore, an analytical model of the energy consumption for acknowledged LoRa transmission is presented in this paper. The graphical abstract of the paper illustrates a medical application of a wireless body area network system where LoRa technology is used to transmit the data to a gateway then the data is transmitted to the doctor using IP based technology. By comparing with a reference system, the simulation results indicate that our system consumes 3 to 10 times less of energy depending on the studied scenario.



**Index Terms**—EWS, Fuzzy expert system, IoT, LoRa, LoRaWAN, LPWAN, Medical applications, Sensors, WBAN, Wireless Technologies.

## I. INTRODUCTION

IN the recent years, Internet of Things (IoT) based systems have been executed using wireless technologies such that WiFi, Bluetooth and ZigBee, with limitations in terms of number of connected devices, range and energy consumption. In addition, the 2.45 GHz band is now very crowded, which leads to a negative impact on the reliability of communications. The Sub-GHz bands including 433, 868 and 915 MHz are the emerging alternative to the 2.45 GHz ISM band for IoT applications [1]. Recently, Low Power Wide Area Networks (LPWAN) technologies become very popular due to their long range, energy efficiency and low cost. Table I represents the characteristics of several wireless technologies for IoT applications, namely, BLE [2], ZigBee [3] [4], WiFi [2],

SigFox [5], Lora [6] and NB-IoT [7]. Compared to Sigfox and NB-IoT, LoRa is the most widely used LPWAN technology where it is deployed in many countries. In addition, LoRa was adopted in our work due to the high communication range. LoRa provides the highest receiver sensitivity with lower power consumption compared to other LPWAN technologies [8] [7]. Moreover, LoRaWAN, the networking protocol of LoRa, is an Open Standard unlike Sigfox and NB-IoT which facilitates the widespread deployment of this technology. In addition, LoRaWAN has the less equipment and installation cost [9]. Furthermore, LoRa is highly immune to interference and its data rate is adapted dynamically according to the employed Spreading factor ( $SF$ ) [7]. In fact, Sigfox technology was excluded from this work due to lack of acknowledgment signals for all uplink messages [10]. This drawback is highly risky for medical applications, especially in critical cases. Compared to NB-IoT, LoRa is selected because LoRa devices consume less power providing longer battery life [11]. Thanks to all these reasons, LoRa is a good network technology choice for the communications between the WBANs and the medical center (see figure 3) in our IoT based healthcare system.

The healthcare systems has taken a great attention aiming to monitor the physiological human body parameters, especially

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Houssein Taleb, Guillaume Andrieux and Eduardo Motta Cruz are with Nantes Université, CNRS, IETR UMR 6164, F-85000, La Roche sur Yon, France (Email: houssein.taleb@etu.univ-nantes.fr; guillaume.andrieux@univ-nantes.fr; eduardo.mottacruz@univ-nantes.fr).

Abbass Nasser and Nour Charara are with the ICCS-Lab, Computer Science Department, American University of Culture and Education (AUCE), Beirut, Lebanon (Email: abbassnasser@auce.edu.lb; nourcharara@auce.edu.lb).

with the spread of Covid-19 pandemic. In fact, the need of WBAN employment has increased in order to use the body sensors to collect data and then send them to the medical center. However, the sent data rate should be reduced to ensure a long life for the battery without losing the necessary information that indicates the patient's medical situation, especially in urgent cases [12].

A list of the acronyms frequently used in this work is given in table II.

TABLE I

THE MAIN CHARACTERISTICS OF BLE, ZIGBEE, WiFi, SIGFOX, LORA AND NB-IOT PROTOCOLS

Technology	Frequency	Data Rate	Range	Battery life
BLE [2]	2400 MHz	1 Mbps	10 m	1 year
ZigBee [3] [4]	2400, 868, 915 MHz	20 kbps, 40 kbps, 250 kbps respec- tively	100 m	weeks
WiFi [2]	2400 MHz, 5000 MHz	600 Mbps	100 m	hours
NB-IoT [7]	licensed bands (e.g., 700, 800, and 900 MHz)	200 kbps	1-10 km	up to 10 years
LoRaWAN [6]	433 MHz, 868 MHz, 915 MHz	50 kbps	2-20 km	up to 10 years
SigFox [5]	915 MHz, 868 MHz	100 bps	10-50 km	up to 10 years

TABLE II

FREQUENTLY USED ACRONYMS

Acronyms	Description
BLE	Bluetooth Low Energy
BW	Band Width
CR	Coding Rate
EWS	Early Warning Score
FIS	Fuzzy Inference System
IoT	Internet of Things
RL	Risk Level
SF	Spreading Factor
ToA	Time on Air
WBAN	Wireless Body Area Network

### A. Related work for health monitoring using LoRaWAN

Recently, the integration of new emerging wireless technologies in the medical systems has received a great attention from the industry and the research community [13], [14], [15] and [16]. Due to its wide range, power efficiency, and many other advantages, LoRa is one of the wireless technologies that could be used in healthcare systems to monitor patients. Hereinafter, we present some LoRaWAN based healthcare systems. The researchers in [17] present a monitoring system using LoRaWAN network where an oxygen saturation,

electrocardiogram, body temperature and pulse rate sensors are explored, followed by a statistical analysis to prove the efficiency of the system. In [15], the authors present a system performed by biomedical sensors that transmit health data to a cloud using a LoRaWAN network. It has been shown that during the transmission, more the distance is longer, more the power consumption increases. In order to minimize the number of healthcare visits and to reduce the communication cost, the work of [18] focuses on the monitoring of the body temperature, the blood pressure and the glucose level, where the collected data are sent to an analysis module via LoRaWAN network. The experiments have shown that a wide coverage area is achieved with a power consumption 10 times less than other long range cellular transmission. In [8], many sensors are used to monitor some environmental parameters that can affect the human health. The collected data are displayed on a graphical user interface and transmitted to a remote server through LoRaWAN network in order to send early warnings for unsafe people. The results have been shown that the system works reliably while consuming less energy. The sensors wake up each minute in order to monitor environmental data. These sensors can also be programmed to monitor continuously according to the users' requirements. In [19], a system that is distributed on three levels (sensors, IoT gateway and Internet cloud) was presented to achieve a safe working environment by reducing health risks of workers in the construction industry. The collected environmental and physiological data is transmitted via Bluetooth Low Energy (BLE), then transmitted using LoRa technology to a gateway. In [20], the paper proposes an energy efficient health monitoring system using LoRa for data communication. A remote health monitoring system is proposed for patients living in places where no Internet or health services are available. The proposed system in [21] aims to monitor the heart rate of a user in addition to its activity. The data is sent via BLE from a smartwatch to an IoT device, and via BLE from the IoT device to the user's smartphone. While information about user's state and its location is transmitted via LoRa technology from the IoT device to the gateway. In [22], the system aims to track and monitor a patient with mental disorder using LoRa technology for the communication between the end devices and the gateway. The doctor can then consult the server via a mobile application installed on his mobile using WiFi and mobile cellular networks.

### B. Contributions and organisation

Table III resumes the contributions of the related work presented in the state-of-the-art. Unlike the existing work, our paper aims to jointly study the performance of LoRa network for medical applications, the energy efficiency, and the data reduction effect of the energy consumption. The contributions of the paper can be summarized as follows:

- First, we investigated LoRa as wireless technology for healthcare data transmission. Due to the need of patient monitoring, the permitted number of transmissions and the energy consumption are considered as two criteria to assess the performance of LoRa.

TABLE III

WORK CONTRIBUTIONS OF SOME STATE-OF-THE-ART LORA BASED SYSTEMS.

Ref.	Study of LoRa performance	Data reduction	LoRa's energetic study
[17]	Yes	No	No
[15]	Yes	No	No
[18]	Yes	No	No
[8]	Yes	No	No
[19]	Yes	No	No
[20]	Yes	Yes	No
[21]	No	Yes	Yes
[22]	Yes	No	No
<i>HeaLoRa</i>	Yes	Yes	Yes

- Second, we proposed an energetic model that analyses the energy consumption of a LoRa wireless based system for healthcare applications.

- Third, we proposed the framework of an energy efficient IoT based healthcare system based on the EWS and using LoRa technology called *HeaLoRa* (Health-LoRa). *HeaLoRa* monitors human physiological parameters including body temperature, pulse rate, oxygen saturation level and blood pressure in order to identify the Risk Level (RL) of a patient and in order to detect any abnormal situation. *HeaLoRa* saves the patient's time by monitoring him remotely therefore reducing the physical presence frequency in hospitals, reducing the medical cost and increasing the hospital's capacity.

- Fourth, extensive simulations are performed in order to verify the energy efficiency for two scenarios: the first is monitoring a patient in normal medical situation and the second in abnormal situation. We investigate the impact of the *SF*, the *CR*, the *BW* and the collisions probability on the system's lifetime.

The rest of this paper is organized as follows. A review of LoRa and LoRaWAN technologies is presented in section II. The basic EWS system is described in section III. The architecture, hardware and the working mechanism of the system are presented in section IV. In section V, an analytical model is proposed to study the performance of the system and numerical results are provided. Finally, we conclude our work in the 6th section.

## II. LORA AND LORAWAN TECHNOLOGIES

In this section, we briefly discuss LoRa and LoRaWAN characteristics. This section is organized in two subsections. The first one provides a general overview of LoRa and LoRaWAN technologies, whereas the second subsection focuses on the physical layer functionality.

### A. LoRa and LoRaWAN overview

LoRa (Long Range) is a physical layer technology working on the ISM bands 433, 868 and 915 MHz [6]. We assume the use of the band 868 MHz for our analysis in this work. LoRaWAN is an LPWAN technology that provides wireless connection for IoT applications. The offered data rate may

vary from 0.3 to 50 kbps, which is an acceptable rate for the collected data in our healthcare system based on the LoRaWAN protocol [6]. Also, LoRa is convenient for our system due to its low cost, low power communication (where the duty cycle is limited to 1%), and the preservation of the data privacy. The range that reaches up to 20 km in rural regions and about 2 km in urban region is another reason for choosing LoRa. Note that an increase in the payload also increases the probability of losing messages due to collisions and interferences [23] [24].

A LoRaWAN network is formed of three basic elements including the end devices, the gateways and the network server [25] [24]. The gateway represents the link between the server and the end devices. End devices use the LoRa physical layer to exchange messages with the gateway, while the gateway forwards data to the network server via standard IP technology.

LoRaWAN specifications distinguish between three classes: A, B and C [6].

Class A: this class allows bidirectional communication between end devices and the network server, this communication is scheduled by the device based on its needs. In this class, each uplink transmission (from the end device to the gateway) is followed by two short downlink messages *RX1* and *RX2* called receive windows (from the gateway to the end device) as shown in figure 1. The duration of a receive window has to be equal to the minimum required time to effectively detect a down-link preamble [25]. Note that class A has the lowest power consumption.

Class B: the end devices in this class open additional receive windows (called ping slot) at a predictable time during a periodic time slot. The gateway initiates a downlink transmission by sending a beacon. Synchronization beacons are transmitted by network gateways once a time every 128 seconds. In order to acquire the beacon, the end device must keep its receiver on for at least one beacon period. When receiving the beacon, the end device initiates the transmissions and opens its receive window at the scheduled time (figure 1). All end devices start and join the network as end devices of class A. Then the end device application can then decide to switch or not to class B. The decision to switch between the two modes is left to the device's application layer. But the reception of the synchronization beacons and the ping slots may cause an additional increasing in power consumption compared to a class A device. Devices should implement a class B communication when there is a requirement to ensure low latency of downlink communication, while keeping the power consumption as low as possible.

Class C: in this class, receive windows are open continuously, only closed when transmitting. Class C end devices use more power to operate than class A or B but they offer the lowest latency for server to end device communication.

In this paper LoRaWAN class A will be studied in order to achieve a low power consumption and a long lifetime.

### B. Physical layer

LoRa is the physical layer for LoRaWAN. It is a spread spectrum modulation technique using the Chirp Spread Spectrum (CSS) technology. Each LoRa symbol is composed of

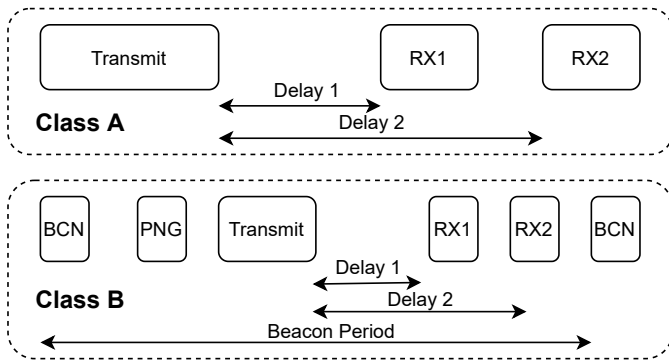


Fig. 1. LoRaWAN device classes A and B

$2^{SF}$  chirps ( $2^{SF}$  bits per symbol). Where  $SF$  is the Spreading Factor which varies between 7 and 12 providing different data rates. Beside the  $SF$ , LoRa has two others major configurable physical layer parameters, which are the BandWidth ( $BW$ ) and the Coding Rate ( $CR$ ). The SX1276 LoRa module used in this work has three optional bandwidths: 125, 250, and 500 kHz, where the smaller one is mostly required for coverage of longer distance and for the best receiver sensitivity while the higher one is usually used when faster transmission is required [20]. The  $CR$  is used for error correction as it is used in any wireless communication and signal-processing module [20]. The expression of the coding rate is given in the following equation:

$$CR = \frac{4}{4 + n} \quad (1)$$

$n$  varies from 1 to 4. The smaller the code, the longer the transmission time.

LoRa has a variable data rate depending on the parameters mentioned above. The expression of the LoRa's data rate is given by:

$$R_b = SF \times \frac{BW}{2^{SF}} \times CR \quad (2)$$

In figure 2, the physical layer message format is detailed. It begins with a preamble of symbols (typically, eight symbols), used to synchronize the receiver with the transmitter. The header field includes information about  $CR$ ,  $SF$ , etc. Header field also contains a Cyclic Redundancy Check ( $CRC$ ) field that allows receiver to ignore packets with an invalid header. After the header, LoRaWAN defines a MAC message carried in the physical payload field. The MAC message contains a MAC header which defines if the frame is a data or an acknowledgment, the protocol version and if the direction is an uplink or a downlink. It also contains a MAC payload which includes a frame header field containing the address of the device and other information, a port field, and finally the frame payload field includes the actual application payload. Note that the frame header has a bit to acknowledge the last received confirmed data message. Finally, the MAC message includes a Message Integrity Check ( $MIC$ ) which is the payload's digital signature. The MAC header has a minimal size of 13 bytes and 28 bytes for maximal size. In our work, the MAC header

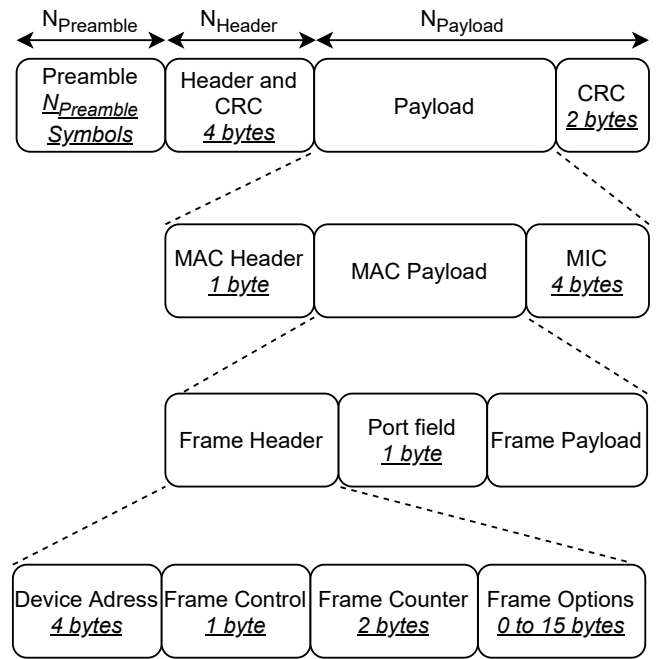


Fig. 2. LoRaWAN physical layer message format

is taken as 13 bytes. At the end of the frame, an optional  $CRC$  for error detection is sent only in case of uplink transmissions [20] [25] [26].

### III. EARLY WARNING SCORE (EWS)

EWS is a medical system using scores to determine the medical situation of patients in order to identify patients in need of urgent intervention [27] [28] [29]. Using EWS, we can determine the degree of criticality of a patient's medical situation, called score. After the determination of the score of each parameter, we can calculate the RL using the fuzzy toolbox of Matlab. The score varies between 0, indicating a normal situation, and 3 which indicates a very emergent situation. A high score corresponds to a high risk or critical medical conditions [30]. In this work, the EWS parameters used are the body temperature, the blood pressure, the heart rate and the oxygen saturation. As shown in detail in table IV, referring to EWS, the normal value of the body temperature is between 36.1 and 38°C. Any variation over or under these values leads to a variation in the score value where the score 1 is for a temperature between 38.1 and 39°C or between 35.1 and 36°C. Score 2 is for any temperature greater than 39.1 °C and score 3 is for any temperature less than 35°C. The normal heart rate which corresponds to 0 score is 51-90 bpm. This score varies to 1 if the heart rate is between 41 and 50 or between 91 and 110, 2 if it is between 111 and 130, and the score is 3 if the heart rate is below 40 or over 131. For the oxygen saturation, the 0 score is for a value equal or greater than 96 %, the score increases with the decrease of the percentage indicating a low level of blood oxygen which requires a medical review where it varies to 1 for a percentage between 94 and 95%, 2 if the percentage is between 92 and 93% and 3 if it is below 91%. For the blood pressure, the

optimal value indicating a 0 score is between 111 and 119, score 1 if it is between 101 and 110, 2 between 91 and 100 and 3 if it is below 90 or over 220. By adding the score of each measured parameter, we obtain the Modified Early Warning Score (MEWS) which indicates the patient's RL [31]. If the MEWS score is 0, it indicates that the patient is in normal case, a score greater than 0 indicates that the patient is in a risk zone. The RL increases with the increasing of the MEWS score [32]. In our work the RL is calculated using the fuzzy logic which is explained in the next section.

It is noteworthy that the medical requirements to be measured and analysed are variable according to the patient's situation. Furthermore, some medical parameters can be less or more serious referring to the medical case of each patient. In order to overcome this problem, the algorithm based on the National Early Warning Score (NEWS) values mentioned in table IV is dynamic and can be modified based on the patient case requirements.

TABLE IV  
THE EARLY WARNING SCORE "EWS"

Score	0	1	2	3
Oxygen Saturations	$\geq 96\%$	94-95%	92-93%	$\leq 91\%$
Temperature	36.1-38°C	38.1-39°C or 35.1-36°C	$\geq 39.1\text{ }^\circ\text{C}$	$\leq 35^\circ\text{C}$
Heart rate	51-90	41-50 or 91-110	111-130	$\leq 40$ or $\geq 131$
Blood Pressure	111-219	101-110	91-100	$< 90$ or $\geq 220$

#### IV. *HeaLoRa* DESCRIPTION

In this section, we describe our proposed system, its architecture, design, working mechanism, hardware and the role of each component. The aim of our system is to analyze data that are collected from body sensors and send them to the doctor or to the medical center in order to monitor and diagnose the patient's situation to prevent medical shocks. The system may work in large areas and it is a very power efficient system.

##### A. Architecture

WBAN is a collection of body sensor nodes. The sensors in our work are supposed to be deployed on the patient's body where the architecture of *HeaLoRa* is separated into three tiers as shown in figure 3 and as discussed below:

The first tier consists of wearable sensors including a temperature sensor to measure the temperature of the user's body, a pulse rate sensor to measure the number of heartbeats of a user per minute, an oxygen saturation sensor to measure the percentage of oxygen level in the user's blood and a pressure sensor to measure human blood pressure. These four sensors are fixed on the patient's body to collect data. The collected measures are sent through wires to a microcontroller. All these components are powered by a single battery fixed on the patient's body. It is worth noted that in order to analyze

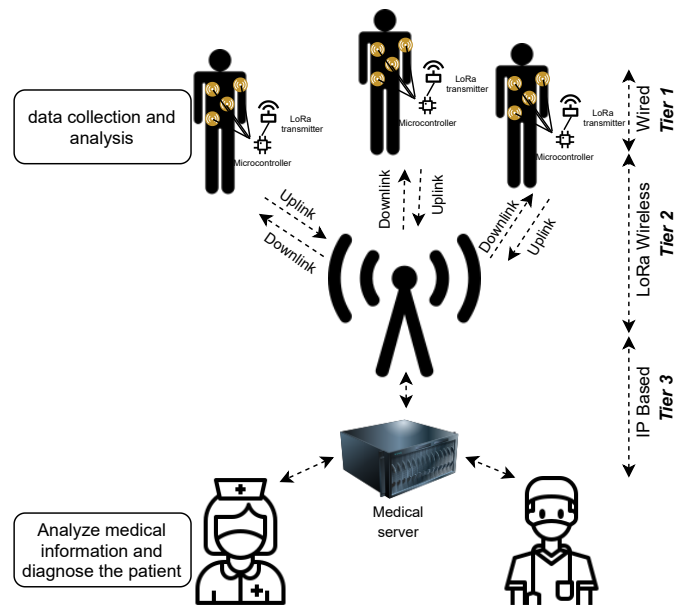


Fig. 3. *HeaLoRa* platform architecture

the variation of the data, which is based on the current and the precedent score, only the latest measured values are stored in the first tier.

The second tier aims to link up the sensors to the gateway. The system decides if the data must be sent or not after been analyzed. If the decision of the microcontroller is to transmit, the data is sent to a gateway using LoRa transmitter.

The third tier consists of the communication between the LoRa gateway and the central point containing the medical server. This communication is done via Internet to forward data to the medical specialists to analyze it and make the final decision on the patient's case. Furthermore, the central point contains all patient's recorded data in terms of history, personal information and current medical status.

##### B. Proposed mechanism

In this subsection, we develop an efficient algorithm in order to diagnose the medical condition of a patient and to detect if there is any abnormal situation.

Our contribution is to prolong the battery lifetime by minimizing the energy consumed by the system. We have developed a dynamic system where the data is sent in a regulated and controlled time, as needed, referring to the criticality state. In case where there is no collection, processing, receiving or transmission of data, the system activates the sleep mode. The sleep mode reduces the consumed power where the system is turned off in unused time. Scores for each of the four measured values are sent only in case of a variation from one state to another one according to the states of "EWS" as following:

- For the first measurement, the sensors collect all the data and send their scores, then the system goes in sleep mode.
- For the other measurements, the system wakes up and measures, if the score of all the parameters is not changed, the data is not sent and the system goes in sleep mode. If the

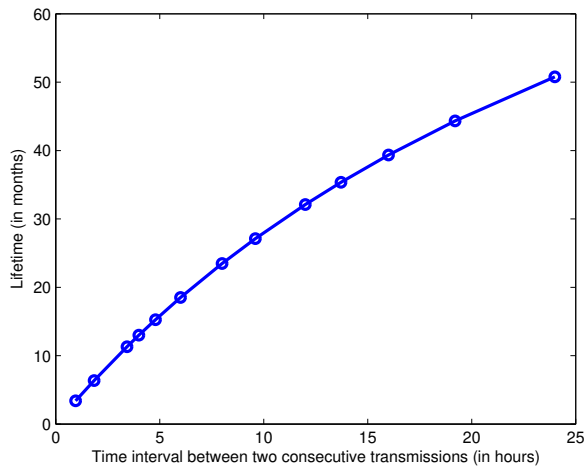


Fig. 4. Effect of the time interval between two transmissions in case of a normal situation on the system's lifetime

score of one parameter, at least, is changed, the system sends the scores of all its measured data then goes in sleep mode.

- In normal case, where there is no score variation, the data is sent once every six hours to ensure that the system is operating normally and to inform the medical staff that the monitored patient is in a stable state. The transceiver only goes in sleep mode for six hours while the other components of the system wake up to measure and analyse data to ensure that no abnormal situation occurs. In case of any abnormality, the transceiver wakes up to send data to the medical server. This randomly selected sleep duration is flexible and could be adapted according to the doctor's need. The sleep mode duration is inversely proportional to the energy consumption. more this duration increases, more the system economizes energy. However, the medical staff will not be updated by the patient situation. The impact of this duration is subjected to be evaluated. Figure 4 shows the effect of the variation of this value on the lifetime of the system.

After taking the decision about sending data or not, basing on the variation of the measured parameters scores, the system goes into sleep mode in both cases. When the sleeping duration ends, the system wakes up and repeats the same process. The time interval between two data collection is based on the RL explained later in this section. The higher the RL, the more we decrease the sleep mode time. The diagram of figure 5 represents the described algorithm. As shown in the figure, the system wakes up, the four sensors measure the medical parameter, then the data is analyzed to study if any score is varied. In case of any variation of the scores, the data is transmitted then the system calculate the RL to determine the duration of the "sleep time" before going into sleep mode. Otherwise, the system calculates the RL and the sleep duration then it goes directly to sleep mode.

### C. Hardware

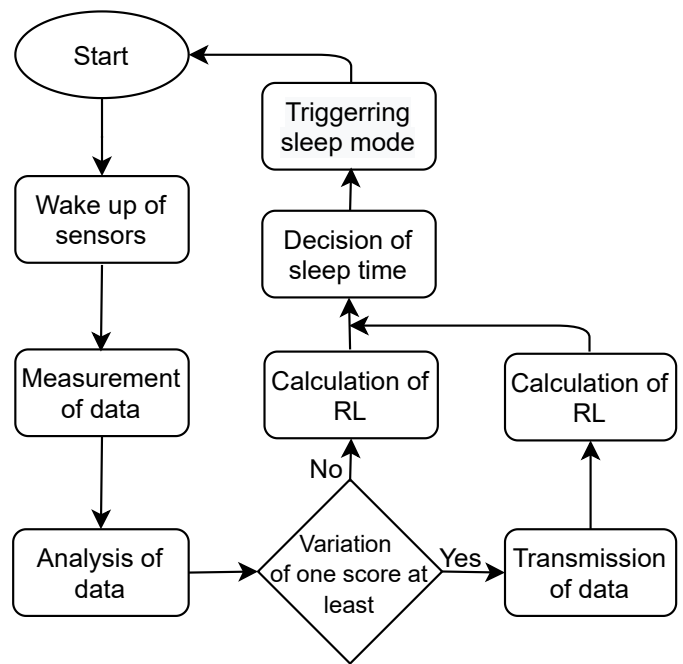


Fig. 5. The dynamic life cycle of the system

Our system is equipped with the three following sensors: MAX30102 sensor (manufactured by Maxim Integrated) to measure the heart beats per minute and the percentage of the oxygen level in blood [33], MPX4250AP pressure sensor (manufactured by NXP Semiconductors) which can be applied as a non-invasive sensor to measure the blood pressure [34] [35], and the BME280 sensor (manufactured by Bosch Sensortec) to measure the human body temperature [36].

Wireless communication with the gateway is achieved via the SX1276 LoRa based wireless module (manufactured by Semtech) [37]. For the power supply, the system is powered by a 5V battery.

### D. Fuzzy Inference System (FIS)

In this work, the RL is calculated using the fuzzy toolbox of Matlab [32] with four inputs representing the four measured medical parameters and one output representing the RL of the patient. Fuzzy inference is the formulation of mapping from specific inputs to outputs using the artificial intelligence fuzzy logic method for dealing with uncertainty using the approximate reasoning of the human mind. In order to design the fuzzy expert system using the Matlab fuzzy toolbox, the steps to follow are: (1) the fuzzification of the input variables, (2) the rule evaluation, (3) the aggregation of the rule outputs, and finally (4) the defuzzification [32] [30]. In the follow, we explain in details each of these four steps:

Input Variables: four inputs presenting the values of the patient's body temperature, heart rate, blood pressure and oxygen saturation are used for the designing of the expert system. In this work, the shape of the membership functions of the fuzzy sets are taken as trapezoidal. Figure 6 shows the implementation of the four inputs based on Mamdani fuzzy inference system using the fuzzy toolbox package of Matlab. We have specified the fuzzy sets for each input variable and

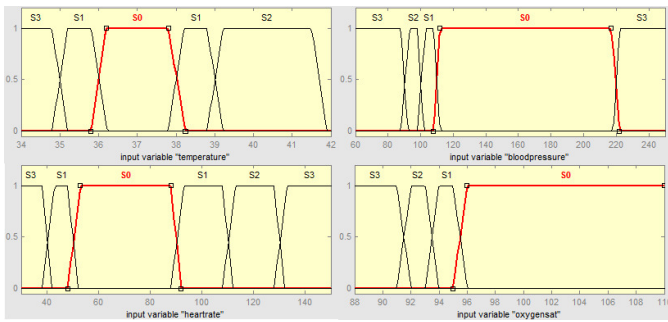


Fig. 6. Mamdani FIS editor with 4 inputs

the corresponding range of each fuzzy set based on the values mentioned in section III.

Fuzzy Rules: for the fuzzy rule base, 256 rules are used by Matlab to cover all possible cases in our work. This number is obtained according to equation 3 by the multiplication of the number of scores with the number of inputs.

$$K = S_0 \times S_1 \times \dots \times S_j \quad (3)$$

Where  $K$  is the total number of possible rules for the fuzzy system,  $S_j$  is the number of scores for each variable and  $j + 1$  is the number of inputs. In our work  $j$  is equal to 3.

Defuzzification: defuzzification is the inverse process of the fuzzification. It combines the fuzzy output of all the rules to give one crisp value. We have used the centroid technique, which is the most popular method to accomplish the defuzzification of the data into a crisp output which is the RL.

Output Variables: as mentioned before, there is one output variable which is the fuzzy representation of the RL.

The sleep time is determined using the RL where the maximum duration between two measurements is 60 min for a normal situation and 1 min for a maximum RL where the patient is in an urgent situation which requires a continuous monitoring. More the RL increases, more the situation becomes more urgent and subsequently the time interval between two measurements must decrease to provide an efficient monitoring. The duration of the sleep time is determined referring to the following equation where  $t$  is measured in min:

$$t = 60 - \frac{RL}{12} \times 59 \quad (4)$$

When the sleep duration is over, the system wakes up again, collects data, calculates the score of each parameter to take the decision about sending or not, and finally calculates the RL to take the decision of the sleeping duration.

## V. RESULTS AND DISCUSSION

In this section, we discuss the performance of our system by studying the daily number of permitted transmissions referring to the LoRa's duty cycle limitations, the power consumption and the system's expected lifetime.

### A. Number of transmissions

In fact, the maximum transmission duty cycle allowed by LoRa end devices in the ISM channels in Europe is 1% for the 868 MHz band. This results that no more than 864 seconds of radio channels can be occupied per day. In addition, the duty cycle constraints translate into delays between consecutive frames. When a frame is sent on a sub-band, the system has to wait  $ToA \times (1/dutycycle - 1)$  seconds before any new transmission on the same sub-band, where  $ToA$  is the time on air explained later in V-B [6]. The limitations of the LoRa duty cycle result in a limited number of permitted transmissions per day. For a duty cycle of 1%, we can deduce that the permitted transmission time of each end device is 36 seconds per hour. Therefore, the maximum permitted number of transmissions per hour is calculated simply as below:

$$n = \frac{36}{ToA} \quad (5)$$

For our system, the maximum required number of transmissions for one hour is when the RL is very high with a variation of the score all the time. In this case, the sleep time is 1 min which corresponds to 60 transmissions needed per hour. In order to represent the impact of the  $SF$  and the  $BW$  on the number of permitted transmissions per hour, figure 7 is plotted using equations 5 and 13. Figure 7 shows that the permitted number of transmissions is minimum for a  $SF=12$  and a  $BW=125$  kHz. It is about 23 transmissions per hour. However, the permitted number of transmissions is maximum for a  $SF=7$  and a  $BW=500$  kHz which is about  $n=2710$  times per hour.

The sleep time  $T_s$  determined using equation 4 must respect the number of permitted transmissions as follows:

$$T_s(\text{mins}) \geq \frac{60\text{mins}}{n} \quad (6)$$

In our system, to avoid exceeding LoRa's restrictions especially when using a high  $SF$  and low  $BW$  and to provide an effective patient monitoring, after each transmission the system calculate the number of remained permitted number of transmissions per hour. For the cases where  $(\text{remained time from one hour in min})/(\text{remained permitted number of transmissions}) \leq 1\text{min}$ , the sleep time for each RL is calculated using equation 4. When the number of transmissions  $N'$  exceeds the half of the number of permitted transmissions per hour, the system increases its sleep time where it becomes equal to the remaining time of the hour divided by the remaining number of permitted transmissions of the hour as follows:

$$T_s = \frac{t_{\text{remaining}}}{n_{\text{remaining}}} \quad (7)$$

### B. Power consumption

In this subsection, an analytical study of the power consumption and the lifetime of the *HeaLoRa* system in different scenarios is provided. Most of the time, the system must be in sleep mode. In our study, the consumed energy is that consumed by the three sensors to measure data, by the microcontroller to process data and by the Lora transceiver in



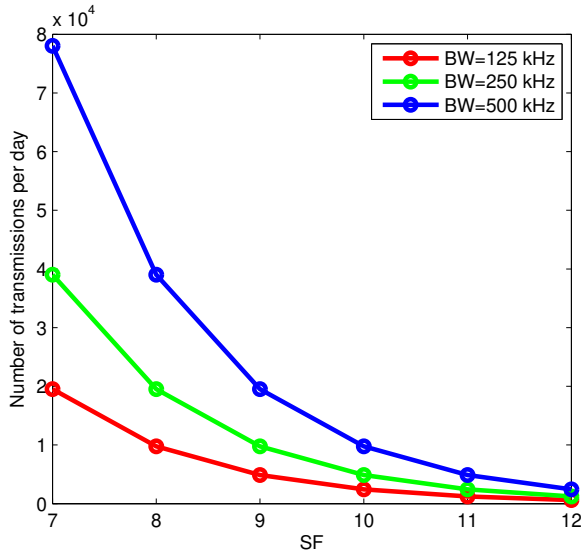


Fig. 7. Effect of the  $SF$  and the  $BW$  on the daily number of transmissions

transmission mode and in reception mode. The total energy consumed by the system during 24 hours is the sum of the energy consumed during active mode  $E_a$  and that consumed during sleep mode  $E_s$  [38], which is determined using the two following equations:

$$E_a = N \times E_T + N' \times P_{S1} \times t_1 + N' \times P_{S2} \times t_2 + N' \times P_{S3} \times t_3 + N' \times P_{pro} \times t_{pro} \quad (8)$$

$$E_s = P'_T \times (24h - t_{active}) + P'_{S1} \times (24h - N' \times t_1) + P'_{S2} \times (24h - N' \times t_2) + P'_{S3} \times (24h - N' \times t_3) + P'_{pro} \times (24h - N' \times t_{pro}) \quad (9)$$

Where the constants  $t_1$ ,  $t_2$  and  $t_3$  are the wake up time for each of the three sensors during 24 hours operation.  $E_T$  is the energy consumed by the transceiver during active mode which explained later in this section.  $t_{pro}$  is the wake up time of the microcontroller.  $N'$  is the number of measurements and  $N$  the number of transmissions during one cycle.  $P$  is the consumed power for active mode and  $P'$  for sleep mode. Each term in these two equations is given, explained, or calculated in this section.

1) *Lora transceiver*: For the lora transceiver SX1276, the supply current in sleep mode is 200 nA, 29 mA in transmit mode for a transmission power of 13 dBm, 10.8 mA in receive mode and 1500 nA in idle mode [37]. Using higher  $SF$  to send data needs more airtime compared to lower  $SF$ , which means more energy consumption. But the use of high  $SF$  has benefits where more airtime gives more opportunities to the receiver to sample the signal, this results in better coverage and sensitivity.

$ToA$  is calculated by adding the preamble and the payload duration. The payload duration is related to the number of transmitted symbols  $N_{payload}$  given in equation 10. Equations 10 to 13 are given by LoRa Semtech [37].

$$T_{payload} = N_{payload} \times \frac{2^{SF}}{BW} \quad (10)$$

The number of transmitted symbols is given in the equation below:

$$N_{payload} = 8 + \max(\text{ceil}[\frac{28+8PL+16CRC-4SF}{4(SF-2DE)}](CR+4), 0) \quad (11)$$

Where  $PL$  is the number of Payload bytes (from 1 to 255).  $SF$  varies from 7 to 12.  $DE=1$  when Low Data Rate Optimization is enabled (for  $SF=12$  and  $SF=11$ ) and  $DE=0$  otherwise. For  $CR$ , 1 corresponding to 4/5, 4 to 4/8.  $CRC$  indicates the presence or not of the  $CRC$  field in the physical message ( $CRC$  is set to 0 if the  $CRC$  field is not present, otherwise,  $CRC$  is equal to 1).

The preamble duration is expressed as:

$$T_{preamble} = (N_{preamble} + 4.25) \times \frac{2^{SF}}{BW} \quad (12)$$

Where  $N_{preamble}$  is the preamble length which is fixed to 8 in our work.

Finally, as we say previously, the  $ToA$  is the sum of the preamble and payload duration:

$$ToA = T_{payload} + T_{preamble} \quad (13)$$

In our study, we model the power consumption of the system for the acknowledged transmission approach in class A. The end device sends an uplink confirmed data message to receive a downlink acknowledgment message in one of the two receive windows that are opened after each transmission. for the SX1276 LoRa transceiver, the first receive window ( $RX1$ ) delay is equal to 1 s (+/- 20 microseconds) and the second  $RX2$  delay is equal to 2 s (first delay + 1sec).

The acknowledgment can be received by the first or the second receive window. In case the acknowledgment is received by the end device in the first receive window, waiting the second one is not needed. If the end device does not receive an acknowledgment, it retransmits the message in a different available channel until it receives an acknowledgment or until a maximum number of transmissions is reached (the recommended default number is eight [6]). Three scenarios can take place in our study. In case A, the message is successfully transmitted and the acknowledgment is received in the first window. In case B, the message is successfully transmitted and the acknowledgment is received in the second window. In case C, the transmitted message suffers a collision, or it suffers one bit error at least or the data message is successfully received but the acknowledgment sent in the first or in the second receive window suffers one bit error at least. Figure 8

illustrates a diagram of these three scenarios with the duration and the current consumption for each state. The consumed energy in each of the three scenarios are presented in the three equations below:

$$E_A = T_{oA} \times P_{Tr} + T_{W1W} \times P_{Idle} + T_{RX1} \times P_{Rec} \quad (14)$$

$$E_B = T_{oA} \times P_{Tr} + T_{W1W} \times P_{Idle} + T_{RX1} \times P_{Rec} + T_{W2W} \times P_{Idle} + T_{RX2} \times P_{Rec} \quad (15)$$

$$E_C = T_{oA} \times P_{Tr} + T_{W1W} \times P_{Idle} + T_{RX1} \times P_{Rec} + T_{W2W} \times P_{Idle} + T_{RX2} \times P_{Rec} + T_{ACKTIMEOUT} \times P_{Idle} \quad (16)$$

As explained before, note that in case C, data must be retransmitted until we get case A or B or until a maximum number of retransmissions is reached.

For the first and second receive windows, their duration can be determined in the two following equations 17 and 18. Equations 17 and 18 are also given by LoRa Semtech [37].

$$T_{RX1} = N_{dsym} \times \frac{2^{SF}}{BW} \quad (17)$$

Where  $N_{dsym}$  is equal to 8 for  $SF = 11$  and 12, and equal to 12 for the other  $SFs$ .

$$T_{RX2} = \frac{2^{SF} + 32}{BW} \quad (18)$$

For  $T_{W2W}$ , it can be determined as:

$$T_{W2W} = DELAY2 - DELAY1 - T_{RX1} \quad (19)$$

According to the LoRa specification, the ACK-TIMEOUT has a random value which is equal to 2 +/-1 sec.  $T_{W1W}$  is taken equal to 1 sec in our study.

The energy  $E_T$  mentioned in equation 8 which is the energy consumed by the transceiver during active mode can be obtain as:

$$E_T = \sum_{i=0}^7 p_{Unsuc}^i \cdot (p_{Unsuc} \cdot E_{Unsuc} + (1 - p_{Unsuc}) \cdot E_{Suc}) \quad (20)$$

Where  $p_{Unsuc}$  is the probability of collisions or errors,  $E_{Unsuc}$  is the energy consumed in case of unsuccessful transmission which is equal to the energy consumed in case C.  $E_{Suc}$  is the energy consumed in case of successful transmission where no collisions or errors occur. The acknowledgment can be received in this case in the first or the second window, so it is calculated as follows:

$$E_{Suc} = E_A \times p_A + E_B \times p_B \quad (21)$$

Where  $p_A$  and  $p_B$  represent respectively the probability to receive the acknowledgment in the first or the second window. A and B are supposed having the same probability in our work.

**2) Sensors:** The BME280 sensor consumes less than 1 mA during measurements and only 5  $\mu$ A during idle mode. The maximum measurement time  $t_I$  of the BME280 sensor is about 11.3 ms [36].  $P_{SI}$  and  $P_{SI}'$  are simply calculated using the consumed current in active and sleep mode (the same for the two other sensors).

The supply current of the MAX30102 sensor for 50 samples per second and for a LED pulse width of 215  $\mu$ s is approximately 0.6 mA and it decreases to 0.7  $\mu$ A in shutdown. The sensor has a LED of 20 mA. For the SpO2 mode, the time of data acquisition and communication is from 15 to 300 ms and the time of the temperature sample is 29 ms. For the heart rate mode, the time for data acquisition and communication is from 15 to 300ms [33].

The supply current of the MPX4250A sensor is 7 mA, its response time is 1 ms and its warm-up time is 20 ms [34].

**3) Microcontroller:** For the processing, the ATmega328P microcontroller is a low power consumer where it consumes 1.5 mA in the active mode and 1  $\mu$ A in the sleep mode [39]. The microcontroller active time  $t_{pro}$  is the overall active time of the system in the different modes.

**4) Battery:** For the battery, the Energizer's 9-volt battery's capacity is equal to 610 mAh which is equal to 5.49 watt-hours.

To calculate the battery lifetime we have to divide the total energy of the battery (mwh) into the total consumed power (mw).

### C. Numerical results

In this subsection, graphical numerical results are presented to illustrate the lifetime of the system in different scenarios. We have calculate the value of the overall energy consumed by the system during 24 hours using real data from the "mimic" platform for 2 patients one in normal situation while the other in an unstable situation. Then we use the values calculated during one day in order to approximately determine the lifetime of the system. Thereafter, we made a comparison between the lifetime of our system and that of a reference one. Note that the reference system used in our study measures and sends data every 15 min without analysis. While our system can sends its data once each 1 min in urgent cases which is more effective.

For a user in normal situation, the system must wake up once an hour, measure, analyse then return to sleep mode. The data is sent once each six hours even in case where the score is not varied. The number of measurements and transmissions increases with the increasing of the RL. We annulate the energy consumed by the LED of the MAX30102 in our study.

Figure 9 shows the impact of the adopted  $SF$  on the lifetime of the system. The  $BW$  and the  $CR$  are fixed at  $BW=250$  kHz and  $CR=1$ . And for collisions, we suppose that  $p_{coll}=0$  for the three figures 9, 10 and 11.  $SF$  varies from 7 to 12

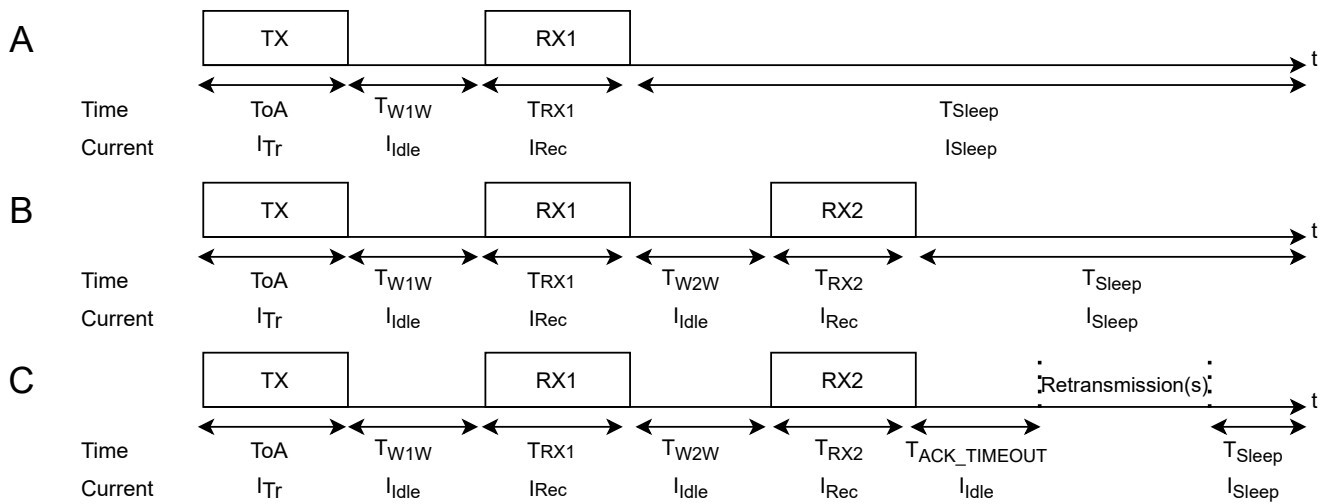


Fig. 8. Scenarios A where the acknowledgment is received in the first window, B where the acknowledgment is received in the second window, and C where there is a collision or an error

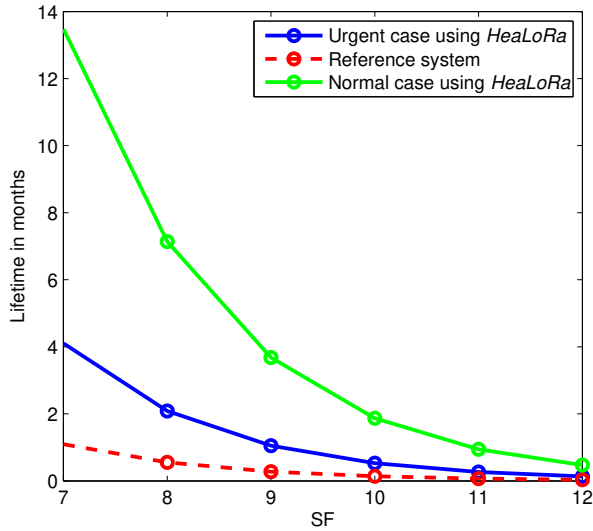


Fig. 9. Impact of the SF on the system's lifetime with  $BW=250$  kHz and  $CR=1$

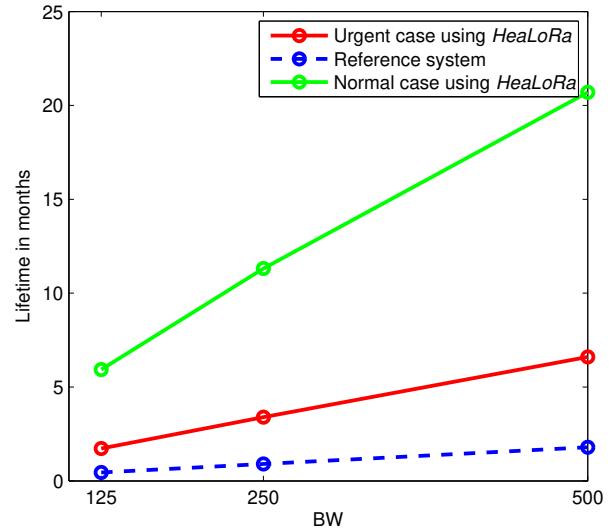


Fig. 10. Impact of the BW on the system's lifetime with  $SF=7$  and  $CR=1$

according to the specifications of LoRaWAN. The lifetime decreases with the increase of the SF for the studied cases. This refers to the increasing of the time taken to send a packet with the increasing of the SF, which leads to an increase in the consumed energy needed to transmit data. It should be noted that even for very high RL, LoRa duty cycle remains respectable as explained in V-A.

Figure 10 shows the impact of the BW on the lifetime of the system. The SF and the CR are fixed at  $SF=7$  and  $CR=1$ . Graphically, it is obvious that the lifetime increases with the increasing of the BW.

Figure 11 shows the impact of the CR on the lifetime of the system. The SF and the BW are fixed at  $SF=7$  and  $BW=250$  kHz. The variation of the CR has a low impact on the lifetime

of the system.

In the last figure, we study the effect of collisions on the lifetime of the system for both normal and urgent cases. Collisions increase the number of transmissions and thus the consumed energy. So as expected, figure 12 shows that the lifetime decreases with the increasing of the collisions probability.

Based on the analytical study, we found that our system has a significant lifetime efficiency compared to a reference system. As an example, for a  $SF=7$ ,  $BW=250$  kHz and  $CR=1$ , the system has an energetic efficiency about 10 times greater than that of a reference system in case of a patient in normal situation. In case of a patient in urgent situation, where the number of measurements and transmissions increases, our results showed an energetic efficiency where the lifetime is

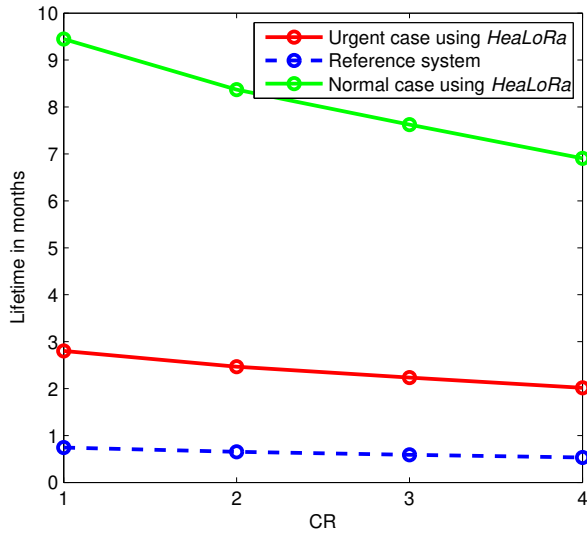


Fig. 11. Impact of the  $CR$  on the system's lifetime with  $SF=7$  and  $BW=250$  kHz

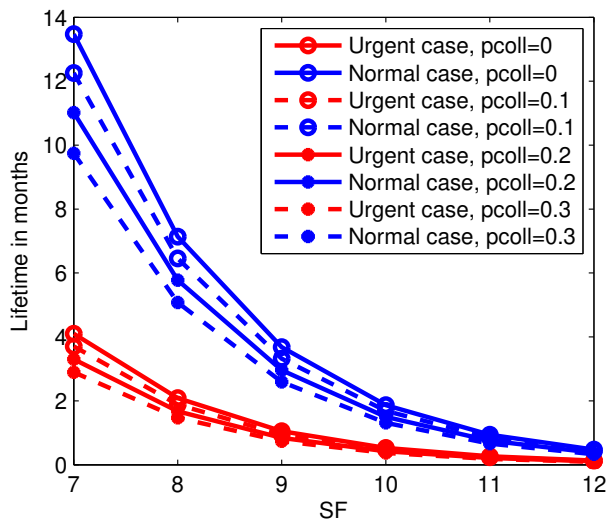


Fig. 12. Impact of collisions on the system's lifetime with  $SF=7$ ,  $BW=250$  kHz and  $CR=1$

4 times greater than that of a reference system. Therefore, our system ensures great autonomy in terms of energy consumption, where when we use one small battery for the whole system, its lifetime can reach more than 12 months in case of a normal situation.

## VI. CONCLUSION

In this paper we proposed a low power system called *HeaLoRa*. *HeaLoRa* uses LoRa wireless network for monitoring physiological parameters of a patient to determine its medical situation, in order to anticipate the aggravation of pathologies for patients, and to reduce the hospitalization time and cost, specially with the spread of the Covid pandemic.

We use the fuzzy-based EWS to specify patient's status by measuring four medical parameters, then a decision of the RL is taken. Finally, a detailed study of the system performance in terms of consumed energy, lifetime and daily permitted number of transmissions are presented. Our results have shown a very good effectiveness in terms of the system's lifetime, with gains in autonomy multiplied by 3 to 10 depending on the studied scenario.

Work is in progress to improve the decision-making aspects based on the storage of patient registers and to realize clinical testing of *HeaLoRa* platform.

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