ZeroPowerTouch: Zero-Power Smart Receiver for Touch Communication and Sensing in Wearable Applications

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Abstract**—The human body can be used as a transmission medium for electric fields. By applying an electric field with a frequency of decades of megahertz to isolated electrodes on the human body, it is possible to send energy and data. Extra body and intra-body communication is an interesting alternative way to communicate wirelessly in the new era of wearable device and internet of things. This promising communication works without the need to design dedicate radio hardware and with lower power consumption. We designed and implemented a novel zero-power receiver targeting intra-body and extra-body wireless communication and touch sensing. To achieve zero-power and always-on working, we combined ultra-low power design and an energy-harvesting subsystem, which extracts energy directly from the received message. This energy is then employed to supply the whole receiver to demodulate the message and to perform data processing with digital logic. The main goal of the proposed design is ideal to wake up external logic only when a specific address is received. Moreover, due to the presence of the digital logic, the designed zero-power receiver can implement identification and security algorithms. The zero-power receiver can be used either as an always-on touch sensor to be deployed in the field or as a body communication wake up smart and secure devices. A working prototype demonstrates the zero-power working, the communication intra-body, and extra-body, and the possibility to achieve more than 1.75m in intra-body without the use of any external battery.**

Keywords—Wearable devices, Zero Power Sensing, Low power Design, Energy Harvesting, Touch Communication.

I. INTRODUCTION

Wearable devices for biomedical applications are increasingly attracting the interest of researchers and industry [1] [2]. Today intelligence wearable device equipped with wireless interfaces and many sensors are a commercial reality for sport & fitness, especially for the big push of companies such as Samsung, Apple and Google, and biomedical applications where companies as Philips are pushing. Especially in biomedical applications, the recent trend is to have many smart sensors deployed on the human body or around it to monitor and process the sensor data [3]-[5] and communicate between them, eventually transmitting data and decisions.

One of the most popular communication interfaces is these smart devices is today done with the radio frequency (RF) wireless transmission[6]. However, is well know that wireless communication in wireless sensors is one of the most expensive subsystems, consuming a few mW of power covering only tens of meters, similar to the power used for video sensors [7]. For wearable devices that are supplied by the battery and tend to be small and light, low power consumption is crucial, as directly affect the lifetime of the devices [8]. A well-known effective technique to reduce power consumption is to reduce the activity of the power-hungry subsystems, like wireless communication, periodically (duty-cycling). However, this technique increases communication latency and the probability of missing messages [9][10].

Moreover, duty cycling not eliminate the consumption in idle-listening that makes the battery-operated nodes not lasting more than few with very aggressive duty cycling[11]. A recent promising approach is to design always-on wireless receivers that provide the capability to detect wireless messages of interest with power consumption in the range of µW[12]. Even more recently, this approach has been augmented with a move toward a zero-power sensing communication, exploiting energy harvesting from the received power. Zero-power communication targets energy neutrality, which enables always-on sensors [13][14].

Today RF wireless communication, such as Bluetooth, is also used to send data in applications where the data need to be transferred to nodes on the same body (intra-body communication) or close to the body with a touch (extra-body communication) [15][16]. A novel and energy efficient approach to communicate is the emerging, Human Body Communication (HBC), which uses the human body as a transmission medium[17]. Human Body Communication is an alternative to conventional radio transmission for short-range RF wireless communication such as Bluetooth (medium short range) or RFID (short range). HBC is a novel wireless communication method and very attractive especially because it requires less power consumption to transmit and receive data[17].

In this paper, we present the design, the implementation and accurate experimental measurement of a novel zero-power intra-body and extra-body communication receiver, which can be used as a touch sensor (for extra-body communication) or as a zero-power wake-up radio (for extra-body and intra-body-communication). The main goal of the design is to achieve a battery-less device that is always waiting for data to be processed. The required energy, to make the receiver works, is harvested over the electric field (with a capacitive coupling) [18] established between electrodes attached to the object/body and the body of the user where is a transmitter. The received embed a digital logic to process the data received on board to perform addressing or even more complex security algorithms that will be investigated in future.

II. INTRA AND EXTRA BODY COMMUNICATION AND TRANSMISSION WRISTBAND

In intra/extra body communication the human body and other dielectric objects are used as a transmission medium, as described in [17], [15] and [16]. The data transmitted are usually modulated in frequency (i.e. FSK) or amplitude (i.e. on-off keying OOK). In literature, various forms of capacitive coupling have been employed to transmit data between wearable transceivers deployed on the human body, or between wearable transceivers and receivers in smart embedded objects. This kind of communication is recently increasing the interest due to the capabilities to send data through the body with very low power consumption and the possibility to design a transceiver and a receiver without complex hardware [19][20]. Moreover, the body can also be the medium to transport energy from the transmitter to the receiver. When a transmitter is connected via an electrode and capacitively coupled to the body, a minimal current in the magnitude of nano/micro-ampere flows through the human body to the receiver as both the receiver and the transmitter, are capacitively coupled to ground. The basic concept is illustrated in Fig. 1.

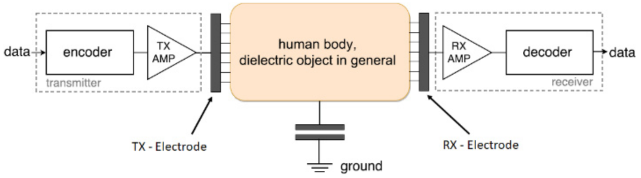

Fig. 1. Concept of the intra/extra body communication

In this work, we used as transmitter an academic wristband. The wristband is a multi-sensor smart device that also includes a body communication sub-system. The transmitter, worn on the body, sends both a preamble, which charges the internal capacitors of the receiver circuit as we will illustrate in details in the following section. The preamble followed by a payload, for instance, an ID (Fig. 2) is sent by the transmitter. The length of the preamble needs to be tuned to provide enough energy to supply the signal processing and evaluating of the ID by digital logic. As we mentioned, the transmitter node does not require any radio hardware, but it can be achieved by a pulse width modulation signal (PWM) generated by a microcontroller. An on-off keying modulation with a frequency of 10 MHz has been used in this work to generate preamble and data Fig. 2. The zero-power receiver can then be used to wake up power hungry hardware or activate external devices that can go into sleep mode consuming zero-power.

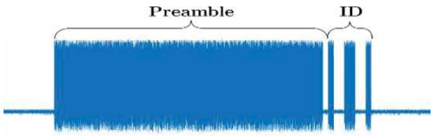

Fig. 2. On-Off Keying message sent by a transmitter. The message needs to have a preamble used to harvest energy and supply the receiver circuits to demodulate and parse the data (ID in this case).

Fig. 3 shows the block diagram of the wristband that includes an Arm Cortex-M4F microcontroller (TI-MSP432), ECG and skin conductivity sensors among others and Bluetooth low energy (BTLE) interface that is not used in this work. The wristband's subsystems are supplied with a 1.8V supply. For the transmission of data via the human body a 10MHz carrier signal with on-off keying modulation is used, by generating pulses with the signal "touch_transmit" with a GPIO of the MSP432 microcontroller. To increase the amplitude of the signal transmitted, the 1.8V signal from the microcontroller is amplified with a high-speed operation amplifier U1 in Fig. 4. The transistor Q1 is used to switch to the amplifier when the transmission in not uses. The total power consumption when the transmission is used has been measured with 1mA@3V including the power consumed by the LDO.

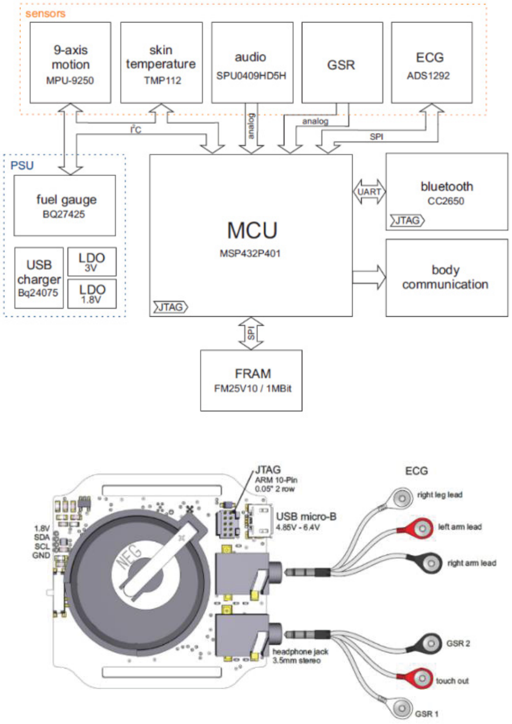

Fig. 3. Block Diagram and prototyped system designed as a wristband to transmit the data with body communication and employed in our experiments as a transmitter designed in [21].

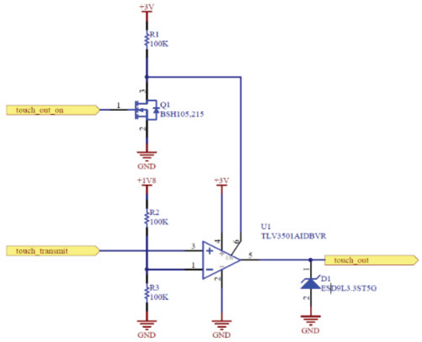

Fig. 4. Intra/extra body communication transmission sub circuit implemented on the wristband device

III. ZERO-POWER RECEIVER ARCHITECTURE

The main contribution of this work is on the design and implementation of a zero-power touch receiver. The block diagram of the receiver for touch communication is illustrated in Fig. 5. There are four main blocks: 1) The receiving electrodes (ground and signal); 2) the energy harvesting subsystem that converts energy from the received data; 3) the data reconstruction, an ultra-low power on-off keying demodulator; 4) the digital logic that can process the data and activate a wake up signal or external peripherals according with the algorithm implemented on it.

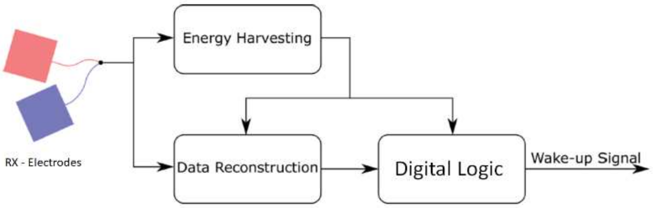

Fig. 5. Block diagram of the zero-power receiver for touch communication and touch sensors.

The main role of the energy harvesting subsystem is to convert and store energy to supply both the demodulator and the digital logic. To achieve this goal, we used a multi-stage charge pump based on a Villard double voltage. The charge pump works with a combination of diodes and capacitors as depicted in Fig. 6

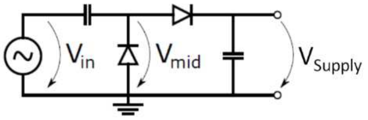

Fig. 6. Basic charge pump for energy harvesting

The working principle is that always one diode is in forwarding mode and the other in reverse mode. Therefore the capacitors are charged alternately, and the voltage sums up on V_{supply} that is used as supply-capacitor, providing energy for the rest of the circuit. V_{supply} needs to be evaluated with the formula given in equation (1), where Vin is the amplitude of the input voltage depending on the size/shape of the electrodes and the transmitted power, while the power received, $V_{forward}$ the forward voltage drop of the diode and N the number of stages. This formula is only valid for a small number of stages, for many stages, one has to take into account the system resistance and the output load

$$V_{Supply} = 2 \cdot N\,(V_{in} - V_{forward}) \tag{1}$$

To maximize the energy harvested we designed our harvesting circuit using Schottky diodes with very low forward voltage. The diodes HSMS-2820 from Avago Technologies has been selected, as they combine a low forward voltage, fast switching time and low reverse leakage current. To achieve a V_{supply} of 1.6V needed for the digital logic we used a 4-stage rectifier. Fig. 7 shows the data reconstruction subsystem that demodulates the received on-off keying messages. A passive envelope detector is the first step to rectify the signal received on the electrodes. A nano-watt comparator, which is the only active component of the data reconstruction circuit, reconstructs then the data generating a "high" value if a bit '1' is received and "low" for the bit '0'. A passive reference generator is needed for the correct work of the comparator. The TLV3691 from Texas Instrument has been employed in this implementation of the prototype, as it consumes only 75nA and starts to work with only 0.9V of VCC. In the final prototype, VCC is the V_{supply} provided by the harvesting circuit.

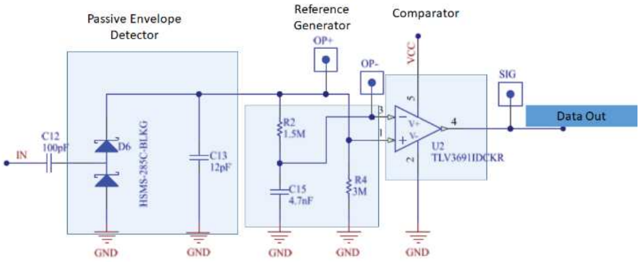

Fig. 7. Ultra-low power on-off keying demodulator.

The Digital Logic provided computational capabilities and can read directly the "Data Out" generated by the demodulator. In this version of the zero-power receiver, we used an ultra-low-power microcontroller PIC12LF1552 from Microchip. The PIC needs less than a microampere in sleep mode and only some hundred microamperes in active mode. Moreover, the PIC works with only 1.6V. The PIC is an 8-bits microcontroller and can be used to achieve addressing to reduce the false positive, to detect the ID of the transmitted to activate external devices only if authorized or it can also implement security algorithms. Due to the low power consumption, the PIC is fully supplied by the energy acquired by the preamble and the data received.

IV. EXPERIMENTAL RESULTS

We designed and implemented a working prototype of the proposed zero-power receiver (Fig. 8). We tested both the functionality and the performance in-the-field. The experimental set-up is shown in Fig. 8. The wearable wrist illustrated in section 2 has been programmed to generate on-off keying messages including a variable energy preamble. Fig. 9 shows the oscilloscope traces during the receiving of the preamble and data on the working zero-power receiver prototype. The first plot (green line) is the received power on the RX electrode. It is possible to see both preamble and data. The yellow line follows the V_{supply} of the harvesting capacitor. It is important to notice that the zero-power receiver can guarantee from the cold start. The bottom plot (purple line) presents the comparator's output, out of the cold start phase, and the capability to reconstruct the data.

TABLE I. ENERGY HARVESTING BEHAVIOR OF THE CIRCUIT FOR DIFFERENT DISTANCES

Distance (cm)	Total Energy (µJ)	ID received
0	164	YES
5	152	YES
10	138	YES
15	118	YES
20	120	YES
25	102	YES
175	15.1	YES

Moreover, to evaluate the range and the energy harvested from the zero-power receiver in intra-body communication. For this experiments, we increased the amplitude of the transmitter to 5.5V increasing the voltage of the amplifier in Fig. 4. A preamble of 200ms has been used followed by 8bits data. Table 1 shows the measured range and the energy harvested at different distances. The limit of 1.75m is due to the max distance achievable from the taller student used in our tests. He is a 190cm tall man, and we measured the 1.75m from his wrist until his big toe. We used 16cm2 round copper electrodes for both transmitter and receiver.

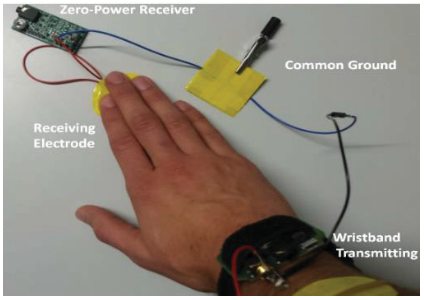

Fig. 8. A working prototype of the zero-power touch receiver and set-up for the experimental results.

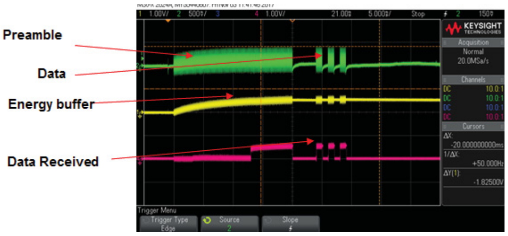

Fig. 9. Experimental evaluations were done with an oscilloscope monitoring the electrode output (first plot), the V_{supply} (second plot, yellow) and the data received by the microcontroller (last plot).

V. CONCLUSIONS

In this work, we presented the design, implementation and in-field evaluation of a novel zero-power receiver that can be used for intra-body extra-boy touch communication and a zero-power touch sensor. The design combines both energy harvesting and low power design to scavenge energy from a preamble of the data transmitter. The receiver included a digital logic based on an ultra-low-power microcontroller to perform addressing and ID detection and can be used in future to implement secure communication. A working prototype demonstrated the whole functionality and the performance in terms of zero-power ability and working in all the body and in extra body communication. The prototype is ready to be tested and show in life demo.

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