Ultra-WideBand Transmitter for Wireless Body Area Networks

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Abstract— **The successful realization of a Wireless Body Area Network (WBAN) requires innovative solutions to meet the energy consumption budget of the autonomous sensor nodes. The radio interface is a major challenge, since its power consumption must be reduced below $100\mu W$ (energy scavenging limit). The emerging Ultra-WideBand (UWB) technology shows strong advantages in reaching this target. First, most of the complexity of an UWB system is in the receiver, which is a perfect scenario in the WBAN context. Second, the very little hardware complexity of an UWB transmitter offers the potential for low-cost and highly integrated solutions. Finally, in a pulse-based UWB scheme, the transmitter can be duty-cycled at the pulse rate, thereby reducing the baseline power consumption. We present a low-power UWB transmitter that can be fully integrated in standard CMOS technology. Measured performances of the pulse generator are provided, showing the potential of UWB for low power and low cost implementations.**

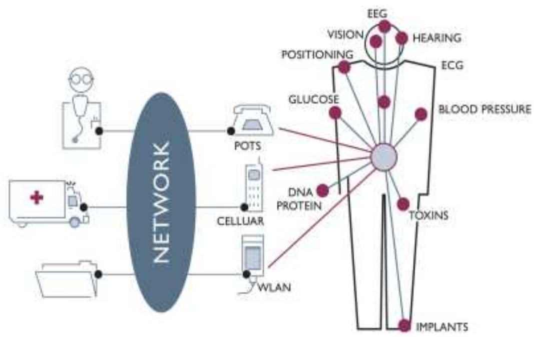

Fig. 1. The technology vision for the year 2010: people will be carrying their personal body area network and be connected with service providers regarding medical, sports and entertainment functions.

I. Introduction

It is expected that technology will enable people to carry their personal body area network (BAN) [1] that provides medical, sports or entertainment functions for the user (Figure 1). This network comprises a series of miniature sensor/actuator nodes each of which has its own energy supply, consisting of storage and energy scavenging devices. The successful realization of this vision requires innovative solutions to remove the critical technological obstacles to realize the BAN sensor nodes. First, the overall size should be compatible with the required form factor. This requires new integration and packaging technologies. Secondly, the energy autonomy of current battery-powered devices is limited and must be extended. Finally, the energy consumption of all building blocks needs to be drastically reduced. This last point is a major challenge for the radio interface.

The average power consumption of the radio in the sensor node must be reduced below 100μW [2]. Today's low power radios such as Bluetooth and Zigbee [3] cannot meet this stringent requirement and new innovative solutions must be found. For instance, if one takes the body environment and the RF properties of the body into consideration, the air interface can be optimized for the body-area network context. A further optimization can be done by taking into account the simple network topologies, the relatively small number of nodes and the specific requirements of body monitoring applications, such as latency. Thanks to the low data rate of typical sensors, the radio can be operated in burst mode with a minimal duty cycle. Moreover, the power budget in the sensor node and in the master device are very different. The sensor has an extremely tight power budget, whereas the master has a slightly more relaxed power budget. In the air interface definition this asymmetry is exploited by shifting as much complexity as possible to the master device. For all these reasons Ultra-WideBand (UWB) modulation is believed to have strong advantages compared to more traditional narrowband radio communication. Indeed, in pulse-based UWB, the transmitter only needs to operate during the pulse transmission, producing a second duty cycle inside the burst. Since most of the complexity of UWB communication is in the receiver, this allows the realization of an ultra-low power, lowest-complexity transmitter and shift the complexity as much as possible to the receiver in the master.

In this paper, we present an UWB transmitter with low power consumption and low complexity to be used in the body-area network context. Section II discusses the general transmitter architecture and in Section III we describe the pulse generator implementation as being the central component in the transmitter. Measurement results of the pulse generator are provide in Section IV. Section V discusses the center frequency and bandwidth calibration of the UWB pulses and Section VI concludes the paper.

II. UWB Transmitter

The FCC has recently authorized Ultra-Wideband (UWB) communication between 3.1GHz and 10.6GHz [4]. An UWB signal must have a minimum bandwidth of 500MHz. This means that the UWB spectrum can be subdivided in several bands. UWB systems with different signal bandwidths have been proposed and are being studied in various standards [5]. We propose in this paper a pulse generator that is flexible in bandwidth and that is targeted to low data-rate applications. It offers a maximum of 2GHz signal bandwidth, useful for positioning applications, and a minimum of 500MHz, which could be required for multiband systems. Our system operates between 3GHz and 5GHz, where we can reach the best power consumption performance. Between 5GHz and 6GHz, interference with WLAN applications will anyway put severe limitations on the use of UWB.

The pulses generated by the transmitter are completely defined by their center frequency and their bandwidth. As will be explained later in the paper, a predefined shape is created for the envelope of the pulse, thereby fixing the signal bandwidth. This envelope is then upconverted to a desired center frequency in order to fit the spectrum inside the 3.1GHz to 10.6GHz mask specified by the FCC. This specific signaling scheme will be defined as a "carrier-based" UWB due to the separate generation of the carrier and the envelope. The overall UWB transmitter architecture is depicted in Figure 2. An important issue in impulse radio is the calibration of the pulse spectrum. As shown in Figure 2, center frequency F_c and bandwidth B_w calibration circuits are used to set these two quantities.

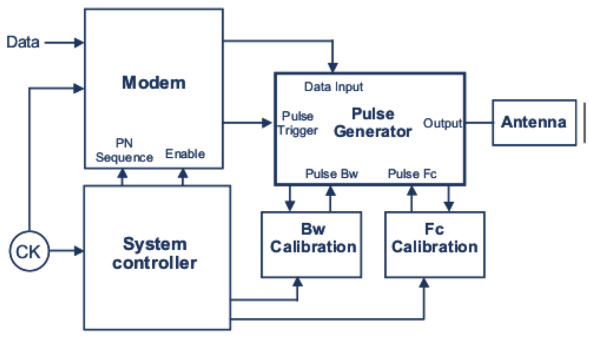

Fig. 2. Impulse-based ultra-wideband transmitter architecture

The system controller in Figure 2 defines the parameters of the communication according to a specified physical layer. It sets the PN sequence allotted to the user as well as the bandwidth and the center frequency of the pulse. Indeed, time-hopped CDMA [6] is often used for multiple access in UWB and to reduce spectral spikes. Therefore, we consider a system controller providing a predefined pseudonoise (PN) sequence, translated by the modem into triggering instants for the pulse generator. This chip sequence has a length equal to the number of pulses per bit. For each chip, the pulse generator creates a pulse that is modulated in time according to Pulse-Position Modulation (PPM), and additionally shifted according to the chip value, as in the general case both shifts need not to be equal and can be added.

III. UWB Pulse Generator

Traditional UWB solutions use components, such as step recovery diodes [7] or choke inductors [8] that are difficult to integrate. CMOS solutions up till now have only been proven in simulations [9] and predict a power consumption that is more than one order of magnitude higher than the solution proposed here. A simpler way to realize the short high frequency UWB signals is by gating an oscillator as proposed in [10]. The oscillator center frequency defines the center frequency and the gate duration the bandwidth. The problem with this technique is that the output pulse features a square shape. The high sidelobe power must be filtered, resulting in poor system efficiency. Moreover, in multiple-band systems, a good sidelobe rejection is mandatory for a good adjacent channel power rejection. The approach presented here is an oscillator whose output amplitude is modulated by a triangular signal to generate an UWB pulse at a given center frequency. The smooth pulse shape offers more than 20dB of sidelobe rejection thereby avoiding the need of additional filtering for regulation purposes or for adjacent channel power rejection. The operation principle is depicted on the top of Figure 3.

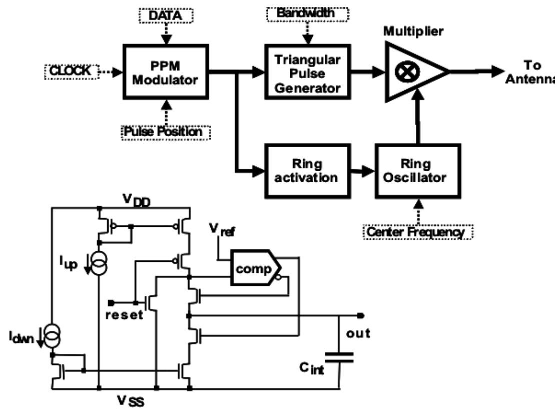

Fig. 3. Block diagram of the pulse generator (top) and circuit principle of the trianglar pulse generator (bottom)

Pulse-based UWB signals in the GHz range with PPM modulation require the generation of accurate timing in the order of nanoseconds. Integrating a fixed current over a linear capacitor generates a voltage that is proportional to time. By comparing this voltage to a reference voltage, a precise time delay is created. This principle, shown for the triangular pulse generator (see bottom of Figure 3), is used in several blocks of the pulser. In this example, charging a capacitor creates a triangular voltage with a time duration that can be modified by changing the capacitance value. By this operation we tune the envelope of the pulse by a few nanoseconds, resulting in a bandwidth between 2GHz and 500MHz. The baseband pulse is then up-converted to a desired RF center frequency by means of a multiplier. The multiplier is a switching differential pair whose tail current is modulated by the baseband triangular waveform. The carrier generator is a three-stage differential ring oscillator. Ring oscillators typically have very low startup times due to their low Q factors. Forcing initial conditions on the circuit has further decreased the startup time. The oscillator reaches its steady state in less than two cycles. Switching on and off the carrier generator between the pulses saves power. Finally, since the system features Pulse-Position Modulation (PPM), the pulse position is varied by delaying the clock signal with a value depending on the level at the data input. Using the capacitor charging principle, different delays are created by changing the capacitance of a discrete capacitor array.

IV. Measurement results

A prototype implementation of the pulse generator described in Section III has been realized in a logic UMC 0.18μm technology. The top picture of Figure 4 shows the measured spectrum of pulses with a bandwidth of 528MHz together with the corresponding time waveform in the top left corner. Three traces are depicted showing three different center frequency settings. Although we target low power applications, the bandwidth and center frequency values are taken from the three first bands of the multiband OFDM proposal in the IEEE 802.15.3a standard [5] as an example. The bottom picture of Figure 4 shows the 2GHz spectrum together with its time domain waveform.

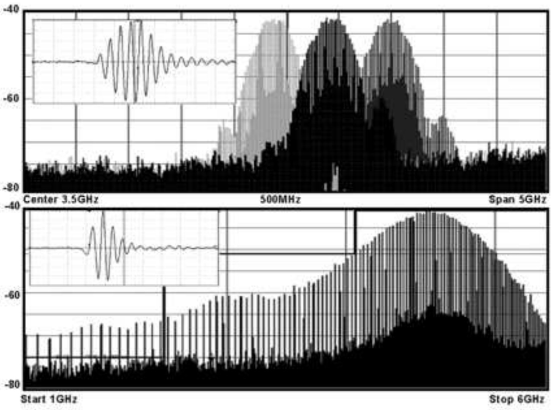

Fig. 4. Measured 528MHz (top, with 3.432GHz, 3.960GHz and 4.488GHz center frequency) and 2GHz (bottom) spectra and time waveform.

Figure 5 shows both modulated positions in time-domain for a 528MHz (top) and a 2GHz (bottom) bandwidth setting. A maximum output voltage of 200mV peak-to-peak on 50Ω is measured. These signals have been measured with a 20GS/s Tektronix TDS7404 oscilloscope and are shown in fast acquisition mode. The position modulation of the pulses can be tuned from 4ns up to 15ns.

Characteristics of this realization are provided in table I and compared to similar state of the art designs. For a pulse bandwidth of 1GHz, the measured active power consumption of the system is 2mW for a pulse repetition rate of 40MHz, that is 50pJ per pulse energy consumption for this repetition rate. A chip microphotograph is given in Figure 6. The chip size is 0.6x0.6 mm^2 including the decoupling capacitors, bondpads and ESD protections. The area of the active part of the chip is 0.2x0.3 mm^2.

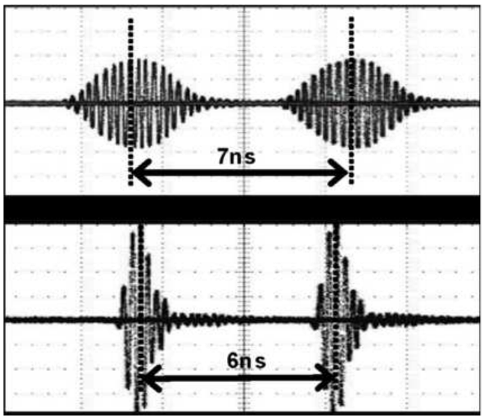

Fig. 5. Measured time waveform of overlapping pulses showing both position modulations for 528MHz pulses (top) and 2GHz pulses (bottom).

	[7]	[8]	[9]	this work
Technology	Discrete	CMOS	BiCMOS	CMOS
Ext Compts	SRD	Choke ind.	None	None
Status	Measured	Simul	Simul	Measured
Output	200mV	1.8V	200mV	200mV
Modulation	/	PPM	PPM	PPM
Pulse length	300ps	200ps	250ps	1.1–4.5 ns
P. cons.	/	57mW	30mW	2mW

TABLE I

Measured performances of the pulse generator and comparison with state of the art.

V. Center frequency and bandwidth calibration

A. *Required precision on center frequency*

Center frequency calibration is done using a phase-locked loop (PLL) [11]. In the creation of wideband signals, phase noise is not an important issue and the PLL can be optimized for fast start-up time. Moreover, in a burst mode operation the calibration of the center frequency can be done only once per burst. To reduce the baseline current consumption, the PLL can then be switched off while storing the tuning voltage value, leaving the ring oscillator in free-running mode. This type of operation relies on the fact that signals with a wide bandwidth make the requirement on the center frequency far less stringent. A drift in the center frequency is usually not acceptable in narrowband communication since the ratio between signal bandwidth and center frequency is very small. In UWB, if energy detection is used at the reception, a drift of the signal spectrum by a fraction of the center frequency keeps most of the power inside the reception window.

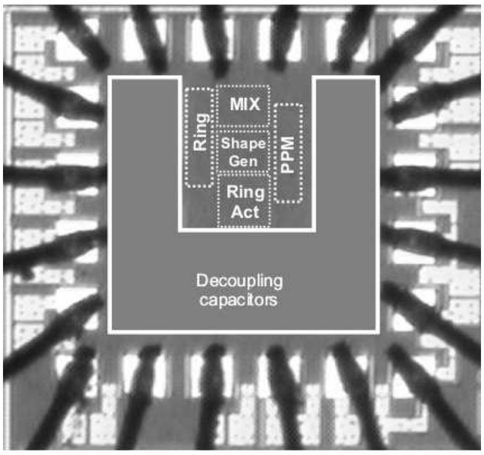

Fig. 6. Chip microphotograph of the UWB pulser realized in CMOS 180nm technology.

B. Bandwidth control

A fixed current, I, integrated over a linear capacitor, C, is used to create the triangular waveform. A Calibration of this triangular waveform must be done to control the bandwidth of the signal. The slope of the triangle that finally defines the duration of the triangle is given by the ratio $\frac{I}{C}$. To accurately fix this ratio, the duration $\frac{V_{ref}C}{I}$ must be compared to the time reference available in the system, which is the clock signal. This can be done digitally. Defining a reference integrating circuit with a capacitor value oversized by a large known factor K, the slope of this reference integration can be calibrated by counting the number of clock cycles for the integration voltage to reach the reference voltage. This number of cycles can then be compared to the desired number of cycles in order to recalibrate the slope.

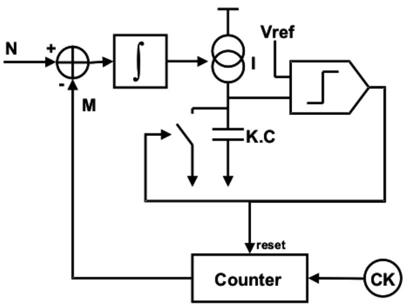

Fig. 7. Current calibration using a reference integrator circuit with an oversized capacitor K.C.

Finally, the desired duration of the triangular voltage used in the generation of the UWB pulse is defined by

$$\frac{C}{I}V_{ref} = \frac{N}{K}T_{clock} \tag{1}$$

VI. Conclusion

We have proven the feasibility of an ultra-low power UWB pulser in a logic CMOS technology. No external inductor, no special antenna or no step recovery diode is required. Smooth shapes of 500MHz up to 2GHz bandwidth are realized with reduced sidelobe power to facilitate the compliance with the FCC specification mask. A 50pJ per pulse is measured at a pulse repetition rate of 40MHz. This work proves the potential of UWB for short-range communication. Given the current momentum around it, we can expect further enhancement both at algorithmic and circuit level to make UWB become a key technology for ultra-low power communications.

VII. Acknowledgment

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