Electromagnetic Energy Harvesting for Wireless Body Area Networks with Cognitive Radio Capabilities

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Abstract—Cognitive radio (CR) is a promising technology for future body area networks (BodyNets). It enables unlicensed (secondary) users to exploit the spectrum allocated to licensed (primary) users in an opportunistic manner. Innovative, energy efficient medium access control (MAC) and routing protocols must be implemented to improve the coexistence between different users, as well as managing the scarce resources in an efficient way. Besides this verification of spectrum opportunities and sensing methods, this work addresses physical (PHY), MAC and network layer design aspects for BodyNets. Furthermore, based on field trials made in real indoor and outdoor environments, we address existing CR opportunities to be applied to potential applications in body area and sensor networks. Our research includes a scenario where a BodyNet is being sustained by radio frequency (RF) energy harvesting devices, that convert low energy RF to direct current (DC), providing an alternative source to power supply the wireless sensor network (WSN) devices.

I. INTRODUCTION

Energy harvesting will have a great impact on the lifetime of future body area networks (BodyNets). This has particular importance as the network size increases, since, for this particular situation, the replacement of the batteries is not practical. Common sources of energy harvesting include: mechanical, thermal, electromagnetic, natural (wind, solar and other) and human body energy. 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 a near future, they will enable to supply all the nodes of a BodyNet without the need of replacement of the primary source of energy (i.e., batteries). The next generation of cognitive radio (CR) networks will be supplied by renewable energy from natural resources, such as solar, wind and radio frequency (RF) energy [1]. This energy could be used overnight to increase the battery charge, or to prevent power leakage. In a hazardous situation, if a battery or a solar-collector/battery package completely fails, harvested energy from radio waves can enable the system to transmit a wireless distress signal, whilst potentially maintaining critical functionalities [2].

Medium access control (MAC) and routing protocols also play an important role in the network performance of the BodyNet. The MAC protocols are responsible for managing the radio transmission and reception through the shared wireless link, whereas the routing protocols are responsible for the selection of the best path in order to send packets from one source to one single-destination or multi-destination. Hence, choosing the best ones has a high effect on the overall network performance as well as on the energy consumption. Driven by the intense usage of some frequency bands, while others are being liberated (e.g., white spaces left by analogue television discontinuation) investigation on multi-hop CR networks has experienced an evolution in the latest years. The authors from [3] use graph theory for the routing algorithms, where the CR aspects are considered by assigning a different colours to each considered frequency band. The developed algorithm is not computationally heavy and based on hop-count for the routing. However, as pointed by the authors, they were not able to mitigate the interference between neighbours. In [4], the authors aim to minimise the interference between nodes. To achieve this objective, they propose the use of relays, with visible gains in the channel utilisation, energy consumption and delay.

This paper is organized as follows. Section II presents the architecture aspects of a BodyNet with electromagnetic energy harvesting and CR capabilities. Section III presents the communication aspects related with the CR approach. Section IV presents spectrum opportunities based on the field trials that where held in Covilhã, Portugal, and addresses the solutions for harvesting the RF energy. Finally, conclusions are drawn in Section V.

II. BODYNETS WITH ELECTROMAGNETIC ENERGY HARVESTING AND CR CAPABILITIES ARCHITECTURE

Dynamic spectrum access (DSA) can be used to mitigate spectrum scarcity. This is accomplished by enabling an unlicensed user (i.e., secondary user) to adaptively adjust its operating parameters and exploit the spectrum which is unused by licensed users (i.e., primary users), in an opportunistic manner. Therefore, CR allows for secondary users (SUs) to seek and utilize “spectrum holes” in a time and location-varying radio environment as long as they do not cause interference to the primary users (PUs) [5]. This opportunistic
use of the spectrum leads to new challenges, making the network protocols to adapt to the varying available spectrum. The extreme flexibility of CR has significant implications in the design of network algorithms and MAC protocols at both local/access network and global inter networking levels.

Therefore, we envisage new cross-layer algorithms which can adapt to the changes in the transmission link, based on the quality of the received signal, radio interference, radio node density, network topology or traffic demand. Hence, it may be required an advanced control and management framework with support for cross-layer information and internode collaboration [6]. Figure 1 shows a typical BodyNet scenario with CR. Depending on the spectrum availability, sensor nodes transmit their results from the sensing, to the next hops and ultimately to the sink [5] in an opportunistic manner.

![Fig. 1. Body area networks scenario with electromagnetic energy harvesting and CR capabilities.](image)

A DSA entity will be used to identify the CR opportunities, in which nodes can be equipped with Powerharvester receivers [7], facilitating to collect energy by converting the energy from the radio frequency waves to DC power. By using RF-based wireless scavenging devices, we intend to eliminate the cost of replacing batteries of wireless sensors, as well as eliminate the service downtime caused by depleted batteries.

Future improvements in RF energy harvesting technology will allow for the creation of a network without the need of a dedicated transmitter to a single-sided system. This is accomplished by enabling the capture of radio frequency waves emitted from existing and commonly used ambient RF energy sources, such as mobile base stations, TV and radio transmitters, microwave radios, and mobile phones, as presented in Fig. 1. Besides, 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 the creation of a always connected ubiquitous wireless power sensor network (UWPSN).

Moreover, a system that cognitively seeks the best signal available from multiple frequencies bands for collecting energy, and simultaneously finds the best transmission opportunities is envisaged. Hence, an adaptive frequency hopping (AFH) algorithm could be implemented, containing a blacklist of the bands which contain interference caused by the same/other protocols.

### A. Topology Aspects

Depending on the application, the scavenging BodyNets with CR capabilities may be applied to different scenarios, as follows:

- **Static Networks**: In ad hoc networks, nodes send their readings to the gateway node in a multi-hop manner. In addition, the bandwidth availability and computing resources (e.g., hardware and battery power) are restricted. Therefore, to overcome these limitations joint optimization between the MAC and physical (PHY) layers, to maximize energy efficiency, must be addressed. In the scenario presented in Fig. 1, a CR node senses several channels simultaneously and chooses the best ones to transmit data to the receiver. Besides, by considering the PHY layer measurements, an RF-based scavenged device can be used, to power the sensor nodes based on local measurements (e.g., by using WiFi inside the hospital).

- **Mobile Networks**: In static networks, node position can be determined once during initialization. However, in a mobility scenario, since nodes frequently change position, some adjustments in the transmission power may be required (e.g., when nodes are close to each other, their transmission power can be lowered). The challenge in node mobility is how to cope with motion on different speeds, which dictates the frequency of transmission power updates. Besides, our CR system must be capable to adapt to the frequent changes in the control and data channels that may vary in different clusters. This requires additional time and energy, as well as the availability of a rapid localization service. Since frequent updates have a great impact in the network performance, we can collect the electromagnetic energy from RF signals by using available the spectrum opportunities.

- **Hybrid**: In a hybrid ad hoc BodyNets, nodes are mobile and stationary. Therefore they are able to form connections at both MAC and network layers. When mobile nodes are inserted into the static network, in order to maintain the connectivity of the network, route information must be set up, which increases the drain of the power source. Hence, mobility-aware dynamic spectrum management CR solutions must be considered to overcome the challenges covered by this additional source of complexity. Spectrum sensing parameters include signal-to-noise ratio (SNR), frequencies available and RF energy harvesting opportunities, based on the energy detection performed at the PHY layer.

### B. Cognitive Sensor Node Hardware

The cognitive sensor node hardware of the BodyNets is composed by four sub-systems: i) communication, ii) comput-
tational and storage, iii) sensing and actuation, and iv) power. Figure 2 presents the general hardware architecture.

The description of each sub-system is as follows:

- **Communication**: The communication sub-system consists of a radio transceiver and an antenna which enables the wireless communications between neighbouring nodes.

- **Computational and storage**: This sub-system allows for data processing and the management of the nodes functionalities.

- **Sensing and Actuation**: The interfaces between the environment and the BodyNet are the sensors and the actuators. Basic environmental sensors include, but are not limited to, light, temperature, humidity, pressure, acceleration/seismic, acoustic, magnetic and sound. Basic environmental actuators include, but are not limited to, light-emitting diodes, speakers and buzzers.

- **Power**: The appropriate energy infrastructure to supply the nodes, includes the batteries and the energy scavenging systems, which allows for supporting the operation of the nodes from a few hours to months or years.

The inclusion of a cognitive radio transceiver in the communication sub-system is the main difference between the hardware structure of CR sensor and classic sensors.

III. COMMUNICATION ASPECTS OF BODYNETS WITH CR CAPABILITIES

This section investigates the specific cross-layer design aspects, between the PHY, MAC and network layers of a cognitive radio sensor node.

A. Physical Layer Aspects

The physical layer acts as a mediator between the data link layer and the physical wireless environment. Since cognitive radios need to sense the spectrum in order to find spectrum opportunities, the physical layer is also responsible of spectrum sensing, reporting it to the microprocessor of the CR node. As presented in Fig 3, the PHY layer also aims at the reconfiguration of the transmission parameters according to the decisions from the microprocessor.

BodyNets which do not consider CR capabilities impose environmental and propagation constraints that must be taken into account in system design:

- Current draw is 400 μA and 1 μA for the active and idle modes, respectively [8].

- Typically, the sensor nodes are placed near the human skin, which imposes restrictions to the transmitter power from the radio transceiver, as the radiation caused by the large wireless transmission power may possibly harm human health. The IEEE 802.15.6 group, which is focused in wireless body area networks (WBANs), already foresees and advises these thresholds. Safe transmitter power thresholds are depend according to the location of the sensor node relatively to the human body.

- The surrounding environment of BodyNets produces situations such as the phenomena of body shadow effect already identified by the authors of [9]. This effect is due to the propagation of signal over the human body.

- The multi-path effect leads to interference due to the reflection of the radiated signal. This is caused by the ground and surrounding objects. In BodyNets the values of reflection signal depends on the position of the sensor node in the human body [10].

- The antenna characteristics cause some negative impact in the overall performance of BodyNets. The coupling effect appears and depends much on the relative positions of the sensor nodes in human body.

BodyNets with no CR capabilities must be able to cope with the majority of the aforementioned effects in order to properly receive the low power signal. Therefore, the use of CR capabilities in BodyNets must also consider these design requirements of the system in order to be efficient.
In addition, to the environmental and propagation constraints, the CR transceiver hardware must be suitable to enable CR operations in BodyNets. The ability of the CR to reconfigure the physical layer parameters (i.e., modulation, channel coding, transmitting power) is the main difference between the wireless sensor network (WSN) and the cognitive radio sensor network (CRSN) physical layer. This *in situ* reconfiguration does not require hardware replacement. To accomplish this reconfiguration, software defined radio (SDR) based RF front-end transmitters and receivers are needed. Special attention is needed in the use of SDRs due to the nodes’ scarce power supply in BodyNets. Energy harvesting is a solution to complement the power supply requirements in the context of SDR in CR sensor nodes. A preferable solution is the development of SDRs specifically to energy-efficient CR sensor nodes. The spectrum sensing task of the CR sensor nodes is a challenging issue due to its limited processing capabilities. Spectrum sensing is a highly demanding signal processing task, since the radio signals in BodyNets are weak and with possible large background noise. Digital signal processing (DSP) hardware and algorithms can be added to the CR sensor node to achieve more efficient wideband spectrum opportunities sensing and detection. Furthermore, if conventional SDRs applied to CR sensor nodes are not considered, it is impossible to support different modulations schemes, waveforms or supporting wideband spectrum sensing, due to the limited processing capabilities of the CR sensor node. Another design consideration aspect in BodyNets with CR capabilities is the development of transmission power and interference adaptive algorithms that cope with interference in the deployment of CR sensor nodes over the human body.

### B. MAC Layer Aspects

The MAC protocols are responsible to determine and change the operation mode of the radio transceiver, allowing for nodes to access the medium in a more fair and efficient manner. Compared to conventional WSNs, the MAC layer of a CRSN nodes 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]. In BodyNets 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 [11]. The use of a CRTS/CCTS mechanism on a separated control channel packets allows for decreasing the number of collisions, whereas the DATA and ACK packets could be transmitted in a group of frequency bands, as shown in Fig. 4. Therefore, compared to conventional WSNs, the MAC layer of BodyNets with CR capabilities must address additional challenges regarding the coordination of dynamic spectrum access, as follows:

- **Spectrum sensing and decision results**: Cooperative sensing [12] and decision results are used to increase sensing accuracy and sharing efficiency. Therefore nodes must share extra control information. The CR MAC protocol must include mechanisms to share information with higher priority.

- **Minimum overhead**: The wide range of MAC protocols for BodyNets use control packets. This type of packets can be received by all nodes within radio range of the sender, resulting in an increase of the power drain in a potentially large number of nodes. Since nodes are required to remain awake in order to receive control packets, the battery life can be significantly reduced. Therefore, it is envisaged a CRSN with minimum exchange of control packets and without the need of having additional hardware requirements (i.e., an extra transceiver or GPS for synchronization). This can be accomplished by using a block acknowledgment (BACK) policy feature [13]. 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 [14].

- **Adaptive duty cycle**: Since the spectrum opportunities are time and location variant, self-adaptive mechanisms must be introduced. Therefore, based on the spectrum sensing measurements we can increase the duty cycle, which means more opportunities to cover multiple neighbours with one forwarding. Besides, since collecting RF energy to power the sensor nodes is foreseen based on the available energy and CR opportunities, a threshold can be implemented to send packets based on the existing energy scavenging opportunities versus interference metrics.

### C. Network Layer Aspects

Cognitive networks and its design aspects are very challenging for the network layer design. In traditional wireless networks, the nodes use the same frequency to communicate with each other. Thus, routing is performed by considering only one link between neighbours. In cognitive radio networks, the network layer is responsible for choosing the best next hop as well as the frequency to use. This brings an extra load to the routing algorithm, since it must also take into account the readings from the spectrum to decide the routes for the packets to follow. Therefore, the first challenge is how to have available information on the spectrum usage. This information

![CRTS/CCTS/DATA/ACK handshake](image_url)
must be provided by an external (to the routing) entity that constantly monitors the communication bands and evaluates its interference or not. This can be performed by the node locally, using its own sensing capacities, can be provided by an external entity dedicated to that task, or by a combination of these two, in which neighbouring nodes exchange information about their spectrum sensing. The second challenge is how to combine the information gathered and choose the optimal path for the packets to be sent. Traditional approaches use hop-count, RSSI strength or Quality-of-Service (QoS) metrics to decide the best routes for the packets; however in CR networks the frequency to be used must also be included in the algorithm. With the dynamic nature of the spectrum, and constant frequency usage by other entities, the algorithm will have to adapt the paths to the current conditions of the channel. However, open research issues are still open, and must be addressed in order to have a complete network solution as follows:

- **Spectrum aware routing**: When nodes send packets through the network, spectrum sensing techniques must be addressed to opportunistically route data packets across paths avoiding spectrum congested areas. To achieve this goal, innovative awareness mechanisms (that facilitate to know 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.
- **Adaptive and QoS routing**: Cross-layer mechanisms will be responsible for providing up-to-date local QoS information for the adaptive routing protocol. Hence, new techniques based on varying channel conditions must be taken into consideration for real time communication in CRNs.
- **Multi-hop routing maintenance and reparation**: In a multi-hop CR scenario the sudden appearance of a PU in a given location may impose an unusable channel for the SUs, leading to unpredictable route failures. Therefore effective signalling mechanism must be addressed to restore the paths with minimal effect on the network performance.

**IV. INDOOR AND OUTDOOR SPECTRUM OPPORTUNITIES**

In order to seek for the best spectrum opportunities, we have conducted several field trial measurements in Covilhã, Portugal, in both indoor and outdoor environments, by using the NARDA spectrum analyser [15]. By analysing the power density measurements in 36 different places locations, we intend to find the best frequencies for harvesting the electromagnetic energy, as well as to identify the best CR opportunities for BodyNets. Besides, the identified spectrum opportunities are being considered to conceive multi-band antennas. The location of the measurements is shown in Fig. 5.

To determine the received power, $P_r$, of the spectrum analyser, we multiply the power density, $P_d$ by the effective receiving area of the antenna, $A_e$ as follows:

$$P_r[W] = P_d \cdot A_e$$  \hspace{1cm} (1)

where the effective area of the antenna, $A_e$ is given by:

$$A_e[m^2] = \frac{\lambda^2 \cdot G}{4 \cdot \pi}$$  \hspace{1cm} (2)

and $P_d$ is given as follows:

$$P_d = \frac{|E|^2}{120 \cdot \pi}$$  \hspace{1cm} (3)

where $P_d$ is the power density in $W/m^2$, $G$ is the antenna gain of the receiver ($G = 1$) and $\lambda$ is the wavelength, in $m$.

To decide which are the best frequency bands to harvest electromagnetic energy in a given location, we calculated the average of all $P_r$, for a wide range of frequency bands, namely covering the frequencies from 75 to 3000 MHz. The average received power, $\overline{P_r}[W]$, for a given frequency is given as follows:

$$\overline{P_r}[W] = \frac{\sum_{i=1}^{n} P_{ri}[W]}{n}$$  \hspace{1cm} (4)

where, $n$ is the number of measurements taken in the same scenario, for each frequency for the indoor and outdoor scenarios and frequencies between 75 and 3000 MHz. The average received power, in $dBm$, is given as follows:

$$\overline{P_r}[dBm] = 10 \cdot \log \left( \frac{P_r[W]}{0.001} \right)$$  \hspace{1cm} (5)

The field trial results for the indoor scenarios are shown in Fig. 5 for the locations numbers 7, 10 and 11. The corresponding values of the average received power are presented in Fig. 6.

In the public building indoor scenario, the set of frequencies with more available harvested energy comprises the range from 79 to 96 MHz (radio broadcast stations), 390 to 392 MHz (emergency broadcast stations), 750 to 758 MHz (television broadcast stations), 935 to 960 MHz (GSM 900 broadcast

![Fig. 5. Locations of the measurement in Covilhã.](image-url)
stations), 1775 to 1761 MHz (GSM 1800 broadcast stations), 1855 to 1868 MHz (GSM 1800 broadcast stations) and 2115 to 2160 MHz (UMTS broadcast stations).

![Fig. 6. Average received power for the indoor scenario.](image)

The location of the field trial results for the public places in a outdoor scenario are identified in Fig. 5 with the numbers 8, 9, 12, 13, 14, 21, 22. The corresponding values of the average received power are shown in Fig. 7.

![Fig. 7. Average received power for the outdoor scenario.](image)

The set of frequencies with more energy available for harvesting are in the range from 79 to 96 MHz (radio broadcast stations), 391 MHz (emergency broadcast stations), 750 to 759 MHz (television broadcast stations), 935 to 960 MHz (GSM 900 broadcast stations), 1854 to 1870 MHz (GSM 1800 broadcast stations) and 2115 to 2160 MHz (UMTS broadcast stations), as shown in Fig. 7.

Table I presents the list of the GSM frequencies being used by the three mobile operators in Portugal. Other spectrum frequency allocations in Portugal are presented in [16].

<table>
<thead>
<tr>
<th>Operator</th>
<th>GSM 900 MHz</th>
<th>GSM 1800 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uplink</td>
<td>Downlink</td>
</tr>
<tr>
<td>A</td>
<td>900.2</td>
<td>935.2</td>
</tr>
<tr>
<td>B</td>
<td>906.0</td>
<td>951.0</td>
</tr>
<tr>
<td>C</td>
<td>898.2</td>
<td>943.2</td>
</tr>
</tbody>
</table>

By comparing the results from Figures 6 and 7 with Table I, we conclude that the RF energy harvesting is a promising future for power supply future BodyNets. Besides, our field trials show that for both indoor and outdoor scenarios, the set of frequencies with more available energy for harvesting also comprises the range of frequencies from the Portuguese mobile operators. In [17], the authors show that energy scavenging (tested from 2 to 18 GHz) could be achieved by employing broad-band rectenna arrays, which allows for converting RF energy in usable DC energy. For specific frequency bands such the 2.4 GHz ISM band, a system for powering sensor nodes has been presented in [18]. The system consists of a 4x4 antenna array followed by a diode detector section, a DC combining section and power control and management module. Besides, powerharvester receivers can be used to power supply the sensor nodes. The configurable frequency range is from 1 MHz to 6 GHz. Additionally, a transmitter can be used to wirelessly power the nodes located at least 10 m away. Therefore, by combining powercast RF transmitters and receivers, we can add new energy harvesting capabilities to the sensor nodes, providing a predictable and reliable power system, that uses controlled broadcasted RF energy for wirelessly charge the battery-based systems. Table II presents the expected power scavenged by using the P2110 powerharvester receiver and the TX91501 powercaster transmitter, and the time needed to recharge a battery with a capacity of 1150 mAh.

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>P [pW]</th>
<th>I [μA]</th>
<th>Recharge time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.52</td>
<td>1925</td>
<td>1604</td>
<td>42.24</td>
</tr>
<tr>
<td>3.05</td>
<td>386</td>
<td>322</td>
<td>210.5</td>
</tr>
<tr>
<td>4.57</td>
<td>139</td>
<td>138</td>
<td>429.40</td>
</tr>
<tr>
<td>5.49</td>
<td>131</td>
<td>109</td>
<td>618.5</td>
</tr>
<tr>
<td>6.10</td>
<td>102</td>
<td>85</td>
<td>797.5</td>
</tr>
<tr>
<td>7.62</td>
<td>50</td>
<td>41</td>
<td>1639</td>
</tr>
<tr>
<td>9.14</td>
<td>19</td>
<td>16</td>
<td>4353</td>
</tr>
<tr>
<td>10.67</td>
<td>5</td>
<td>4</td>
<td>3517</td>
</tr>
<tr>
<td>10.97</td>
<td>1</td>
<td>1</td>
<td>70019</td>
</tr>
</tbody>
</table>

Based on Table II and Figure 7, we state that sensor management strategies must be implemented based on the CR frequency availability and electromagnetic energy harvesting opportunities. Therefore, properties such as power consumption, mobility and available frequencies must be accounted when designing RF harvesting BodyNets with CR capabilities. Besides, cross-layer design must be as efficient as possible to minimise the energy cost of the software application. New energy models, based on CR measurements, must also be addressed, which allows for estimating the battery lifetime based on the electromagnetic energy harvesting opportunities, as well as the discharge duration based on transmitted packets. Additionally, and based on Table II, controllable broadcasted RF energy transmitters could be used to work in locations where other potentially intermittent energy scavenging sources (e.g., solar, vibration and heat) are not available.

Over the past years, several different WSN suppliers have appeared, showing that the sensor nodes could operate for several years. However, in real time situations, it is not easy to predict the real lifetime of a sensor node. This is explained by...
the fact that they can have different traffic demands which, in turn, can change the duty cycle of sensor nodes. Our vision is that there must be a compromise between the communication and the processing tasks, allowing for balance the BodyNet lifetime with the energy supplied by the batteries plus the energy of the scavenging device. Figure 8 presents an RF-based energy harvesting scenario. This widespread wireless power coverage scenario will enable future BodyNets to operate without the need of replacing batteries, as well as providing a more predictable power supply for the wireless sensor nodes. Moreover, this emerging RF-based energy harvesting devices reduce the maintenance costs of replacing batteries.

Fig. 8. Body area networks scenario with RF energy harvesting.

V. CONCLUSIONS

In this paper we present a scenario for CR enabled WSNs with electromagnetic energy harvesting capabilities. The BodyNet considered scenario consists of a BAN gathering physiological information from a patient and sending it to the hospital, regardless his/her location. We presented the PHY, MAC and network challenges that are brought by the CR, and discussed how they can be addressed. Besides, energy scavenging is considered to power the WSN nodes. We studied the spectrum opportunities to utilise the received power for 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 (radio broadcast stations), 391 MHz (emergency broadcast stations), 750 to 758 MHz (GSM 900 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), comprising the range of frequencies from the Portuguese mobile operators. An RF energy harvesting mechanism has been proposed enabling future BodyNets to operate without the need of replacing batteries. This study is going to be utilized in the context of PROENERGY-WSN [19], Portuguese Foundation for Science and Technology (FCT) project.

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