



A pulse oximeter system, *OxiSense*, with embedded signal processing using an ultra-low power ASIC designed for testability

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ABSTRACT

This paper presents a complete IoT enabled pulse oximeter (PO) system, called *OxiSense*, made using a custom designed low power application specific integrated circuit (ASIC) for signal conditioning. One of the novel aspects of the developed system is the testability of all the important modules of the ASIC (both analog and digital) using auxiliary circuits implemented in the ASIC. Another novel aspect is a new embedded and efficient signal processing algorithm which is robust to small motion artifacts. This new algorithm has been implemented on a low-power micro-controller (embedded processing mode) as well as on PC using Python (remote processing mode). The PO ASIC is fabricated in 180 nm mixed-mode CMOS technology and it works at 1.8 V supply voltage. The average power consumption of the analog front-end is 176 μ W and that of the digital module controlling the analog front-end is 23 μ W. The prototype PO system made using the custom ASIC operates from a 3.7 V lithium ion battery and consumes about 8 mW power. The prototype is housed in a 3D printed casing and it connects with a display device via USB or wirelessly to laptop/smartphone/tablet. Readings on 20 subjects, both in the lab and in hospital, show less than 2% deviation in the measured SpO₂ level and worst case deviation of 2.7 beats per minute for the measured heart rate, when compared with the commercial POs.

1. Introduction

In a developing country like India, there is a severe shortage of medical practitioners and other medical staff in hospitals. This shortage is more acute in rural areas. According to an estimate [1], there are only 0.7 doctors and 1.5 nurses per 1000 people in India, significantly lower than WHO global average of 2.5 doctors and nurses per 1000 people. Thus, there is a strong case for countering this shortage through technology. With the advancement in Internet of Things (IoT) and the launch of 4G services in India, it is envisaged that a fewer number of medical staff will be required in hospitals to monitor the same number of hospital beds. Hence, more of the medical devices are now required to have internet connectivity. Further, according to [2], 50.6% of visits to a primary health care centre in India are due to respiratory symptoms. Hence, an instrument like a Pulse Oximeter which is used to measure arterial blood oxygen saturation is very important. Fig. 1 depicts a typical application scenario of IoT enabled medical device for remote health diagnostics and prognostics.

Pulse oximetry is a technique of determining the arterial blood oxygen saturation. This technique has gained popularity due to some of its features like non-invasiveness, continuous monitoring, fast response and no requirement of medical expertise to operate [3]. It has found application in diverse areas such as intensive care units, operating theaters, trauma care centers in hospitals, in ambulances and in sleep studies [4–6]. It is also finding a lot of interest in areas such as wearable and portable medical applications [7,8] and biometric security devices [9]. SpO₂ is defined as the percentage of hemoglobin in the arterial blood that is in oxygenated state. If [HbO₂] and [Hb] represent concentration of oxygenated and de-oxygenated hemoglobin, respectively, then by definition,

$$SpO_2 = \frac{[HbO_2]}{[HbO_2] + [Hb]} \cdot 100\% \quad (1)$$

A typical pulse oximeter uses 660 nm (red) and 940 nm (infra red) wavelengths for measurements [7]. From the measurements, a parameter which is only dependent on SpO₂, known as ratio-of-ratios (R) is

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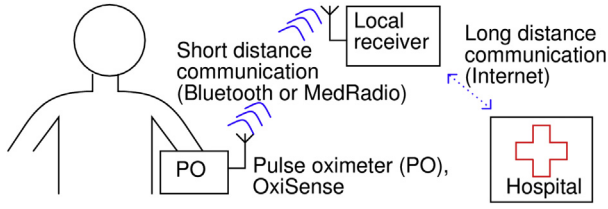


Fig. 1. A typical application scenario of IoT enabled pulse oximeter.

determined. R is defined as $R = (AC_R/DC_R)/(AC_{IR}/DC_{IR})$ where $AC_{R,IR}$ and $DC_{R,IR}$ represent the ac and dc component of photodetector current due to red/infra red LED, respectively. The AC components is only about 1–4% of the DC component [5]. Each pulse oximeter is calibrated and an empirical relationship is determined between SpO_2 and R [6].

In Ref. [4], a logarithmic transimpedance amplifier is proposed which is used in the PO front-end. It is a fully analog implementation and achieves a low power consumption of 4.8 mW excluding the power for digital processing. In Ref. [10], the authors have demonstrated the possibility of integrating a reflectance PO in an electronic wearable patch with wireless connectivity using commercial-off-the-shelf (COTS) components and used it to perform clinical evaluation on three subjects. However, using ASIC helps to reduce size, weight and power consumption. In Ref. [11], a technique to control the baseline drift of PPGs in digital domain without using any filter is proposed. Again, in this work COTS components were used to design the proof-of-concept prototype. In Ref. [5], the first implementation of a fully integrated PO based on mixed-signal approach is presented. In this work, the authors have demonstrated a proof-of-concept system where PO front end consumes only 0.85 mW excluding power for digital processing. This mixed-signal approach has gained momentum to alleviate some of the design challenges in analog circuits in scaled technology nodes [12]. In Ref. [6], the authors have proposed a method to reduce power consumption of the PO front end by targeting an optimum SNR using pulse width modulation to control LED power-on time. Further, power reduction is achieved by applying predictive sampling to sample the photodiode current only near the peaks of PPGs where the useful information lies, as far as extracting arterial blood oxygen saturation and heart rate information is concerned. In Ref. [7], a PO is demon-

strated that is embedded in a smart hand-held device and it is made of COTS components. The proposed system features chopper modulation technique to achieve high resilience to interference caused by ambient light. The authors also propose: 1) an adaptive trough detection technique to achieve improved HR and SpO_2 detection and 2) a PPG validation scheme using correlation between PPGs.

In this paper, we present a fully integrated PO measurement system designed and developed using custom PO ASIC in 180 nm CMOS technology. The motivation behind our work is to demonstrate the design of a fully integrated PO ASIC keeping in mind the testability of individual modules of both analog and digital sections in the ASIC. This approach can serve as a guideline, for development of such similar complex bio-signal measurement systems in wearable application scenario where fully integrated approach is essential from different aspects such as: 1) high signal integrity, 2) low power consumption, 3) small form factor, 4) robust hardware design and 5) low cost. Further, we have developed a robust and efficient signal processing algorithm for processing PPG signals and implemented it on a low-power micro-controller. For remote monitoring, PPG signals are communicated from the sensor node to a nearby (~3 m distance) local receiver, which could be any hand held device like mobile phone or a PC. Short range wireless communication of PPG is achieved by using sub-mW transmitter (TX) and receiver (RX) of the Bio-WiTel system [13], which operates in the medical device radio communication (MedRadio) freq. band of 401–406 MHz [14].

This paper is organized as follows. In Sec. 2 we present the proposed PO system. In Sec. 3 the details of design for testability of the PO ASIC and its testing is presented. Sec. 4 presents the details of the designed PO systems. Sec. 5 and 6 presents the signal processing aspects and measurement results, respectively. Finally, we conclude in Sec. 7.

2. The proposed system - OxiSense

OxiSense, is a complete medical system meant for the measurement of arterial blood oxygen saturation (SpO_2) and heart rate. Fig. 2 shows the top-level block diagram of the system. The block diagram shows the inter-relationships amongst the main sub-systems. At the core of the system, lies the custom designed “IIT Bombay Pulse Ox ASIC”. This PO ASIC is a standalone signal conditioning module at the front-end of *OxiSense*. To explain the working of the system, we shall first discuss

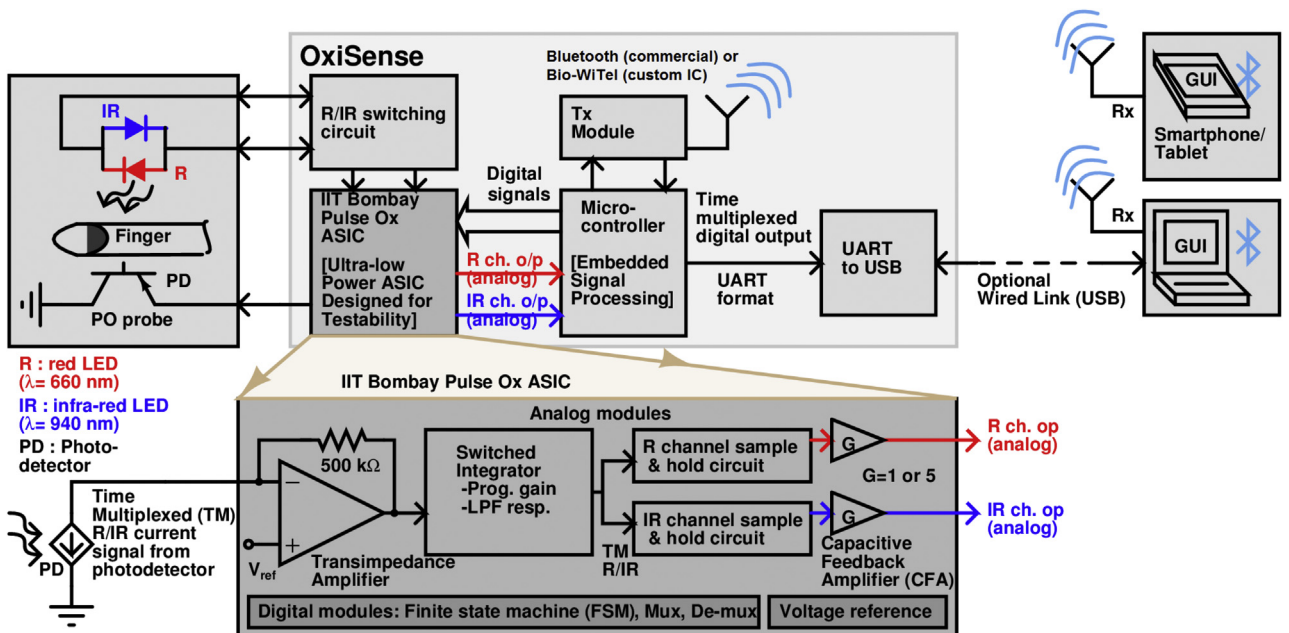


Fig. 2. The proposed pulse oximeter - *OxiSense*.

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