System Level Design of Low Rate, Low Power 3.1-5GHz IEEE 802.15.4a UWB Transceiver for Medical Monitoring Applications

Imen Barraj, Hatem Trabelsi, and Mohamed Masmoudi
National School of Engineering of Sfax, University of sfax, Department of Electrical Engineering, Micro-Electro Thermals Systems laboratory (METS), Tunisia
Email: imen.barraj@gmail.com, hatem.trabelsi@isetsf.rnu.tn, mohamed.masmoudi@enis.rnu.tn

***Abstract*—Low power consumption is one of the main targets in designing a radio for a Wireless medical devices for healthcare monitoring applications. The IEEE 802.15.4a standard has proprieties that make it a viable solution for this type of applications and environments. IEEE 802.15.4a standard adopts Impulse Radio Ultra Large Band (IR-UWB) to afford low data rates, low power and low complexity communication systems with enhanced communication range and robustness. This paper discusses the architecture parameters selection for low power, monolithic wireless sensor like frequency allocation, data rate, mean PRF, pulse shape and radio architecture. Then, link radio budget parameters required for the transceiver implementation have been established.**

***Index Terms*—IR-UWB, IEEE 802.15.4a, link budget, transceiver, Medical monitoring, non coherent receiver**

I. Introduction

Wireless sensor networks have been used for many applications including healthcare monitoring and medical applications. There are increasing requirements for the vital sign monitoring systems as population aging is progressing rapidly in many industrialized countries which is accompanied by an even more dramatic increase in the number of old people suffering from chronic diseases and disabilities [1].

Low power and Low cost are the most important criteria for designing an emerging sensor network for healthcare monitoring. IEEE 802.15.4a standard has proprieties that make it a promising standard for this type of applications due to the large data bandwidth, the excellent immunity to interference with nearby channels, the coexistence with others systems and the extremely low emitted power spectral density. Ultra Wide Band (UWB) signals are usually defined as signals having a bandwidth of at least 500MHz or at least 20% of the center frequency set to -10dB [2]. The transmitted power spectral density (PSD) should be less than -41.3dBm/MHz and having a maximum peak power level of 0dBm/50MHz. The Federal Communications Commission (FCC) allocated the unlicensed frequency band from 3.1GHz to 10.6GHz for the UWB application except 5-6GHz ISM band assigned for WLAN applications [3].

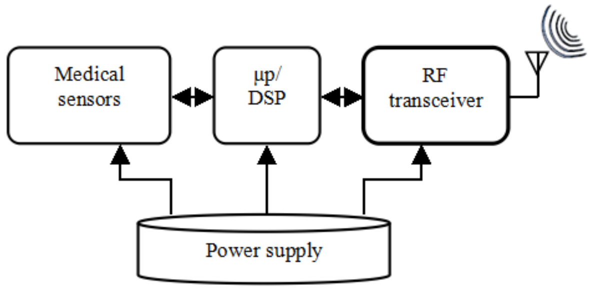

Figure 1. Generic architecture of the sensor node

The wireless sensor node should be able to operate for severs years under battery energy supply. A generic architecture of the expected devices node is shown in Fig. 1. It typically acquires vital signal data from different medical sensors then it transmit them to a remote personal server, where they will be analyzed with appropriate software.

In this paper, we focus on the RF transceiver front end. Section II describes transceiver architecture design selection. In section III, system level analysis has been detailed. Section IV concludes this paper.

II. IEEE 802.15.4a Transceiver Architecture Design Selections

A. Frequency Allocation

The set of operating frequency bands is defined in Table I [4]. IEEE 802.15.4a standard support three band of operation: sub-gigahertz band, which consists of a single channel and occupies the spectrum from 249.6MHz to 749.6MHz, low band, which consists of four channels and occupies the spectrum from 3.1GHz to 4.8GHz and high band, which consists of eleven channels and occupies the spectrum from 6.0GHz to 10.6GHz. For the sub-gigahertz operation, channel 0 is defined as the mandatory channel, for the low-band operation, channel 3 is the mandatory channel and for the high-band operation, channel 9 is the mandatory channel.

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TABLE I. IEEE 802.15.4A BAND ALLOCATION

Band group	Channel N °	Center frequency f_c (MHz)	Bandwidth (MHz)	Mandatory /Optional	Admissible region
Sub-Gigahertz	***0***	***399,36***	***499,2***	***Mandatory below 1 GHz***	***USA***
Low Band	1	3494,4	499,2	Optional	USA, Europe
	2	3993,6	499,2	Optional	USA, Europe, Japan
	3	***4492,8***	***499,2***	***Mandatory in low band***	***USA,Europe,Japan***
	4	3993,6	1331,2	Optional	USA, Europe, Japan
High band	5	6489,6	499,2	Optional	USA, Europe
	6	6988,8	499,2	Optional	USA, Europe
	7	6489, 6	1081,6	Optional	USA, Europe
	8	7488	499,2	Optional	USA, Europe, Japan
	9	***7987,2***	***499,2***	***Mandatory in high band***	***USA,Europe,Japan***
	10	8486,4	499,2	Optional	USA, Japan
	11	7987,2	1331,2	Optional	USA, Japan
	12	8985,6	499,2	Optional	USA, Japan
	13	9484,8	499,2	Optional	USA, Japan
	14	9984	499,2	Optional	USA, Japan
	15	9484,8	1354,97	Optional	USA, Japan

The sub-gigahertz band faces regulatory challenges in many countries. On the other hand, high-band incurs greater path loss which results in reduced range. Based on these considerations, the low band of 3.1-4.8GHz has been adopted as the operating band. Also, it is easy to realize the transceiver prototype with a moderate CMOS process. Then, the designed transceiver will cover channels 1, 2 and 3 from the low band, which correspond to the centre frequencies 3494.4MHz, 3993, 6MHz and 4492,8MHz respectively with 499,2MHz channel bandwidth.

B. Data Symbol Parameters, Data Rate and Mean PRF

IEEE 802.15.4a standard uses a combination of burst position modulation (BPM) and binary phase shift keying (BPSK) to support both coherent and non-coherent receiver's architecture. The combined BPM-BPSK is used to modulate symbols, with each symbol being composed of a burst of UWB pulses. The structure and timing of IEEE 802.15.4a symbol is illustrated in Fig. 2. Each symbol consists of an integer number of possible chip positions, N_c, each with duration, T_c=2.003ns. The overall symbol duration is given by $T_{sym}=N_cT_c$. Furthermore, each symbol is divided into two BPM intervals each with duration $T_{BPM} = T_{sym}/2$ which enables the binary position modulation.

A burst is formed by grouping N_{cpb} symbol interval. A single burst event is transmitted. The total number of burst durations per symbol, N_{burst} , is given by $N_{burst} = T_{sym}/T_{burst}$. In order to limit the amount of inter-symbol interference caused by multi-path only the first half of each T_{BPM} period contains a burst, therefore, only the first $N_{hop} = N_{burst}/4$ possible burst positions are candidate hopping burst positions within each BPM interval. Each burst position can be varied on a symbol to symbol basis according to a time hopping code.

The various data rates are supported through the use of variable-length bursts. Each UWB channel allows for several data rates (Table II column "Bit Rate") that are obtained by modifying the number of chips within a burst ("Chips Per Burst"), while the total number of possible burst positions ("Burst Positions Per Symbol") remains constant. Therefore, the symbol duration, *Tdsym*, changes to obtain the stated symbol rate and bit rates.

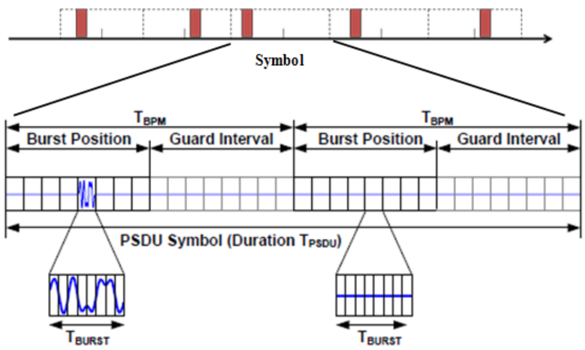

Figure 2. IEEE 802.15.4a data symbol structure

Three possible mean PRFs are defined: 3.9MHz, 15.6MHz and 62.4MHz. The motivation for different mean PRFs stems from the fact that the devices will operate in environments with widely varying delay spreads. The low PRF is mainly intended for operation in environments with high delay spreads, particularly if the receiver uses energy detection. For coherent reception in high-delay-spread environments and for any receivers in low-delay-spread environments, operation with the higher PRF is preferable. The admissible data rates, preamble code lengths and mean PRFs parameters are listed in Table II.

Coherent-receiver based devices offer longer range and better BER performance in noisy channel condition. However, these types of devices generally have higher complexity (hence high cost) and power consumption. In many applications where cost and energy consumption are critical, non-coherent devices are desirable even though they may have shorter communication range and inferior performance under certain channel conditions. As, we aim to develop a low power prototype, non coherent receiver is more appropriate. Then, a mean PRF of

3.9MHz has been adopted. A data rate of 110kbps satisfies the need of our applications. Thus, a burst of 32 chips is positioned either in the first or second half of symbols with a duration of 8200.14ns representing one bit of data.

TABLE II. IEEE 802.15.4a RATE DEPENDENT AND TIMMING RELATED PARAMETERS

Mean PRF (MHz)	Bit Rate (MBps)	Preamble/SFD		PHR		Data	
		Chips per Symbol	Spreading Factor	Chips per Symbol	Chips per Burst	Chips per Symbol	Chips per Burst
3.9	0.11	1984	64	4096	32	4096	32
	0.85	1984	64	512	4	512	4
	6.81	1984	64	512	4	64	2
15.6	0.11	496	16	4096	128	4096	128
	0.85	496	16	512	16	512	16
	6.81	496	16	512	16	64	2
62.4	0.11	508	4	4096	512	4096	512
	0.85	508	4	512	64	512	64
	6.81	508	4	512	64	64	8

C. Pulse Shape

The design and generation of an efficient appropriate UWB pulse shape with a power spectral density (PSD) fulfilling the mandated Federal Communications Commission (FCC) spectral masks and the emission mask defined by the IEEE 802.15.4a standard is one of the major challenges of IR-UWB systems design. For IR-UWB communication, pulse generator design is subject to several criteria: they should be simple, compact, energy efficient, compatible with integration with low-cost, compatible with popular UWB modulation formats like binary phase shift keying modulation (BPSK) and pulse position modulation (PPM) and ideally would feature some flexibility to respond to potentially changing constraints of the signal environment or channel. Few of the proposed pulse shaping methods can lead to very high transmission power efficiency. Many topologies make use of Gaussian pulse and its derivatives [5] [6], or more complex shapes as prolate spherical [7] or the modified Hermite orthogonal polynomials functions [8]. Although the compatibility of these shapes is acceptable, it does not provide low power consumption and needs complex circuit for generation using CMOS technology.

To ensure low power and low complexity we have introduce a novel UWB pulse shape in [9]: the modified triangular shape as shown in Fig. 3. It consists of combining two triangular pulses. The first is characterized by a positive amplitude (A_{01}) and duration (τ_1) while the second one is characterized by negative amplitude (A_{02}) and duration (τ_2). Noted, that these shape comply with IEEE 802.15.4a requirements [4]. The temporal expression of the modified triangular pulse is:

$$p(t) = \begin{cases} A_{01}\left(1 - \frac{|t|}{\tau_1}\right) & \text{For } -\tau_1 < t < \tau_1 \\ A_{02}\left(1 - \frac{|t-\tau_1-\tau_2|}{\tau_2}\right) & \text{For } \tau_1 < t < \tau_1+2\tau_2 \\ 0 & \text{otherwise} \end{cases}$$

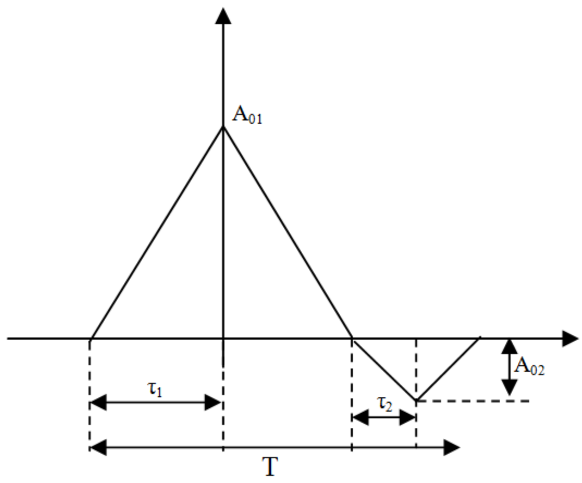

Figure 3. Parameters of the modified triangular pulse.

D. Radio Architecture

IR-UWB transceiver is based an analog/digital partitioning as shown in Fig. 4. The analog radio front end is used to transmit and receive RF modulated signals. At the baseband, common baseband operations such as channel coding, decoding, burst position modulation and binary phase shift keying are performed.

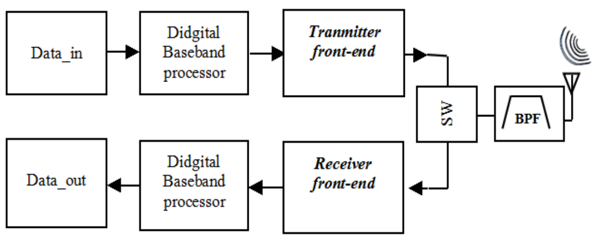

Figure 4. Transceiver baseband processing principle

The main objective of the transmitter (TX) is to generate well shaped modified triangular pulses fitting the IEEE802.15.4a rectangular emission spectrum mask as shown in Fig. 5. The more accurate is the shape, the better it will be detected at the receiver (RX). As a combination of a burst position modulation (BPM) and binary phase shift keying (BPSK) is used for transmitting data, well pulses with correct polarity at the required positions should be generated.

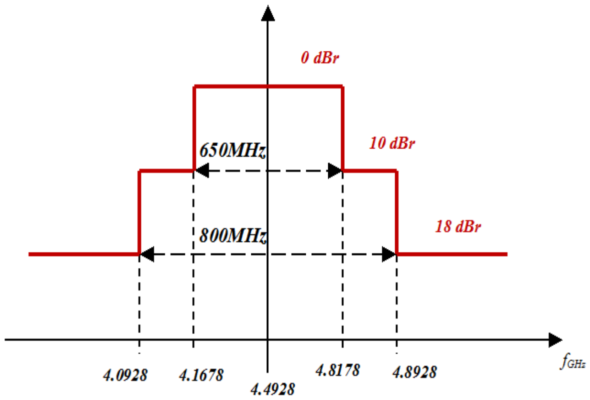

Figure 5. Transmit spectrum mask for channel 3

IR-UWB transmitter architecture can be classified into two groups: carrier-less and carrier-based systems.

Considering the carrier-less approach, the transmitter is designed to occupy the spectrum of a single channel. Moreover, this type cannot allow the multiband switching. Also, this class isn't suitable for low power and low-cost design. Thus, carrier based architecture is adopted to cover different multiband of the low band. The transmitter front end is shown in Fig. 6. It consists mainly on three blocks: the pulse generator, the up conversion mixer and the driver amplifier. The pulse generator is responsible for generating the correct wave form to drive the up-mixer in the case of transmission of a pulse or a burst. Enable, Polarity and Trigger are control signals issues from the baseband processing signal. The Enable signal is used to activate the pulse generator only during pulse emission, where the polarity signal present a data signal image. It provides the information about the data polarity "0" or "1". At each rising edge of the trigger, we have a pulse at the output. Therefore, we notice that the mixer, whose inputs are inputs are a synthesis of RF frequency and a baseband pulse, allows the transposition toward the high frequency. To ensure an IEEE 802.15.4a compliant operation, considering the power constraints and general practical aspects, the up conversion mixer has to provide high linearity, low power consumption and LO drive. The up conversion mixer is followed by a power amplifier to bring the signal to a power level corresponding to the specification of the PSD mask antenna which is directly connected.

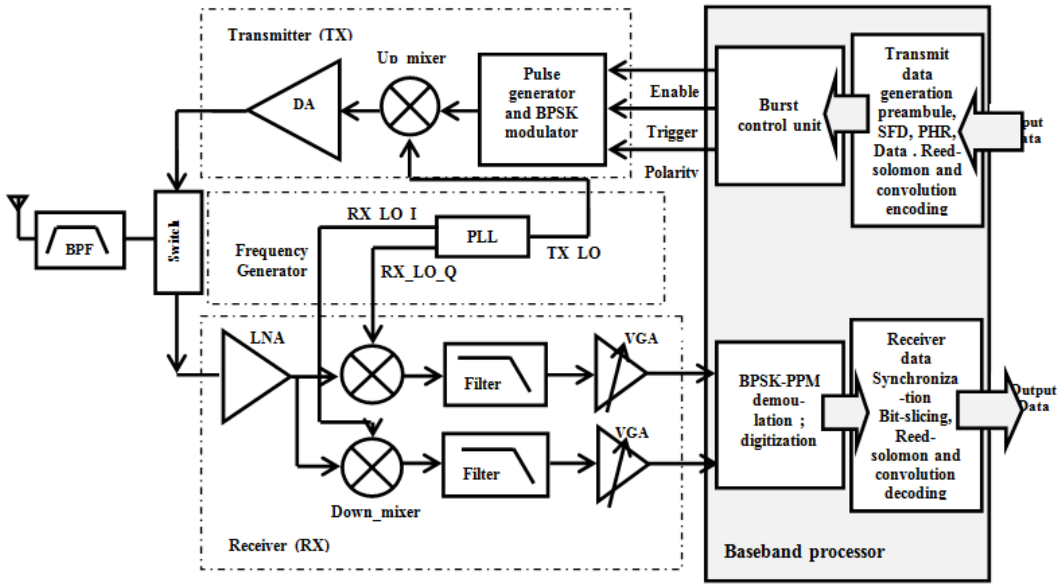

Figure 6. IEEE 802.15.4a BPM-BPSK transceiver architecture

The main architecture of IR-UWB receiver can be categorized into superheterodyne receiver and direct conversion receiver [10] [11] which are quiet similar as those traditional narrow-band RF receivers. A superheterodyne receiver provides high dynamic range, selectivity and sensitivity. However, several off-chip passive filters, which are difficult to be integrated in CMOS technology and led to increase the cost, are required. Thus superheterodyne receivers are less attractive in single-chip implementation and low-power. The second commonly used architecture is direct conversion architecture where The RF signal is directly down-converted to a base band signal without any intermediate frequency. Thus the off-chip components can be eliminated, and then the cost and size of the overall receiver are reduced and full integration on monolithic chip made possible. In addition, since only one-step frequency translation is needed, the power consumption of a direct conversion receiver is much lower than a superheterodyne receiver. Taking on consideration the design criteria which are simplicity of implementation, low energy consumption, Zero-IF architecture is retained.

As stated previously, non-coherent energy detection is adopted due to its affordable complexity and corresponding power efficiency. Fig. 6 gives the receiver front end architecture. First, the received pulse is amplified with a low noise amplifier (LNA) then down converted with the hopping LO and a down conversion mixer to zero-IF. A low pass channel-select filter passes only the selected user's received signal and suppresses adjacent channels. The filtered signal is amplified by a VGA stage to achieve the sufficient dynamic range. Once the proper gain is set and the signal is brought to the level high enough above the noise background, the digitization is carried out for the baseband reception.

III. System Level Analysis

The important specifications for designing an integrated transceiver are the required noise figure, sensitivity, linearity, dynamic range, phase noise and output power while staying in an extremely tight power consumption budget. Note that the maximum range has been set to 50m.

A. Link Budget

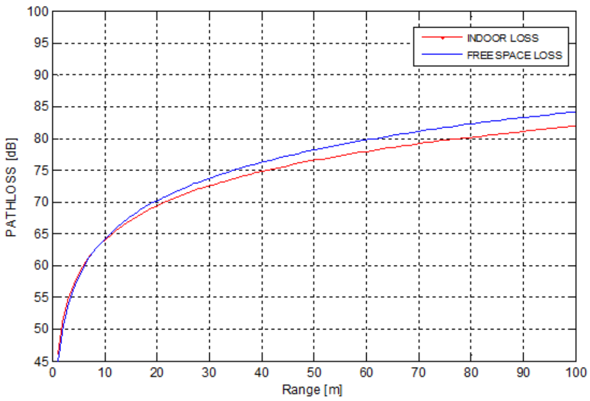

Figure 7. Estimate indoor and free space path losses

For the upper band defined between 3.1 GHz to 10.6GHz, the estimated transmitted and received powers are computed as:

$$P_{TX} = PSD_{FCC} + 10 \log10 (B) - ML_{dB} \quad (1)$$

$$P_{RX} = PSD_{FCC} + 10 \log10 (B) - ML_{dB} - PL_{dB} \quad (2)$$

PSD_{FCC} correspond to the maximum power spectral density restricted by the FCC to -41.3dBm/MHz. B represents the signal bandwidth. ML is the mask loss and accounts for the fact that real signals do not perfectly fit with the rectangular emission mask. PL corresponds to the path loss caused by the distance (d) between the RX and TX in a specific channel configuration.

It is well known that PL can be expressed as a function of d and an exponent [12]:

$$PL_{dB} = PL_0 + 10 \text{ n } \log_{10}\left(\frac{d}{d_0}\right) + \delta_{dB} \quad (3)$$

with:

$$PL_0 = 20 \log_{10}\left(\frac{4\pi f_0}{c}\right) \quad (4)$$

δ_{dB} is a zero mean normal random variable which refers to the large scale fading (or shadowing) in the channel. is the intercept point at the reference distance d_0. Usually d_0 is set to 1m and PL_0 is often given by the free space path loss at d_0 taken at the geometric central frequency f_0 = (f_{min} and f_{max} represents the lower and upper edge of the frequency band). n is path loss exponent that depends on the channel environment.

$$PL_{free\_space} = 78.18\text{dB}$$

$$PL_{indoo\_loss} = 76.53\text{dB}$$

In [12] for LOS UWB residential indoor channels a path loss exponent of 1.79. Supposing data range of 50m, as shown in Fig. 7:

Considering channel bandwidth of 499.2MHz and mask loss of 0.45dB, the maximum transmitter power P_{TX} is -13.62dBm. With a PL of 76.53dB. The minimum sensitivity required to be able to detect a 500MHz UWB signal transmitted at a distance of 50meters from the receiver can be computed as:

$$S_{min} = P_{TX} - PL_{free} \quad (5)$$

with PL_{free} represents the free space path loss between TX and RX. Thus, the minimum sensitivity is -91.8dBm.
The noise floor is given by:

$$\boldsymbol{N = -174dBm/Hz + 10log_{10}(B)} \quad (6)$$

Considering an ideal 500MHz receiver, the required noise floor N is -87dBm.

The minimum and the maximum SNR are as follows:

$$SNR_{in,min} = S_{min} - N \quad (7)$$

$$SNR_{out} = \left(\frac{E_b}{N_0}\right) - G_p \quad (8)$$

with E_b is the average energy of a bit (J), N_o is the noise power spectral density (W/Hz) and G_p represents the processing gain.

The total processing gain can be written as:

$$G_p[dB] = 10log_{10}(N_{cpb}N_{burst}) \quad (9)$$

$SNR_{in,min}$, at the entrance of the receiver is hence equal to -4.8dB. At the output of the receiver -26.7dB SNR_{out} is needed for detection of the BPSK signal with a bit error rate of 10^{-3} (Fig. 8).

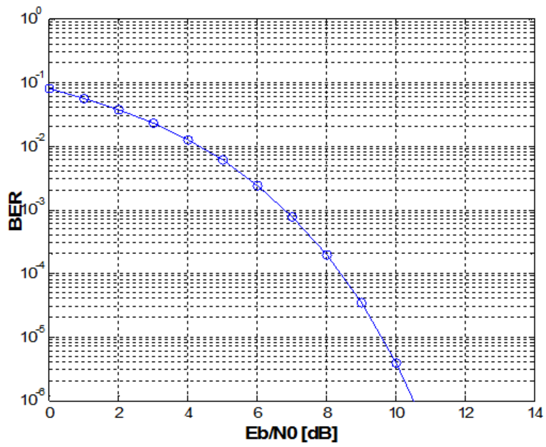

Figure 8. Probability of bit error for BPSK in AWGN channel

The maximum noise figure is gives as:

$$NF_{max} = S_{min} - N - SNR_{out} - M \quad (10)$$

Taking into account 5dB implementation margin (M) (for board losses, external component losses and digital loses), this gives a maximum noise figure of the front-end in UWB mode of 17dB.

B. Linearity

For the IR-UWB, the largest interference is caused by the 802.11.a WLAN standard, which can transmit up to 20dBm. To withstand this interferer, when positioned at a distance of ≥ 1m, the minimum jamming resistance level at the receiver is -38.5 dBm. From this specification, the required IIP_3 and P_{-1dB} can be derived based on the following formula [13]:

$$IIP_3 = \frac{1}{2}\left(3P_{in} + SNR_{in,min} - P_s\right) \quad (11)$$

$$P_{-1dB} = IIP_3 - 10dB \quad (12)$$

P_{in} is the maximal interference power (-38.5dBm), $SNR_{in,min}$ the minimum required SNR at the entrance of the receiver and P_s is the desired signal power at the entrance of the receiver at the moment a signal pulse arrives. Taking into account multipath losses, this corresponds to a signal power of -83.18dBm. Thus, an IIP_3 of -18.56dBm and P_{-1dB} of -28.56 dBm are required for a minimum sensitivity input signal. The receiver gain represents the maximum power level at the output of the VGA. Thus, a voltage gain of approximately 80 dB is needed to raise the minimum signal level to the full scale of the baseband A/D converter [14].

C. Dynamic Range

A receiver ability to accommodate both large and small signal is indicated by its dynamic range. Two definitions of dynamic range are used: spurious-free dynamic range (SFDR), and blocking dynamic range (BDR).

$$\boldsymbol{SFDR = \frac{2}{3}(IIP_3 - S_{min} + SNR_{out}) - SNR_{out}} \quad (13)$$

$$\boldsymbol{BDR = P_{-1dB} - S_{min}} \quad (14)$$

Then, we obtain SFDR= 58.68dB and BDR=63.24dB.

D. Oscillator Phase Noise

In ultra wideband mode as the narrowband mode, the phase noise requirements will be determinate by the jamming resistance through the effect of reciprocal mixing. The maximum allowed phase noise PN can be computed as [13]:

$$PN = P - P_{in} - SNR_{in,min} - 10log_{10}(B) - M_1 \quad (15)$$

with P represents the desired signal power, P_{in} the interferer power and M_1 a 10dB margin. Then, phase noise up to -134.62dBc/Hz at an offset of 1MHz.

Table III summarizes the transceiver specifications.

TABLE III. TRANSCEIVER SPECIFICATION

Overall	
Modulation schema	PPM-BPSK
Supported channel	1;2;3
Center frequency	f_{c1}=2494.4MHz;f_{c2}=3993.2MHz; f_{c3}= 4492.8MHz
Channel Bandwidth down3dB	499,2MHz
Channel Bandwidth down10dB	650MHz
Channel Bandwidth down18dB	850MHz
Data rate	110kbps
Mean PRF	3.9MHz
Chips per Burst	32
Symbol rate	0.12MHz
Maximum range	50 meters
Transmitter	
Maximum output power spectral density	-41.3dBm/MHz
Maximum output power	-13.62 dBm
Pulse shape	Modified triangular pulse
Load impedance	50Ohm
Oscillator phase noise	134.62 dBc/Hz at 1MHz
Receiver	
Sensitivity	-91.8 dBm
Noise figure	17dB
Path loss	76.53 dB
Gain	≥80dB
IIP3	≥ -18.56 dBm
P_{-1dB}	≥-28.56dBm
SFDR	58.68dB
BDR	63.24dB

IV. CONCLUSION

A complete system-level analysis for a short range, low data-rate radio IEEE 802.15.4a transceiver dedicated for medical monitoring application has been presented. The transceiver is designed for PPM-BPSK modulation and it communicates at a maximum rate of 110Kb/s. The transceiver operates in the low band and cover channels 1, 2 and 3. Non coherent architecture has been selected to ensure lower energy consumption. A link budget analysis leads to define a set of specifications which will serve as a start point for the modeling and design of the selected architecture. The proposed transceiver architecture can be easily integrated with the medical sensors and the baseband processor as a monolithic circuit at low-cost and ultra-low power. Our future work will be focused on the design of the transceiver at transistor level using a moderate CMOS process.

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Imen Barraj was born in Tunisia, in 1986. She received the Electronic Engineer Diploma from the Southern Private University of Sfax, Tunsia in 2010 then the Master degree in electronic in 2011 from National Engineers School of Sfax, Sfax, Tunisia. She joints the Micro-Electro Thermals Systems (METS) research group since 2010. She is currently a Ph.D student. Her current field in research is in radio architectures and design of Analog CMOS RF integrated circuits for Impulse Radio Ultra Wide Band IEEE 802.15.4a transceivers.

Hatem Trabelsi was born in Sfax, Tunisia in 1969. He received the engineering degree in electrical engineering from the National School of Engineers of Tunis in 1993, the aggregation degree in 2001 and Ph.D. in electrical engineering from the National School of Engineers of Sfax in 2009. His doctoral research was mainly focused on design and implementation of ultra low power transceivers for Wireless Sensor Network. He is currently an Assistant Professor at the Electrical Engineering Department of the National School of Engineers of Sfax. He is a member of the research laboratory METS LAB ENIS, where he is working in the field of analog and RF circuit design for ultra-wideband systems. His research interests are single-chip CMOS transceivers, RF front-ends, Ultra wideband analog circuit design.

Mohamed Masmoudi was born in Sfax, Tunisia, in 1961. He received the Engineer in electrical Engineering degree from the National Engineers School of Sfax, Sfax, Tunisia in 1985 and the PhD degree in Microelectronics from the Laboratory of Computer Sciences, Robotics and Microelectronics of Montpellier, Montpellier, France in 1989. From 1989 to 1994, he was an Associate Professor with the National Engineers School of Monastir, Monastir, Tunisia. Since 1995, he has been with the National Engineers School of Sfax, Sfax, Tunisia, where, since 1999, he has been a Professor engaged in developing Microelectronics in the engineering program of the university, and where he is also the Head of the Laboratory Micro-Electro Thermals Systems. He is the author and coauthor of several papers in the Microelectronic field. He has been a reviewer for several journals. Dr. Masmoudi organised several international Conferences and has served on several technical program committees. He has served as Guest Editor for special issue for several journals.