In Vitro and In Vivo Operation of a Wireless Body Sensor Node

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Abstract. A wireless Body Sensor Node (BSN) and its operations are presented. The BSN comprises all the necessary components (i.e., antenna, electronics, batteries and bio-sensor) to allow continuous monitoring of physiological data. In vitro characterization validates the simulated performances, while in vivo experiment shows the capability of the system for real life telemedicine applications.

Keywords: Body Sensor Node (BSN), implantable antennas, implantable telemetry system, Medical Device Radiocommunications Service (MedRadio), Telemedicine.

1 Introduction

Wireless implantable systems promise large improvements in patients' care and quality of life. For this purpose, small biocompatible devices have been recently presented for different applications such as pH monitoring [1], gastro-intestinal tract exploration [2, 3] or cardiovascular pressure control [4]. In this work we present a complete Body Sensor Node which has been tested in vitro and applied in vivo in a porcine animal for local temperature monitoring. The system performs data telemetry with an external Base Station in the Medical Device Radiocommunications Service band (MedRadio, 401-406 MHz) [5] and the Industrial, Scientific and Medical band (ISM, 2.4-2.5 GHz).

2 Body Sensor Node

The proposed BSN aims at a high system integration of all its components, namely: the Multilayered Spiral Antenna (MSA), the electronics (the RF transceiver and

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the Digital Signal Processor), the batteries and the bio-sensor. Fig. 1 depicts the complete packaging of the device. All the elements fit in a biocompatible cylindrical housing which measures 10 x 32 [mm].

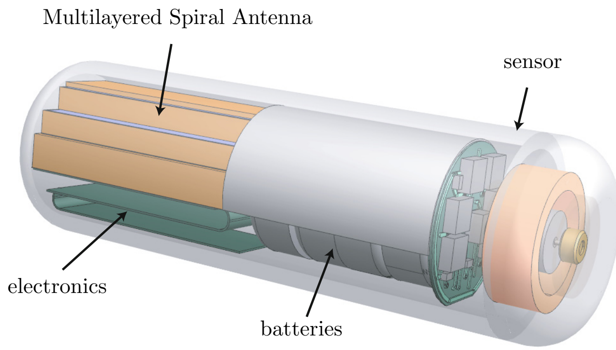


Fig. 1. Complete packaging of the proposed BSN. The biocompatible casing is in light gray. As a possible sensor, the driver and rotor for glucose microviscometer described in [6] are illustrated.

The MSA consists in a conformal radiator whose main resonating element is a three dimensional spiral metallization developed on a *pyramidal* assembly as described in [7, 8]. Polyetheretherketones (PEEK) was used for the biocompatible housing, as it is very easy to machine and its biocompatible characteristics are well established [9, 10]. The housing thickness (0.8 mm) was selected to improve the electromagnetic radiation of the implanted radiator in agreement with the results reported in [11]. The MSA has dual band capabilities working in both the MedRadio and the ISM bands and its radiation performances (maximum gain equal to -29.4 and -17.7 dBi in the lower and higher frequency ranges, respectively) provide a robust communication link for applications targeting a minimum working range of 2 m.

The electronics components were assembled on a flexible Printed Circuit Board (PCB) [12] to fit in the small available volume. The RF communication is provided by an ultra-low power Integrated Circuit (IC), the ZL70101 [13] manufactured by Zarlink, operating in both the MedRadio and ISM bands. The BSN operations are executed by an ultra-low power digital signal processor: the Ezairo 5900 manufactured by ON Semiconductor. Four coin type 377 batteries (1.5 V/ 27 mAh), manufactured by Energizer, were selected to provide the required power supply.

The conception of the proposed BSN gives a broad freedom regarding the monitoring device or bio-actuator to be included. The front-end electronics to drive the glucose microviscometer presented in [6] and the potentionstat described in [14] are just examples of possible sensors.

3 Power Consumption

In order to reduce the power requirements and to extend the life time of the BSN, the system is kept in a *sleeping* state. In this condition only the 2.45 GHz *wake-up* part of the transceiver is active and the power consumption is 2 μW. A signal received in the ISM band wakes up the IC; subsequently, the measurements are performed and the bidirectional communication occurs in the MedRadio frequency spectrum. Considering the TMP112 temperature sensor (from Texas Instruments (used in the in vivo experiment), the total active phase lasts 430 ms and consumes 15.7 mW. If one measurement is taken every 5 minutes, the embedded batteries provide a life time of 284 days. The power ratio of each part of the BSN is depicted in Fig. 6 (RF 91.9%, DSP 8.0%, sensor 0.1%). The RF portion can be separated in the actual power used to transmit data (RF_{TX}=2.7%), to establish the MedRadio communication channel (RF_{est}=14.6%) and to reserve the channel until the data are ready to be sent (RF_{ch}=74.6%), as illustrated in Fig. 2.

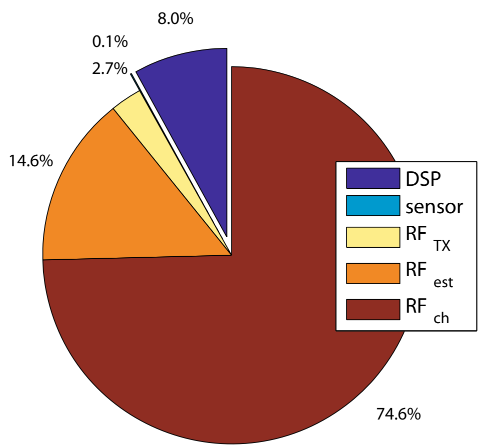


Fig. 2. Power consumption repartition among the different components of the BSN during the active phase

Comparing the performances of implantable devices with telemetry capabilities is not an easy task as many different conditions (working frequency, data rate, duty cycle dimension, implant location, purpose, power supply) can be considered. In Fig. 3 once can notice the good compromise of the proposed BSN among volume occupation, power consumption and life time when compared to other implantable systems[1].

[1] The selected implantable sensors are only chosen to show examples of different applications as the list is by no means exhaustive.

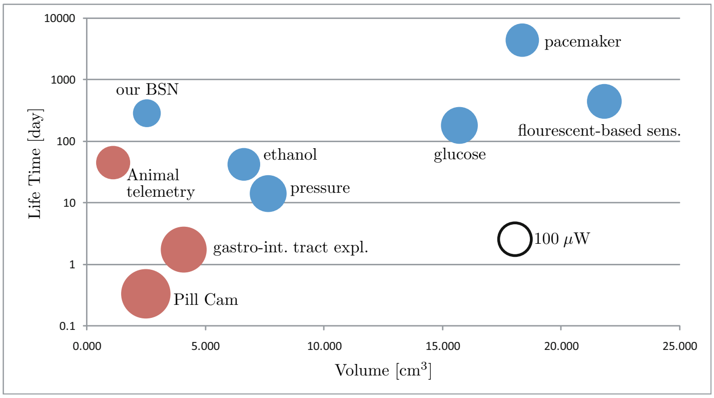


Fig. 3. Graphical comparison of active implantable devices with far field (blue) and near field (red) communication capability: flourescent-based sens. [15], pacemaker [16], glucose [17], pressure [18], ethanol [19], gastro-int. tract expl. [3], Pill Cam [2], Animal telemetry [20] and our BSN. The size of the bubble reflects indicated the power consumption computed as the ration between life time and the battery supplies.

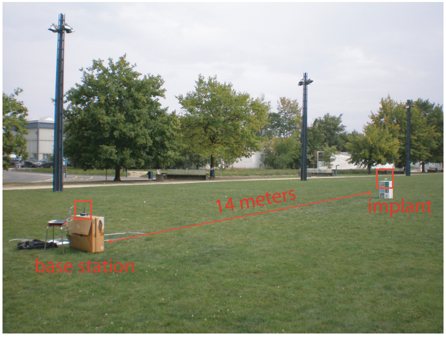
4 In Vitro Characterization

In vitro tests were performed in order to check the functioning of the realized device and validate the MSA radiation characteristic. The BSN was inserted in a liquid body phantom. The latter has dielectric properties equivalent to the human muscle tissue and has a cylindrical shape (80 x 110 [mm]). Outdoor test were carried out to assess the capability of the MedRadio communication link (as illustrated in Fig. 4-(a)), while the *wake-up* performances in the 2.45 GHz ISM band were verified in an anechoic chamber.

Maximum working ranges, reported in Fig. 4-(b), confirmed the simulated performances of the MSA. Considering the power link budget characteristics of the IC ZL70101 and the Base Station provided by Zarlink, the maximum registered ranges correspond to antenna gain values equal to -30.5 and -18.6 dBi in the MedRadio and ISM bands, respectively. These values, which take into account the mismatch and the losses within the electronics assembly, closely agree with the predicted characteristics, i.e., -29.4 and -17.7 dBi.

5 In Vivo Experiment

Two BSNs were implanted in a large animal model (Göttingen minipigs) chosen for the similarity between their and the human tissues. A temperature sensor was included into the BSNs to study the correlation between local temperature and the healing process of a deep wound in the settings of a cultured epidermal autograft. In fact, it has been observed that the temperature has an important impact on epidermal stem cell behavior in vitro [21].



(a)

Frequency	Range [m]
403 MHz	14.0
2.47 GHz	4.8

(b)

Fig. 4. In vitro characterization: (a) outdoor communication tests and (b) maximum registered ranges for both working frequencies

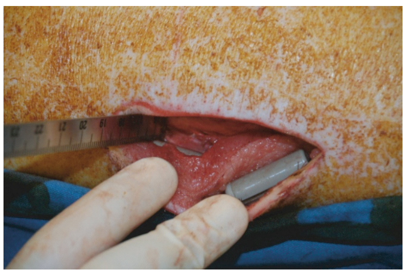


Fig. 5. Implantation, in accordance to all ethical considerations and the regulatory issues related to animal experiments, of the two BSNs at different depths. A subcutaneous location (5 mm deep) and an intra-muscular one (30 mm deep), were chosen.

In vivo experiment lasted for 15 consecutive days. During this period the animal dwelled most of the time in a farm and periodically, it was taken away for a follow-up at the hospital. Fig. 6 shows the registered temperatures during one of these follow-ups. Values measured by a rectal probe are also reported to appreciate the effect of the placement of the two BSNs.

While being at the farm, the animal was maintained indoor in a cage of dimensions 1.3 x 2.7 [m]. In order not to interfere with the farm daily life (feeding of the animals, cleaning, etc.), the Base Station was placed in the mansard above the cage room at a distance of 2.5 m.

The overall performances during the entire test period are reported in Table 1. During the 2696 interrogations between each BSN and the external Base Station the relative number of failed communications are 5.82% and 16.10% for the subcutaneous and intra-muscular BSN, respectively. From the point of view of communication protocol, three sources of error are identified in Table 1: MedRadio, ISM and firmware. One can appreciate that the data transmission in the MedRadio was found to be the most critical on for the deepest

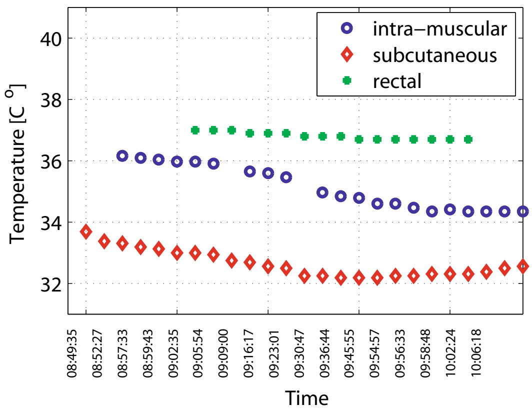


Fig. 6. Measured temperature values at the hospital

sensor ($err_{MedRadio}$=12.46%), while the *wake-up* communication showed a relative number of errors err_{ISM} lower than 5% for both BSNs. Almost negligible problems were caused by the driving firmware ($err_{firmware}$ <0.2%). Explanations for the registered errors have been found observing the pig activity in the cage and the consequent relative positions between the BSNs and the Base Station.

Table 1. Communication Performances during the In Vivo Experiment

BSN	**Number of Measurements**	$err_{MedRadio}$ [%]	$err_{firmware}$ [%]	err_{ISM} [%]	err_{tot} [%]
intra-muscular	2696	12.46	0.00	3.63	16.09
subcutaneous	2696	1.67	0.11	4.04	5.82

6 Conclusion

This work presented the operation of a complete wireless Body Sensor Node. The node integrates all the necessary components in a cylindrical volume (10 x 32 [mm]). Communication with an external Base Station placed in a few meters working range (up to 14 m) has been proven. The results obtained by the in vitro and in vivo tests confirm the promising capabilities of the proposed BSN and pave the way for future research oriented to the making of complete telemedicine systems.

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