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Emitters and Receivers for Impulse Radio Ultra-WideBand and Their Healthcare Applications

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Abstract—Healthcare applications requirements are presented in this paper and a state-of-the-art analysis shows that Impulse Radio Ultra-WideBand (IR-UWB) is particularly suitable in terms of energy efficiency for this type of short range communications for which different data rates are needed. Power saving strategies for emitters and receivers are then discussed and three examples of implementations are presented with their measurement results. The first is a versatile transmitter with tunable bandwidth which exhibits 0.9Vpp pulses and a power consumption of at least 11.03mW at 50Mbps. The second is a 3.1-10.6GHz transmitter with a power management scheme implemented on-chip which exhibits 2Vpp pulses and a power consumption of 7.3μW at 100kbps and 3.4mW at 100Mbps. The last is a non-coherent 3-5GHz receiver with -89dBm sensitivity at 100kbps and 144pJ/bit energy consumption when used in a power gated 100Mbps burst mode.

Keywords—Healthcare Applications; Impulse Radio; Power Gating; Data Rate Management; UWB; Transceiver

I. INTRODUCTION

Modern biomedical monitoring or stimulation systems use wireless communications to avoid the use of wires which is uncomfortable for the patient and the medical workers, and reduces the reliability of the overall system. The needs in biomedical application are very specific and depend on the monitored parameters or the stimulated parts [1][2][3]. As presented in TABLE I, physiological monitoring needs low or medium data rates and can be realized with an unidirectional link, whereas next generation of brain machine interfaces needs a large number of interconnections which leads to high data rates up to 100Mbps [3]. Concerning the power consumption, the needs are also very widespread since the transmitter life can vary from few hours for ElectroCardioGraphy (ECG) to few years when in-body stimulation systems are considered. The communication range appears to be the most relaxed constraint since the on-body or in-body transmitters are close to the receiver which can consist of a simple hub that concentrates the data and sends it to a remote monitoring system.

Due to this large variety of needs, several wireless technologies have been used to implement biomedical monitoring and stimulation systems as: i) High Frequency Radio Frequency IDentification (HF-RFID; 13.56MHz) [4][5], ii) Ultra-High Frequency RFID (UHF-RFID; 900MHz) [6][7], iii) 400MHz Narrow Band (400MHz-NB) [8][9][10], iv) 2.45GHz-NB [11][12][13], and v) Impulse Radio Ultra-

WideBand (IR-UWB) [14][15][16]. The most encountered systems are based on HF-RFID and 400MHz-NB technologies which are the most mature. Moreover, biomedical standards have been specified for the 400MHz-NB whereas HF-RFID is quite attractive since remotely powered transponders can be achieved with commercial off the shelf RFID devices. However, 2.45GHz-NB systems are recently emerging essentially due to the growth of Bluetooth Low Energy (BLE) [12][13] and the ease of interconnecting the transponder with standardized systems.

In the field of biomedical applications, IR-UWB appears first to be a new comer since it seems to offer a large number of advantages such as low power consumptions, high data rates or low radiated power which allows IR-UWB to comply with Specific Absorption Rate (SAR) specifications [14]. As shown in Fig. 1 which compares four essential performances of a wireless link (ie. range, data rate, TX and RX energy efficiency in bit/nJ equals to the data rate divided by TX and RX power consumption), NB technologies are the best suited to achieve long range and data rates around 1Mbps. RFID systems appears to be the best suited when ultra-low power is needed since it can operate without battery but it fails to achieve medium or high data rates and are quite limited in terms of range (lower than 1m for HF-RFID systems). IR-UWB is a technology that allows both high and low data rates communications at low power. This is due to the ease of duty cycling transceivers which allows the energy efficiency to be always maximized. However, IR-UWB can only achieve short range communications when non-coherent receivers are used but this is not critical for the considered applications.

This paper is organized as follows. Section II deals with power saving strategies for IR-UWB emitters and receivers, and provides design considerations and power management schemes. In section III, prototypes of two emitters and of one receiver are presented with their measurement results and their expected power saving abilities.

II. POWER SAVING STRATEGIES IN IR-UWB

IR-UWB systems use pulse modulations to transmit data and the emitted symbols can also be coded by the presence or the absence of a particular pulse at a particular time. Since pulses duration (few ns) in UWB is generally short compared to the mean Pulse Repetition Period (PRP_{MEAN}), the power consumed by an IR-UWB emitter (resp. receiver) can be considered equal to a constant power P_{DC} when no pulse is emitted (resp. received). Otherwise, an extra energy E_{AC} is

consumed when a pulse has to be emitted (resp. received). In IR-UWB, it is also possible to write the power consumption P_C as follows:

$$P_C = P_{DC} + E_{AC} \times PRF_{MEAN} \quad (1)$$

where PRF_{MEAN} is the mean Pulse Repetition Frequency (PRF).

A. Pulse Modulation Choice

The dynamic part P_{AC} of the power consumption P_C can be written as a function of the bit rate D_b (bit/s) as follows:

$$P_{AC} = E_{AC} \times PRF_{MEAN} = E_{AC} \times D_b / N \quad (2)$$

where N is the mean number of bits conveyed by pulse which depends on the modulation used. To reduce the P_{AC} , a tradeoff must be done. On the TX side, the higher N is and the lower the P_{AC} is. On the RX side, a high N increases the complexity and reduces the P_{AC} . Thus, On-Off Keying (OOK) type modulations ($N = 2$) is a good compromise and can be demodulated with simple non-coherent receivers whose power consumption is less than the coherent receivers [17]. Moreover, standard OOK can be replaced by the Randomly Alternate OOK (RA-OOK) defined in [14] which allows the authorized bit rate and/or range to be increased compared to BPSK at the same mean Equivalent Isotropically Radiated Power (EIRP) thanks to the properties of pulse modulations [14].

B. Design Considerations for IR-UWB emitters

In IR-UWB, emitters are based on pulse generators which emit a pulse according to their control inputs when an active edge is provided on their trigger input. However, the pulse generator inputs need to be controlled with the help of a baseband manager in order to implement pulse modulations. For usual Pulse Amplitude Modulations (PAM) as OOK, the baseband manager requires only CLOCK and DATA digital inputs to provide the input signals needed by the pulse generator and its required trigger signal.

By using the following definition of the emitted power P_E :

$$P_E = E_P \times PRF_{MEAN} \quad (3)$$

where E_P is the emitted energy by each pulse, it is possible to defined the power efficiency η_P of an IR-UWB emitter as follows:

$$\eta_P = \frac{P_E}{P_C} = \frac{E_P \times PRF_{MEAN}}{P_{DC} + E_{AC} \times PRF_{MEAN}}. \quad (4)$$

When this equation is differentiated with respect to PRF_{MEAN} , it appears that the power efficiency remains constant and maximized regardless of PRF_{MEAN} if P_{DC} is null. Thus, to optimize the power efficiency of an IR-UWB emitter, it is necessary to minimize P_{DC} by using functions for which most of the power consumption is dynamic and depends on the number of switching per second as CMOS logic gates, or by using fast on/off switchable architectures [18] which can be easily implemented since pulse generation times are known from the pulse generator point of view on contrary to the

receiver side. However, it exists a particular value of PRF_{MEAN} for which P_{DC} can be considered negligible compared to P_{AC} without the use of power saving methods. Depending on the bit rate needs, it is critical to reduce the P_{DC} for energy efficiency optimization. Thus, for low rate applications, this parameter is the most limiting as far as the power consumption is concerned.

To illustrate this subsection, the design of an all-digital pulse generator, where different logic families can be used as CMOS logic or Current Mode Logic (CML), is considered. In the first case, the main component of the power consumption is P_{AC} and to improve power efficiency it is necessary to implement leakage reduction techniques to decrease P_{DC} [18], whereas in the second case the main part comes from P_{DC} . However, in this case, it is easy to change the power sharing between P_{DC} and P_{AC} by switching on/off CML gates by disabling their current sources [19] with the help of the baseband manager since pulse generation times are known.

TABLE I. TECHNICAL REQUIREMENTS FOR BIOMEDICAL APPLICATIONS

Application	Location	Sample Size (bit)	Sampling Frequency (Hz)	Bit Rate (bps)
Oxygen Saturation, Blood Pressure, Body Temperature	On-body	16	1/3600	4.4m
Drug Dosage, Glucose Monitoring	In-body			
Heart Beat Rate	On-body	8	1	8
ElectroCardioGraphy ^a (ECG)	On-body	12	250	3k
ElectroMyoGraphy (EMG)	On-body	16	4k	64k
Hearing Aid	On-body	16	22.05k	200k
Deep Brain Stimulation	In-body	-	-	1M
Capsule Endoscopy ^b	In-body	307.2k	6	1.8M
Brain Machine Interface	In-body	-	-	>10M

^a. For one channel only.

^b. Resolution of 320x320.

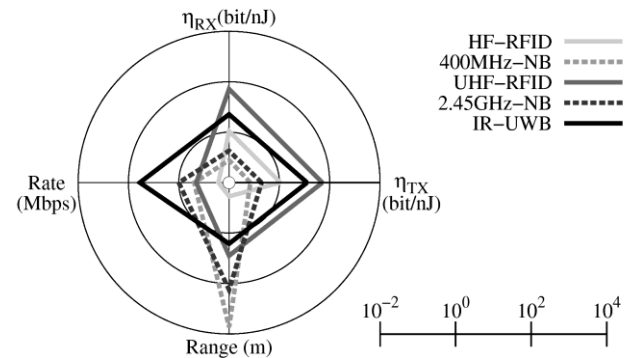


Fig. 1. Wireless technologies comparison from averaged results of previous published works (HF-RFID: [4][5], 400MHz-NB: [8][9][10], UHF-RFID: [6][7], 2.45GHz-NB: [11][12][13], IR-UWB: [14][15][16]).

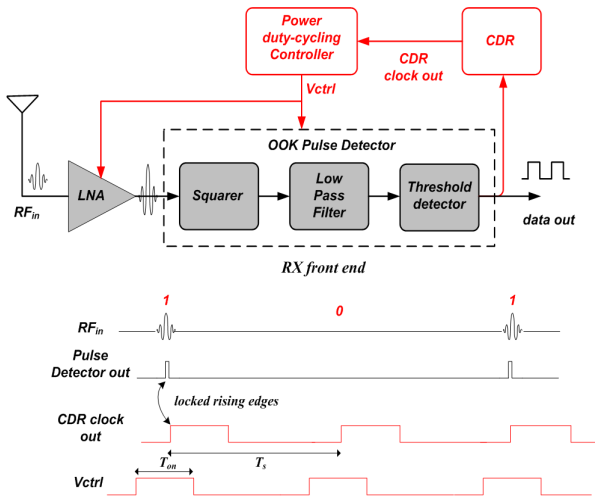


Fig. 2. Self synchronized and duty-cycled receiver architecture.

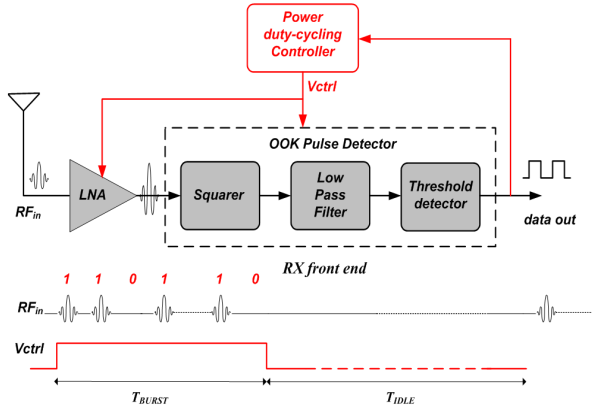


Fig. 3. Burst scale duty-cycled receiver architecture.

C. Power Management Schemes of IR-UWB receivers

Low-power consumption can be achieved for both NB and UWB receivers by using very simple architectures. Such architectures operate with OOK modulation scheme in non-coherent receivers when an envelope detector can be used for the demodulation of the encoded data. By using this technic, low power consumption can be achieved for the RF front end at the cost of sensitivity degradation. In [20], a NB receiver is presented with $54\mu\text{W}$ power consumption at 100kbps data rate with -72dBm sensitivity. An example of usual non-coherent IR-UWB receiver is shown in Fig. 2 and Fig. 3. The circuit is composed of a Low Noise Amplifier (LNA) and an OOK pulse detector. Non-coherent IR-UWB receivers can also achieve low power consumption at low and medium data rate by duty cycling RF front end blocks between two received symbols. [21][22][23] give some examples of duty cycled UWB receivers where microwatt range power consumptions are achieved for low and medium data rates.

Typical architecture of a self-synchronized and duty cycled receiver is given in Fig. 2. A duty cycled operation at the pulse scale which is used here needs the synchronization of the receiver with the emitter. This operation can be achieved by a

Clock and Data Recovery (CDR) which can be implemented with low power consumption [21][22]. However, an acquisition mode time slot, where the RX is always on while receiving a synchronization frame, is necessary. This acquisition mode, which has duration greater than several tens of bits [21], degrades the power consumption efficiency especially when a short amount of data has to be sent. After the acquisition mode cycle, the LNA is duty-cycled with a steady state on time duration T_{on} . T_{on} has to be set according to the peak to peak CDR jitter, the settling time of the RF front end blocks, and the pulse duration. The settling time of the RF front end blocks is typically around few nanoseconds, while the CDR jitter depends on the symbol rate and is typically equal to tens of nanoseconds at 1Msps. In [21], a self-synchronized and duty cycled UWB receiver exhibits $750\mu\text{W}$ power consumption for the entire receiver at 2Mbps data rate with -76.5dBm sensitivity.

To avoid the long acquisition mode time slot a duty cycle operation at the frame scale can be used instead of duty cycle operation at the pulse scale. The sequence of regularly spaced pulses is replaced by bursts giving the same mean data rate. To avoid changes in the mean EIRP, PRF_{MEAN} must be kept constant during 1ms which is the spectrum analyzer sweep time imposed by Federal Communications Commission (FCC) to measure the mean EIRP. The maximal burst duration is then given by:

$$T_{\text{BURST}} [\text{ms}] = \frac{\text{PRF}_{\text{MEAN}}}{\text{PRF}_{\text{BURST}}} \times 1\text{ms} = \eta_{\text{BURST}} \times 1\text{ms} \quad (5)$$

and the receiver can be turned off during:

$$T_{\text{IDLE}} [\text{ms}] = 1\text{ms} - T_{\text{BURST}} [\text{ms}] \quad (6)$$

By using $\text{PRF}_{\text{BURST}}$ much greater than PRF_{MEAN} , the frame scale duty cycling ratio η_{BURST} is low and a great improvement in the power consumption can be achieved with relaxed synchronization constraints. The receiver does not also need a CDR and its associated acquisition time slot, since its output (data out) can be sampled and stored in a memory sized according to T_{BURST} and $\text{PRF}_{\text{BURST}}$, and demodulated during T_{IDLE} . Obviously, this communication scheme is only practicable for low and medium mean data rates since the instantaneous data rate is increased. Such frame scale duty cycled receiver architecture is depicted in Fig. 3. The synchronization between the burst position and the turn on command has relaxed constraints and can be achieved by a low power microcontroller where the clock could be synchronized with other clocks of the network using standard synchronized networks protocols or by using an ultra-low power wake up triggering protocol which is out of the scope of this paper.

III. EXAMPLES OF MEASURED PROTOTYPES

To illustrate the proposed power saving strategies for IR-UWB, two emitters and one receiver are presented. They have been designed using the 130nm CMOS technology from STMicroelectronics and measured under a supply voltage of 1.2V.

A. Versatile IR-UWB emitter

A versatile transmitter with tunable bandwidth has been proposed in [24]. This pulse generator uses elementary pulse combination method which allows an arbitrary pulse to be synthesized according to the targeted bandwidth. As shown in Fig. 4, it is constituted of an elementary pulses generator using a CMOS Voltage Controlled Delay Line (VCDL) and a combination circuit using multiple parallel H-bridges. Its core area is $0.25 \times 0.45 \text{ mm}^2$ and its die area is $0.6 \times 1.3 \text{ mm}^2$. From measurement results, it is able to generate pulses composed of 1 to 8 elementary pulses with a central frequency between 2.35GHz and 5.55GHz. When it is programmed to generate a 3-5GHz pulse, it achieves 0.9Vpp pulse which leads to an energy emitted by pulse E_P of 2.08pJ on a 100Ω differential load. In the worst case (when all elementary pulses are set to their maximum values), P_{DC} is equal to 0.58mW and E_{AC} is equal to 209pJ/pulse. As CMOS logic has been only used, P_{DC} is only due to high leakage currents since MOS transistors have been designed large enough to achieve very fast pulses. To stay energy efficient for low data rate applications, leakage reduction methods are required but not implemented here. For high data rate application the maximum energy efficiency is close to 4.78bit/nJ whereas it falls to 0.17bit/nJ@100kbps.

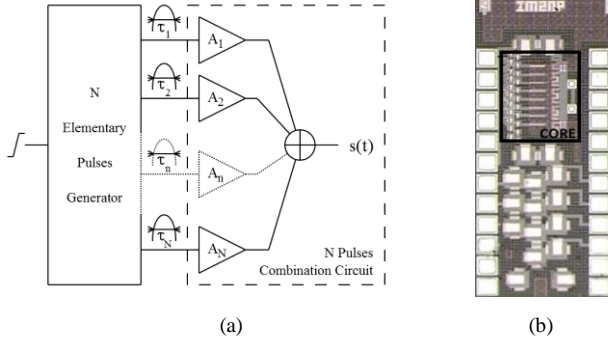


Fig. 4. Architecture (a) and die photography (b) of the versatile transmitter.

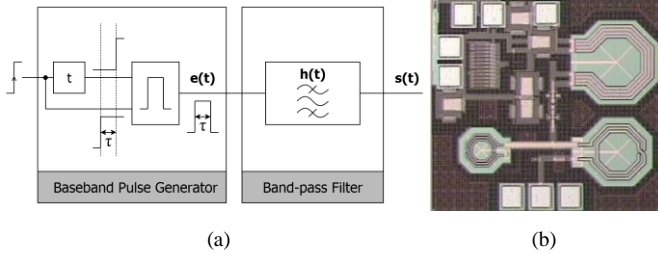


Fig. 5. Principle (a) and die photo (b) of the ultra low-power transmitter.

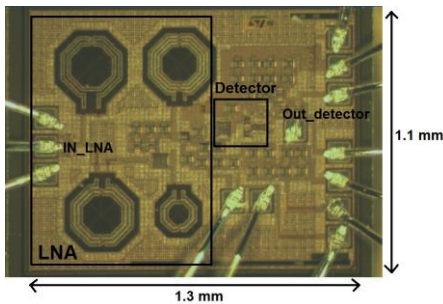


Fig. 6. Die photography of 3-5GHz IR-UWB Front End receiver.

B. Ultra low-power 3.1-10.6GHz emitter

To reach energy-efficient IR-UWB transmitter for low bit rates and high bit rates, a pulse generator based on filter excitation technique has been presented in [18]. As shown in Fig. 5, this method requires the generation of a baseband pulse which is filtered by a band-pass filter. The baseband pulse generator is constituted of a CMOS VCDL and the band-pass filter is a 3.1-10.6GHz third order Bessel filter. To reduce the static part of the power consumption and also the leakage currents, an on/off system which uses low leakage MOS transistors has been designed to supply the baseband pulse generator using high speed MOS transistors. The measured pulse generator has a die area of $0.7 \times 0.8 \text{ mm}^2$ and exhibits 2Vpp pulses centered at 6.3GHz with a 10dB bandwidth of 5.2GHz, which leads to an energy emitted by pulse of 2.15pJ on a 50Ω load. From measurement, P_{DC} is equal to $3.91\mu\text{W}$ and E_{AC} is equal to 68pJ/pulse which gives a power consumption of $7.3\mu\text{W}$ at 100kbps and 3.4mW at 100Mbps for an OOK modulation. This leads to a maximum energy efficiency of 14.7bit/nJ when high data rate applications are targeted and an energy efficiency of 13.7bit/nJ@100kbps.

C. 3-5GHz IR-UWB Front End receiver

In [14], a low power 3-5GHz IR-UWB receiver front-end for WBAN and biomedical applications is proposed. This non-coherent receiver is designed for OOK signaling and uses very simple front end architecture, such as depicted in Fig. 2 and Fig. 3, based on a high gain LC filter LNA followed by a pulse detector composed of a self-mixing squarer, a low pass filter and a threshold detector. This asynchronous front end receiver does not need any external frequency reference. The LC filter LNA provides a second order band pass response helpful for unwanted signals rejection. Since self-mixing squarer conversion gain drops drastically at low input levels, the LNA must provide enough gain to allow the signal to be higher than the noise floor of the following stages at the targeted maximum communication range. For this purpose the voltage gain of the LNA has been maximized resulting in a high power consumption which represents the main contribution of the whole front end receiver consumption. Fig. 6 shows the microphotograph of the die. A summary of the front end receiver performance is given in TABLE II.

TABLE II. SUMMARY OF 3-5GHz UWB-IR RECEIVER PERFORMANCE

Parameters	Values
Die Area	1.43 mm^2
Bandwidth	3-5GHz
LNA : Voltage gain Noise figure	$35.3 \text{ dB} \pm 0.2 \text{ dB} \parallel 3.8 - 5 \text{ dB}$
RX power consumption: Always On Always off	$14.4 \text{ mW} \parallel 36 \mu\text{W}$
RX energy consumption @ maximum data rate	$144 \text{ pJ} @ 100 \text{ Mbps}$
RX energy efficiency	$6.94 \text{ bit/nJ} @ 100 \text{ Mbps}$
	$0.007 \text{ bit/nJ} @ 100 \text{ kbps}$
RX sensitivity @ BER = 10^{-3}	$-59.3 \text{ dBm} @ 100 \text{ Mbps}$
	$-89.3 \text{ dBm} @ 100 \text{ kbps}$
RX minimum consumption in burst mode for $T_{BURST} = 1 \mu\text{s}$, $T_{FRAME} = 1 \text{ ms}$	$50.4 \mu\text{W} @ 100 \text{ kbps}$
RX energy efficiency in burst mode for $T_{BURST} = 1 \mu\text{s}$, $T_{FRAME} = 1 \text{ ms}$	$1.98 \text{ bit/nJ} @ 100 \text{ kbps}$

The receiver sensitivity is $-89.3\text{dBm}@100\text{kbps}$. The receiver power consumption is 14.4mW at the maximum data rate of 100Mbps and shows an energy efficiency of $6.94\text{bit/nJ}@100\text{Mbps}$ which falls to $0.007\text{bit/nJ}@100\text{kbps}$. This front end has not been designed to allow pulse scale duty cycling which requires nanosecond scale T_{on} time and it is also not possible to optimize the energy efficiency easily. However, it can be easily used with a burst frame duty cycling such as described in Fig. 3. In this case, the receiver could consume only $50.4\mu\text{W}$ at 100kbps mean data rate which leads to an energy efficiency of 1.98bit/nJ if turn on/off times are considered instantaneous with T_{BURST} equals to $1\mu\text{s}$, $\text{PRF}_{\text{BURST}}$ equals to 100Mbps , and T_{IDLE} equals to $999\mu\text{s}$. The total frame period is also set to 1ms to comply with the FCC requirements for EIRP measurement.

IV. CONCLUSION

Due to the gated nature of IR-UWB communications, it appears that the higher the data rate is, the more energy-efficient IR-UWB emitters and receiver are. IR-UWB is intrinsically well-suited for short range healthcare applications when high data rate are required. However, many healthcare applications require low data rate applications. It is then feasible to drastically reduce the static part of the power consumption to achieve an energy efficiency closed to its maximum. To do so, some design strategies for emitters and power management schemes for receivers have been proposed and their efficiency is demonstrated on existing circuits.

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