

# Identification of the Opportunistic Radio Frequency Bands for Energy Harvesting in Wireless Body Area Networks

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**Abstract**—This paper presents the spectrum opportunities for radio frequency (RF) energy harvesting enabling to power supply future wireless body area networks (WBANs). The field trials have been performed in Covilhã by using the NARDA-SMR spectrum analyser with measuring antenna. Besides, this work addresses physical (PHY), medium access control (MAC) and network layer design aspects, by considering cognitive radio (CR) opportunities by means of the identification of the most promising bands.

**Keywords**—Energy Harvesting, Cognitive Radio, Body Area Networks

## I. INTRODUCTION

Energy harvesting generally relates to the process of using ambient energy and enables long-term and self-powered wireless body area networks (WBANs). This has particular importance as the network size increases, since, for this particular class of wireless sensor networks (WSNs), the replacement of the batteries is not practical. There are several possible sources of ambient energy including: mechanical, thermal, solar, acoustic and radio frequency (RF) that can be used to power the sensor modules or portable electronic devices [1]. Nowadays, energy harvesting devices efficiently and effectively capture, accumulate and store energy, to power the sensor nodes for short periods of time, in order to perform a helpful task. However, our vision is that, in the near future, they will enable to power supply all the nodes of a WBAN without the need of replace the primary source of energy (i.e., batteries). The spectrum scarcity in wireless sensor networks (WSNs), due to the increase of devices that operates in the 2.4 GHz industrial scientific and medical (ISM) band, is also a new challenge. Therefore, cognitive radio (CR) technology must be addressed, allowing for improving the efficiency of spectrum utilization. Future improvements in RF energy harvesting technology will facilitate the creation of a network with no need of dedicated transmitters, as a reliable source of wireless energy power. This can be accomplished by enabling the capture of the energy from radio frequency waves transmitted from existing and commonly used ambient RF energy sources, such as mobile base stations, TV and radio transmitters, microwave radios, and mobile phones. Moreover, future improvements in the performance of the electronic components

will lead to a decrease of the power consumption, which results in faster charge times and more frequent broadcasts of data, enabling for the creation of an always connected ubiquitous wireless power sensor network (UWPSN).

Early work on electromagnetic energy harvesting for WBANs with CR capabilities was published in [2]. This paper includes significant extensions to this previous work in the indoor measurements. It also includes the physical (PHY), medium access control (MAC) and network requirements constraints of typical WBAN, by considering the CR opportunities. The remainder of the paper is organized as follows. Section II presents the communication aspects of WBAN with CR capabilities. Section III addresses the spectrum opportunities based on the field trials that were held in Covilhã, Portugal. Finally, conclusions are drawn in Section IV.

## II. COMMUNICATION ASPECTS OF WBANs WITH CR CAPABILITIES

The RF energy harvesting system to be developed in the context of the PROENERGY-WSN project [3] consists of an impedance matching circuit, rectifier and energy storage as shown in Fig. 1.

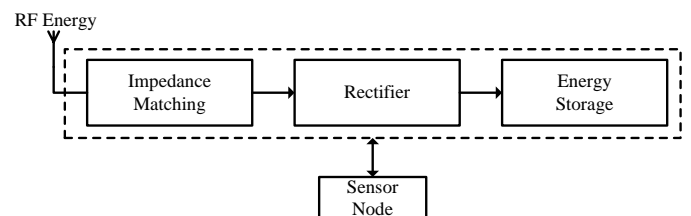


Figure 1. Block diagram for RF energy harvesting.

Therefore, energy efficient cross-layer protocols must be implemented since the WBAN's energy consumption is dominated by the node's radio processor/communication components. This section addresses the cross-layer design aspects for the PHY, MAC and network layers for future WBANs with CR capabilities being power supplied by RF energy harvesting devices.

### A. Physical Layer Aspects

The PHY layer of a WBAN node with CR capabilities is responsible for spectrum sensing, reporting the measurements to the CR node microprocessor. As presented in Fig. 1, the PHY layer also aims at the reconfiguration of the transmission parameters according to the decisions from the microprocessor. The design challenges imposed by the environmental and propagation constraints are the following:

- The node's current draws are 16 mA, 17 mA and 8  $\mu$ A for the RX, TX and SLEEP modes [4], respectively.
- The body shadowing effect (due to the propagation of signal over the human body) has been already addressed in [5]. Therefore, multi-band antennas must be conceived by considering the coupling effect that appears and depends much on the relative positions of the sensor nodes in human body.
- The multi-path effect caused by the ground and surrounding objects must be taken into account. In WBANs, the value of reflection signal depends on the position of the sensor node in the human body [6].

### B. MAC Layer Aspects

MAC layer provides the mechanisms for scheduling and allocation of the shared wireless channel. It is responsible for how and when PHY functions should be used to access the physical medium shared by the devices. Other function is the topology control. So, it must have knowledge of the initial topology and have the ability to react to a changing topology. Compared to conventional WSNs, the MAC layer of WBAN nodes with CR capabilities must handle additional challenges, such as silent spectrum sensing periods and the need for high-priority access mechanism, for the distribution of spectrum sensing and decision results [5]. The MAC layer challenges regarding energy efficiency are the following:

- **Spectrum sensing and decision results:** Cooperative sensing [7] and decision results are used to increase sensing accuracy and sharing efficiency. Therefore, nodes must share extra control information and include information about the priority of packets.
- **Minimum overhead:** The wide range of MAC protocols for WBANs use control packets. Therefore, it is envisaged a cognitive radio sensor node (CRSN) with minimum exchange of control packets. This can be accomplished by using a block acknowledgment (BACK) policy feature [8]. This way, every time a node accesses to the medium, it optimizes the transmission time by reducing the amount of overhead, whilst increasing the channel capacity. The piggyback mechanism (PM) could also be used, in which a receiver station is allowed to piggyback a data frame to a sender station once if the receiver station has a frame to send to the sender [9].
- **Adaptive duty cycle:** Since the spectrum opportunities vary with time and location, self-adaptive mechanisms must be introduced. Based on spectrum sensing measurements, we can increase the active period, which means more opportunities to cover multiple

neighbours with one forwarding. Besides, since collecting RF energy to power supply the sensor nodes is foreseen based on the available energy and MAC opportunities, a threshold can be considered to send packets based on the existing RF energy harvesting opportunities versus interference metrics.

- **Idle listening:** One of the sources of MAC inefficiency is idle listening. Idle listening occurs when a node that is in idle state is ready to receive possible traffic but is not currently receiving anything. To avoid this type of problems one solution is switching off the transceiver.
- **Overhearing:** Overhearing loss refers to energy wasted by a node that has its radio in RX mode while a packet is being transmitted to another node. Most of the WSN MAC protocols reduce overhearing by trying to ensure that a node is only awake when there is traffic being transmitted to it.
- **Dedicated control channels:** In WBANs with CR capabilities, sensor nodes may use a Control-channel-Request-To-Send and Control-channel-Clear-To-Send (CRTS/CCTS) handshake mechanism to negotiate on the channel before transmitting packets [10]. The use of a CRTS/CCTS mechanism on a separated control channel allows for decreasing the number of collisions, whereas the DATA and ACK packets could be transmitted in a group of frequency bands.

### C. Network Layer Aspects

With the dynamic nature of the spectrum, and constant frequency usage by other entities, network algorithms play an important role in choosing the best paths based on the current channel conditions. In CR networks, the network layer is responsible for choosing the best next hop as well as the frequency to use. The open research issues that are still open, and must be addressed in order to have a complete network solution are the following:

- **Spectrum aware routing:** Nodes opportunistically route data packets across paths avoiding spectrum congested areas. To achieve this goal, innovative awareness mechanisms (that facilitate knowing about the presence, characteristics and requirements of other wireless devices in the same area) that consider spectrum mobility and resource constraints must be employed to find the optimal traffic according to the available spectrum resources.
- **Node capabilities:** In a multi-hop CR scenario the sudden appearance of a primary user (PU) in a given location where it may impose an unusable channel for the secondary users (SUs), leading to unpredictable route failures. Therefore, effective signalling mechanisms must be considered to restore the paths with minimal effect on the network performance.
- **Adaptive and quality of service routing:** Cross-layer mechanisms are responsible for providing up-to-date local quality of service (QoS) information for the adaptive routing protocol. Hence, new techniques

based on varying channel conditions must be taken into consideration for real-time communication.

- **Energy aware routing:** In multi-hop network, nodes must select the path that guarantees fairly equal battery consumption by all the nodes, that is, nodes whose battery is depleted shall not be used for relying information. In [11] the author propose a global routing protocol based on Dijkstra's algorithm with a novel link cost function specialized for balancing energy consumption and increasing network lifetime.

### III. INDOOR AND OUTDOOR SPECTRUM OPPORTUNITIES

In order to seek for the best spectrum opportunities for RF energy harvesting, we have conducted several field trial measurements in Covilhã, Portugal, in both indoor and outdoor environments, by using the NARDA spectrum analyser with measuring antenna.

#### A. Average Received Power

By analysing the power density measurements in 36 different locations, we intend to find the best frequencies for harvesting the electromagnetic energy. Besides, the identified spectrum opportunities are being considered to conceive multi-band antennas. The locations for the measurements are shown in Fig 2.

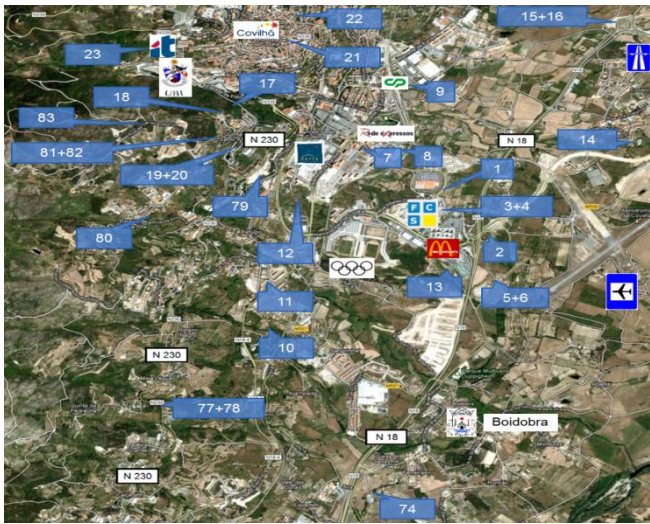


Figure 2. Locations for the measurements in Covilhã.

To convert the electric field measured by the spectrum analyser to the received power, we consider the power density,  $P_d$ , in  $W/m^2$ . To compute the received power,  $P_r$ , as a function of  $P_d$  we consider the effective area of the receiver antenna and gain  $G = 1$  (0 dBi) as follows:

$$P_d = \frac{|E|^2}{120 \cdot \pi} \quad (1)$$

$$P_{r[dBm]} = 10 \cdot \log \left( P_d \frac{\lambda^2 \cdot G}{4 \cdot \pi} \right) + 30 \quad (2)$$

where  $E$  is the electric field and  $\lambda$  is the wavelength.

To identify the best frequency bands for electromagnetic energy harvesting, we have calculated the average of each of the  $n$  values of the received power,  $P_{r_i}[W]$ , in linear terms, in different indoor and outdoor scenarios, where  $n$  is the number of taken measurements, for each frequency. The average received power, in  $dBm$ , is given as follows:

$$\overline{P_{r[dBm]}} = 10 \cdot \log \left( \frac{\sum_{i=1}^n P_{r_i}[W]}{n} \right) + 30 \quad (3)$$

#### B. Indoor Opportunities

The location of public places in the indoor scenario for the field trial results over Covilhã city are shown in Fig. 2, for the locations numbers 7, 10 and 11. The corresponding values of the average received power have already been presented in [2].

Figure 3 presents the indoor spectrum opportunities for the higher education institution in Covilhã, the set of frequencies with high energy available for harvesting comprises the range from 934 to 960 MHz (GSM900), 1854 to 1892 MHz (GSM1800), 2116 to 2160 MHz (UMTS), 2359 MHz (amateur, SAP/SAB applications, video), and 2404 to 2468 MHz (Wi-Fi).

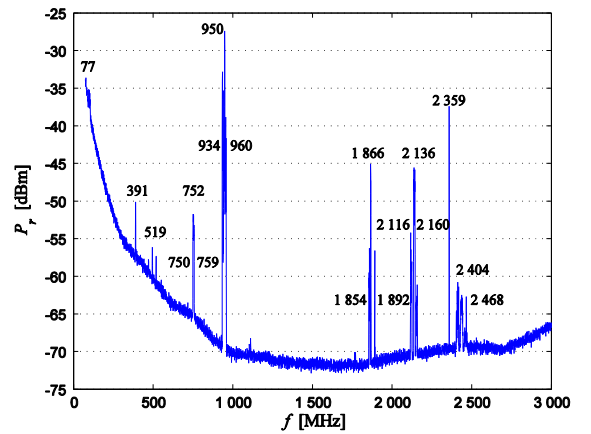


Figure 3. Average received power as a function of the frequency for the University scenario (indoor).

The results from Fig. 3 show that, at 77 MHz and 950 MHz, the average received power is approximately -35 dBm and -25 dBm, respectively. This can be explained by the fact that these measurements have been taken very close to the base station that is on the top of the student's residence (location number 80).

#### C. Outdoor Opportunities

The location of public places in the outdoor scenario for the field trial results are identified in Fig. 2, for the locations numbers 15, 16, 74, 77, 78, 79 and 83. The corresponding values of the average received power are shown in Fig. 4. In this suburban scenario, the range of frequencies with more available energy for harvesting is 391 MHz, from 750 to 758 MHz (television broadcast stations), 935 to 960 MHz (GSM900), 1 855 to 1 869 MHz (GSM1800) and 2 115 to 2 160 MHz (UMTS).

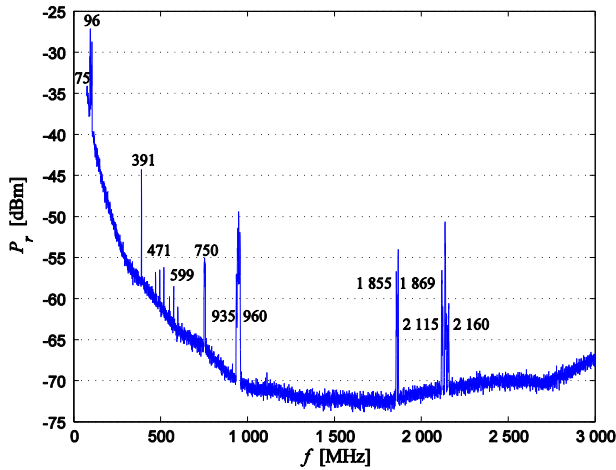


Figure 4. Average received power for the outdoor scenario.

#### D. RF Energy Harvesting and CR opportunities

Based on the spectrum measurements for the indoor and outdoor scenarios we conclude that management strategies must be implemented based on the CR frequency availability and electromagnetic energy harvesting opportunities (i.e., based on spectrum opportunities as well as on energy available, data transmission will be balanced avoiding service downtime caused by depleted batteries). A system with multiband antennas and different RF harvesting circuits is envisaged allowing for maximizing the spectral efficiency based on medium access control opportunities and increase the harvested energy. To conceive an energy efficient circuit which enables to rectify and amplify the input signal, the Cockcroft–Walton and Dickson voltage multiplier circuits are been considered [12]. The output of Cockcroft-Walton is not exactly pure direct current (DC), since part of RF input signal appears in the output which originates the ripple effect. This effect does not occur in the Dickson voltage multiplier, being more suitable for RF energy harvesting applications. The voltage of a N-stage Cockcroft-Walton and Dickson voltage multipliers is given as follows [13]:

$$V_{out} = 2 \cdot N \cdot (V_{RF} - V_T) \quad (4)$$

where  $N$  is the number of stages,  $V_{RF}$  is the amplitude of the RF input signal, and,  $V_T$  is the forward conduction voltage of the schottky diodes.

#### IV. CONCLUSIONS

In this paper we have presented the PHY, MAC and network challenges brought by WBAN by using CR technologies, and discussed how they can be addressed. We have studied the spectrum opportunities for RF energy harvesting to power supply the wireless sensor nodes in real indoor/outdoor scenarios. The set of indoor/outdoor most promising frequency bands are 79 to 96 MHz (mobile/radio broadcast stations), 391 MHz (emergency broadcast stations), 750 to 758 MHz (television broadcast stations), 935 to 960

MHz (GSM 900 broadcast stations), 1855 to 1868 MHz (GSM 1800 broadcast stations) and 2115 to 2160 MHz (UMTS broadcast stations). This study is going to be considered in the context of PROENERGY-WSN [3], Portuguese Foundation for Science and Technology (FCT) project. Because of the increasing applicability of WBAN for healthcare, similar spectrum measurements will be conducted in medical environments.

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