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Wearable System-on-a-Chip UWB Radar for Health Care and its Application to the Safety Improvement of Emergency Operators

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Abstract— **A new wearable system-on-a-chip UWB radar for health care systems is presented. The idea and its applications to the safety improvement of emergency operators are discussed. The system consists of a wearable wireless interface including a fully integrated UWB radar for the detection of the heart beat and breath rates, and a IEEE 802.15.4 ZigBee radio interface. The principle of operation of the UWB radar for the monitoring of the heart wall is explained hereinafter. The results obtained by the feasibility study regarding its implementation on a modern standard silicon technology (CMOS 90 nm) are reported, demonstrating (at simulation level) the effectiveness of such an approach and enabling the standard silicon technology for new generations of wireless sensors for heath care and safeguard wearable systems.**

I. INTRODUCTION

The recent advances in the standard CMOS silicon technologies, has led up to highly miniaturized, low cost, and ultra low power integrated circuits. This fact allows the realization of high-potential systems-on-a-chip for a large number of new applications. One of the most interesting fields of application of fully integrated systems-on-chip is represented by the emerging wireless body area networks (WBANs) for the human health care and safeguard.

The wearable UWB radar systems allows us to monitor directly the mechanics of heart and chest, instead of their indirect measurements by means of electrocardiograph (ECG) or echocardiograph systems. However, the limitations of the ECG for the detection of cardiac pathologies [1] and the high costs of the echocardiography, added to the evidence of the respiratory effects on the cardiac activity [2], have led us to research a new cardiac investigation method for an exhaustive cardiac monitoring.

The work described in this paper is part of the ProeTEX project (FP6-2004-IST-4-026987), a European Integrated Project aimed at developing a new generation of equipments for the market of emergency operators, like fire-fighters and Civil Protection rescuers. The main goal is to improve operator's safety when working in dangerous condition, but also to increase the efficiency and the coordination during interventions. The purpose of the project is not only to build devices based on currently available technologies, but also to develop a new generation of electronic devices, mainly based on textile technologies, in order to reduce their weight and volume, thus improving their wearability. Based on these technologies, the consortium of the project is developing both sensors to measure physiological and environmental variables, and also flexible wearable antennas to enable the transmission of data collected by the sensors. Moreover, ProeTEX partners are designing low-weight flexible batteries for energy storage. In this way the final output of the project will be a textile platform where all the monitoring, communication and power management systems are integrated in a fully functional wearable garment. The first prototype has been designed following the specification given by the end users partners (civil protections and firefighters) [3]. It mainly integrates sensors developed with already assessed technologies, in order to monitor physiological parameters (heart and breathing rate, body temperature), position and motion of the operators, and environmental temperature. The current release consists in two garments: an inner garment, based on a cotton tee-shirt, which adheres to the skin of the operator and hosts the sensors for physiological measures (heart and breathing rate, internal temperature), and an outer garment based on a jacket containing the other sensors (motion/activity, environmental temperature), the alarm systems, an electronic unit for signal processing, the batteries and a textile antenna. Moreover,one of the main aim of the project is to perform research activity on novel sensors and microsystems to be integrated in future prototype releases such as the ones described in this paper..

This paper focuses the afore mentioned topic and reports the idea of a novel wearable wireless interface for monitoring the heart wall and chest movements, for a contactless detection of the heart and breath rates.

The paper is organized as follows. In Section II, the idea of the next generation wearable interface for the human healthcare and safeguard is presented. In Section III, the main results obtained by a feasibility study of an ultra-wide-band (UWB) radar sensor for monitoring the heart and breath rates are summarized. Finally, in Section IV, the conclusions are drawn.

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II. WEREABLE WIRELESS INTERFACE FOR HEART MONITORING: SYSTEM OVERVIEW

In February 2002 the Federal Communications Commission (FCC) gave the permission for the marketing and operation of a new class of products incorporating ultra-wide-band

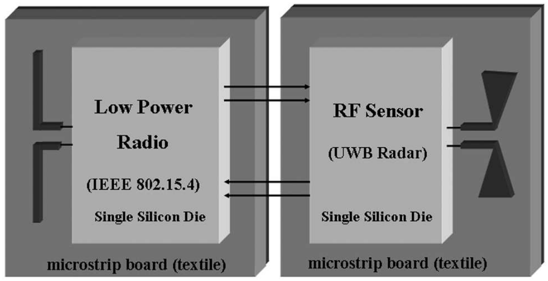

Fig. 1. Wereable wireless interface for the heart monitoring: system idea.

(UWB) technology [4]. The FCC, through a modification of the 47 CRF Part 15 regulations [5], decided the allocation of the UWB systems in a unlicensed band 7.5 GHz wide, in the range of the radiofrequency spectrum 3.1-10.6 GHz. Since UWB systems are intended to operate in regions of spectrum in which other services are already operating, the mask of the maximum power spectral density (PSD) allowed for UWB devices has been set to very low values (-41.3 dBm/MHz in the 3.1-10-6 GHz band).

One of the most promising class of applications of the UWB systems consists of the medical imaging. Particularly, we are interested in realizing UWB radar sensor for the monitoring of the heart wall and chest movements, in order to detect in real time the heart and breath rates, respectively.

The modern silicon technologies (the transistors of the standard CMOS 90 nm technology have cut-off frequencies higher than 150 GHz) allow us to realize ultra-small and ultra-low-power wireless UWB sensors for WBAN applications. WBANs consist of sensor networks, in which the sensors are placed around the human body in order to monitor constantly the vital parameters. The information collected by these sensors can be sent, by means of radio-frequency data link, toward remote data acquisition and signal processing units or even to a personal server, which can forward the data to the medical centers and hospitals by means of internet. In this way, the medical staff can investigate on the manifesting of the heart deseases over the all daily activity of the subject under observation.

The overall system idea is shown Fig. 1. It consists of a fully integrated UWB radar sensor and a low-power radio interface. Both for the radar system and radar interface, we deal with their realization by means of a standard CMOS 90 nm by STMicroelectronics (STM).

In the scheme of Fig. 1 each antenna is realized on a microstrip substrate; however, in a most advanced realization, they can be realized directly by means of proper conductive layers tissued within clothes [6]. In particular, such a sensor will be included into the inner garment weared by emergency operators, which is shown in Fig. 2.

The proposed fully integrated UWB radar (Fig. 3) detects the heart and breath rates by sending very short electro-magnetic pulses (hundreds of picoseconds) and detecting the echoes generated by the reflections at the heart wall (due to the different characteristic impedances between the heart muscle and the blood flowing inside the heart itself). The basic principle of operation is described in [7], [8].

Fig. 2. Inner garment in which will be inserted the wireless interface of Fig. 1 (it will be inserted in the selected area).

It is worth mentioning that, the UWB pulses (3.1-10.6 GHz) are not influenced by clothes or blankets and they can be exploited efficiently for the monitoring of the heart rate [8].

Moreover, the UWB pulses have a very low-density spectrum if compared with the narrow band conterparts, reducing drastically the risk of cellular ionization on the human beings [9]–[14]. In addition, since UWB transceivers present a lower circuit complexity, the requirements in term of power consumption are moderate, and this allows us to maximize the energy saving for a longer life of the battery.

III. System-on-a-chip UWB Radar Sensor for the Heart and Breath Rates Monitoring

The main block of the proposed wereable wireless interface for the monitoring of the heart is represented by the UWB radar sensor. The radar architecture is shown in Fig. 3.

In detail, the system operates by sending extremely short electromagnetic pulses toward the heart. Due to the different characteristic impedance of the two media, a part of the incident energy is reflected at the interface between the heart muscle and the blood which flows inside, due to the different characteristic impedances of the two media. After a delay equal to the time-of-flight of the pulse, from the radar to the heart and then again to the radar, a delayed replica of the transmitted pulse is correlated with the echo received from the heart wall. The typical flight time amounts to 2 ns (in accordance with the layers of the Gabriel's model), whereas

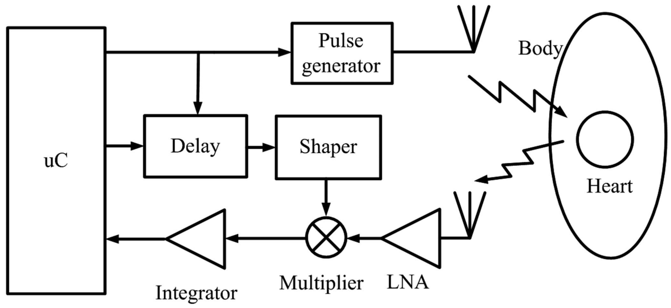

Fig. 3. Block diagram of the proposed fully integrated UWB radar for the detection of heart and breath rates.

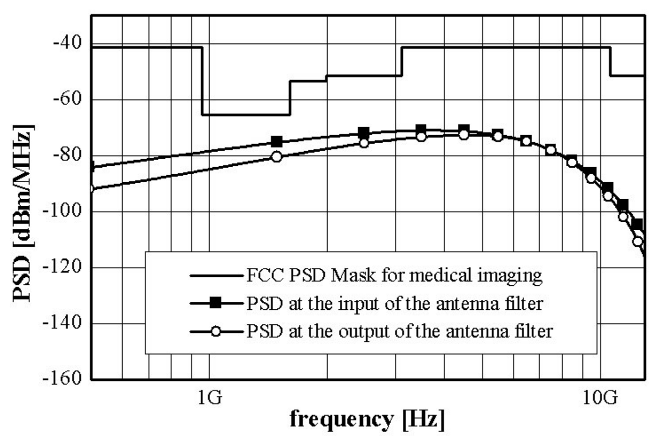

Fig. 4. Power Spectral Density (PSD) of the train of gaussian monocycle pulses (200 ps short and 1.2 Volts peak-to-peak wide each) with a PRF of 1 MHz and that obtained at the output the antenna filter.

the maximum heart-wall displacement (1.5 cm) causes a variation of 400 ps. The delay can be digitally programmed (to be remotely set as well), in order to calibrate properly the wearable device on the person under observation and extend its adaptibility over the all range of the anatomical variability of the population.

A pulse repetition frequency (PRF) greater than 1 MHz allows us to consider the heart almost motionless between two consecutive pulses.

The voltage amplitude of the output signal of the multiplier reaches the maximum when the received echo and the delayed local replica of the transmitted pulse are perfectly time-aligned. Then, the amplitude of the signal at the output of the multiplier is related to the heart position.

The output voltage of the receiver front-end is averaged by integrating over a large number of pulses. This operation allows us to increase significantly the signal-to-noise ratio at the output of the receiver. Moreover, the amplitude of the continuous output signal of the integrator is related to the time-varying position of the moving object under observation (the heart wall, in our case). Thus, the output signal provided by the integrator includes the tones of the heart beat and the breathing frequency.

A. Summary of the Feasibility Study of the UWB Radar Sensor

In order to demonstrate the feasibility of such a UWB radar sensor, a system analysis has been carried out by means both a theoretical model and simulations by means of CAD tools [15], [16].

Firstly, the theoretical analysis has been carried out. We have developed a theoretical model of the channel in which the pulse propagates. The properties of the body tissues have been extracted by the parametric models developed by C. Gabriel and his collegues at the Brooks Air Force Base (U.S.A.) [17], [18]. As for the layers, we considered the model proposed in [8], which is based on the Visible Human Project and the Gabriel's data book. The loss channel model has been derived taking into account i) path loss, ii) attenuation in the tissues and iii) losses due to the reflections at the interface between different tissues. Near field equations have been employed to carry out the analysis, since the UWB radar sensor operates in proximity of the human chest. The overall losses result equal to about 60 dB at 3 GHz and they became higher as the frequency rises (about 160 dB at 10 GHz). Simulation results have shown that the average power loss of the pulse in the 3.1-10.6 GHz band is aproximately equal to 80 dB.

Then, the specifications of the building blocks have been derived taking into account the characteristic performance of the standard process CMOS 90 nm by STM, which has been considered for their implementation on silicon.

Then, the system analysis by means of CAD tools has been carried out. In order to validate the theoretical model of the radar, the overall system has been simulated by means of the Ptolemy simulator within Agilent ADS2005A™. Each building block was characterized by frequency response and noise contribution achievable realistically with the CMOS 90 nm process. Simulation results have confirmed the feasibility of a fully integrated system-on-a-chip UWB radar sensor on silicon. The most representative results are reported in Figg. 4, and 5.

The power spectral density (PSD) of a train of a sequence (train) of pulses (200 ps short and 1.2 Volts peak-to-peak wide each) with a PRF equal to 1 MHz is shown reported in Fig. 4, both for the input and output of the antenna filter. Note that the radar signal is compliant with the FCC mask for the UWB medical imaging systems.

The voltage at the output of the integrator is shown in Fig. 5. This signal has the same frequency of the time-varying surface (i.e. the heart wall) under observation. A heart movement having a period of 20 ms has been considered. The period has been compressed with respect to the real heart movement in order to reduce the simulation time. This does not impair the analysis since the radar reaches widely the steady state within ten milliseconds.

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The recent advances in silicon CMOS technology allow the realization of more and more miniaturized, low-cost

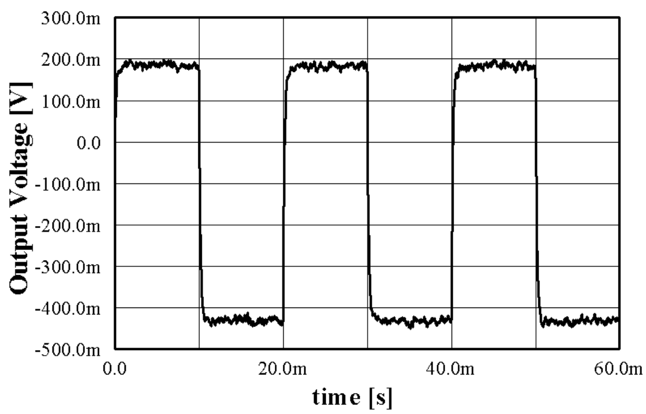

Fig. 5. Output voltage of the integrator filter of the radar sensor. The output signal has the same frequency of the movement imposed for the heart wall. A time-varying surface with a period of 20 ms has been considered for the simulation (this period is short with respect to the real heart moving, in order to reduce the simulation time. This does not impair the analysis since the radar reaches widely the steady state widely within ten ms).

and low-power integrated system-on-a-chip sensors. These sensors can be employed in the wireless body area networks, for advanced and continuous monitoring of vital parameters.

Particularly, the system overview of a next generation of wearable wireless sensors for human health care and safeguard has been presented herein. Such a system is composed by a novel fully integrated ultra-wide-band radar sensor for the detection of the heart and breath rates and a low-power radio interface (IEEE 802.15.4, ZigBee), which collects the data provided by the sensor and sends these data to an acquisition unit or even in internet by means of a personal server. Thus, the physiological data of a person under observation (e.g. a patient) can be sent in real time to the hospital and, then, the doctors could act in-time in case of anomalies in the vital parameters monitored.

A detailed feasibility study of the UWB radar on silicon technology (CMOS 90 nm) has been carried out, by considering both theoretical and CAD tool simulations. The simulation results have shown a wide agreement with the theoretical model of the radar, demonstrating the feasibility of the proposed system-on-a-chip radar sensor realized on a modern silicon technology.

B. Future Works

Present and future works are addressed to the antenna design, channel model verification by means of measurements, building blocks design and their co-integration, system-on-a-chip prototyping and experimental characterization.

V. Acknowledgments

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