

Antennas and Circuits for Ambient RF Energy Harvesting in Wireless Body Area Networks

Norberto Barroca¹, Henrique M. Saraiva¹,
Paulo T. Gouveia¹, Jorge Tavares¹, Luís M.
Borges¹, Fernando J. Velez¹, Caroline Loss²
and Rita Salvado²

¹Instituto de Telecomunicações/DEM
²Textile and Paper Materials Research Unit
Universidade da Beira Interior
Covilhã, Portugal
{d708, m5212, m4788, m1612, lborges,
fjv, m4280, rita.salvado}@ubi.pt

Pedro Pinho^{3,4}, Ricardo Gonçalves^{3,5}
and Nuno Borges Carvalho^{3,5}

³Instituto de Telecomunicações,
Aveiro, Portugal
⁴Instituto Superior de Engenharia
de Lisboa, Lisboa, Portugal
⁵Universidade de Aveiro, Aveiro, Portugal
ppinho@deetc.isel.pt, goncalves@av.it.pt,
nbcarvalho@ua.pt

Raúl Chavéz-Santiago and
Ilangko Balasingham

Intervention Centre,
Oslo University Hospital
Institute of Clinical Medicine
University of Oslo
Norwegian University of Science
and Technology (NTNU)
raul.chavez-santiago@rr-research.no,
ilangko.balasingham@medisin.uio.no

Abstract—In this paper, we identify the spectrum opportunities for radio frequency (RF) energy harvesting through power density measurements from 350 MHz to 3 GHz. The field trials have been performed in Covilhã by using the NARDA-SMR spectrum analyser with a measuring antenna. Based on the identification of the most promising opportunities, a dual-band band printed antenna operating at GSM bands (900/1800) is proposed, with gains of the order 1.8-2.06 dBi and efficiency 77.6-84%. Guidelines for the design of RF energy harvesting circuits and choice of textile materials for a wearable antenna are also discussed. Besides, we address the guidelines for designing circuits to harvest energy in a scenario where a wireless body area network (WBAN) is being sustained by a TX91501 Powercast[®] RF dedicated transmitter and a 5-stage Dickson voltage multiplier responsible for harvesting the RF energy. The IRIS motes, can perpetually operate if the RF received power is at least -10 dBm.

I. INTRODUCTION

Future improvements in radio frequency (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 [1]. This can be accomplished by enabling the capture of electromagnetic energy from multiple available ambient RF energy sources, such as mobile base stations, TV and radio transmitters, microwave radios, and mobile phones. Moreover, since wireless body area network (WBAN) nodes are battery operated, energy recharging is a possibility, avoiding the need of battery replacement. However, the service lifetime of the electronic components could be a major concern if there is no possibility to collect enough energy to generate the voltage needed to drive the sensor mote. Medium access control (MAC) and routing protocols also play an important role in the network performance [2]. As a consequence, choosing the best opportunities has a high effect on the overall network performance, as well as on the energy consumption. In the context of WBANs, electromagnetic RF energy harvesting is accomplished by using wearable antennas that allow for power supplying the sensor nodes [3]. Ubiquitously available RF sources, operating at different bands, are therefore exploited for RF electromagnetic energy harvesting purposes.

In this work, we have identified the opportunistic radio frequency bands for RF energy harvesting. Moreover, based on power density measurements, we have been able to identify the best spectrum opportunities that may be considered in order to conceive multiband antennas for electromagnetic energy harvesting. Besides, we present the guidelines for the development of wearable flexible antennas and designing circuits to harvest RF energy. The RF energy harvesting system to be developed in the context of the PROENERGY-WSN project [4] consists of an impedance matching circuit, rectifier and energy storage.

The remainder of the paper is organized as follows. Section II addresses the spectrum opportunities based on the field trials that were held in Covilhã, Portugal. Section III describes an efficient dual-band antenna for collecting RF energy. The guidelines for the choice of textile materials to be used in future wearable antennas are also presented. Section IV presents simulation results for the dimensioning of a 5-stage Dickson voltage multiplier for collecting RF energy and the simulation results are presented and discussed. Section V discusses the variation of the power harvested in a WBAN being sustained by dedicated RF energy transmitters. Finally, conclusions are drawn in Section VI.

II. 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-SMR spectrum analyser with a measuring antenna.

A. Average Received Power

By analysing the power density measurements in 36 different locations, we intend to find the best frequencies for RF energy harvesting. Besides, the identified spectrum opportunities are being considered to conceive multi-band antennas. The location for the measurements is shown in Fig. 1. 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 , and gain, $G=1$, as follows:

$$P_d[W/m^2] = |E^2|/(120 \cdot \pi) \quad (1)$$

This work was supported by the Ph.D. FCT grants FRH/BD/66803/2009, SFRH/BD/38356/2007, by PEst-OE/EEI/LA0008/2011, Marie Curie Reintegration Grant PLANOPTI (FP7-PEOPLE-2009-RG), the European Social Fund (ESF), UBIQUIMESH, OPPORTUNISTIC-CR, PROENERGY-WSN, INSYSM, CREaTION, COST IC905 "TERRA" and COST IC1004.

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

where E is the electric field and λ is the wavelength.



Figure 1. Locations of the measurements in Covilhã, Portugal.

To decide the best frequency bands for electromagnetic energy harvesting, we have determined the average of each of the n values of the received power, P_{ri} [W] in linear units, in five different locations, where n is the number of taken measurements, for each frequency. The average received power, in dBm, is given as follows:

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

B. Indoor Opportunities

Figure 2 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).

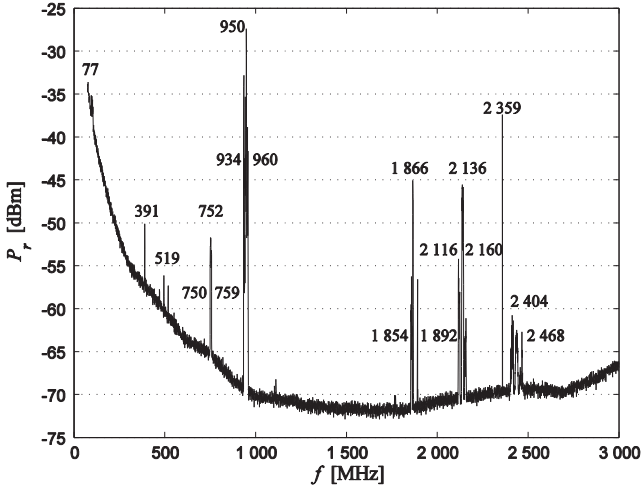


Figure 2. Average received power as a function of the frequency for the University scenario (indoor).

C. Outdoor Opportunities

The location of public places in the outdoor scenario for the field trial results are identified in Fig. 1, for the locations

numbers 8, 9, 12, 13, 14, 21 and 22. The corresponding values of the average received power are shown in Fig. 3. The set of frequencies with more energy available for harvesting are in the range from 79 to 96 MHz (mobile/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).

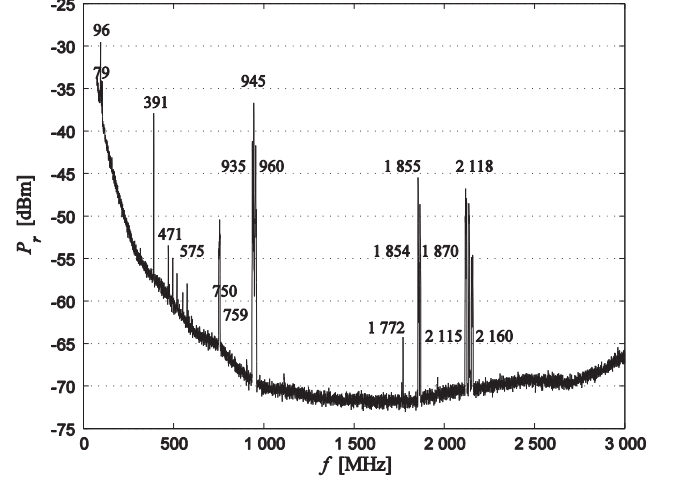


Figure 3. Average received power for the outdoor scenario.

III. ANTENNA FOR RF ENERGY HARVESTING

A. Dual-band antenna

In the previous section we have identified the GSM (900/1800) has the most promising bands for RF energy harvesting. In this section, we propose a dual-band antenna suitable for possible implementation within clothes for body worn applications based on spectrum opportunities, as shown in Fig. 4. Table I presents the corresponding dimensions [5].

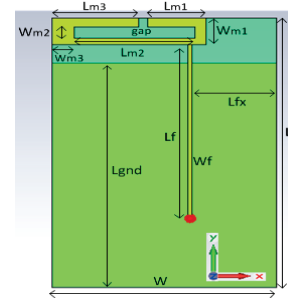


Figure 4. Proposed dual-band antenna geometry.

TABLE I. PROPOSED DUAL-BAND ANTENNA DIMENSIONS

Parameter	Dimension [mm]
L, L_{gnd}, L_f, L_{fx}	120, 100, 78, 30
$Lm1, Lm2, Lm3, gap$	21, 43, 31, 3
$W, W_f, Wm1, Wm2, Wm3$	80, 1.5, 12, 5, 8

A *Cordura*[®] cloth type was considered which presents a permittivity, ϵ_r , of 1.9, loss tangent, $\tan \delta$, of 0.0098 and relative height of 0.5 mm. For the conductive sections of the antenna an electrotextile (*Zelt*), with an electric conductivity 1.75×10^5 S/m was considered. The return loss obtained from

numerical simulations of the proposed dual-band antenna is presented in Fig. 5, considering a return loss $S_{11} < -10$ dB (shaded area in Fig. 5).

The lowest frequency band considered is from 820 MHz to 1000 MHz, covering the entire E-GSM band, while the highest considered band is in the range 1690 MHz to 1930 MHz, covering the entire DSC1800 band. It is worth noting, however, that the radiation pattern for the dual-band antenna suffers a deformation at 1800 MHz. The obtained radiation pattern in the YZ and XZ planes (see Fig. 4) for the proposed antenna, based on numerical simulation and is shown in Fig. 6.

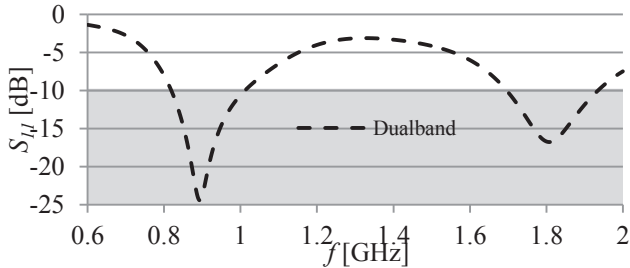


Figure 5. Simulated return loss of the dual-band antenna.

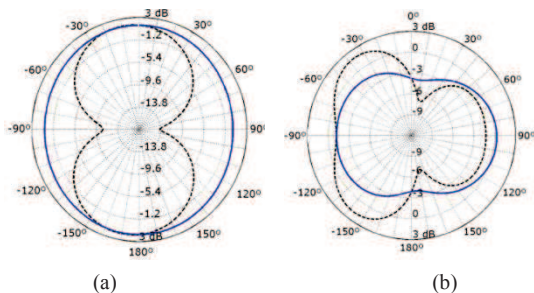


Figure 6. Simulated radiation pattern for the dual-band antenna in the YZ plane (dashed) and XZ plane (blue solid), at a) 900 MHz and b) 1800 MHz.

The gains for the dual-band antenna are about 1.8 dBi and 2.06 dBi, with a radiation efficiency of 82% and 77.6% for the lowest and highest operating frequency bands, respectively.

B. Guidelines for the development of wearable flexible antennas

Specific requirements for wearable antennas are the planar structure and flexible materials. Textiles, being universally used and easily available, are appropriate materials to design wearable antennas. However, some characteristics of the materials highly influence the performance of the antenna. For instance, the selection of fabrics for dielectrics must take into account the dielectric constant and the loss tangent, for a specific frequency, the thickness, the moisture content in a specific environment (Regain), as well as the geometrical and mechanical stability of the fabric. In general, ordinary textiles present a very low dielectric constant, in the range between 1 and 2 (as they are very porous). However, textile materials are constantly exchanging water molecules with the environment which might increase their dielectric constant. Therefore, fabrics for dielectrics should present a low Regain. For the conductive components of planar antennas, specific electrical conductive textiles have been successfully used, and are available on the market.

IV. RF ENERGY HARVESTING CIRCUITS

One of the main factors that influence RF energy harvesting is the path loss. The Friis free-space equation relates the received power, P_r , at a distance, d , with the transmitted power, P_t , as follows:

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \quad (4)$$

where, G_t and G_r are the antenna gains of the transmitter and receiver, respectively. Based on equation (4), we can observe that, the received power depends on the frequency (the higher the frequency the lower the received power is), and decreases with the square of the distance (path-loss exponent equal to 2). To conceive an RF energy efficient rectifier which enables to rectify and amplify the input voltage (corresponding to P_r), the Cockcroft–Walton and Dickson voltage multiplier circuits can be considered, as shown in Figs. 7 a) and b). This work only addresses the Dickson voltage multiplier since, according to [6], both topologies have a similar performance.

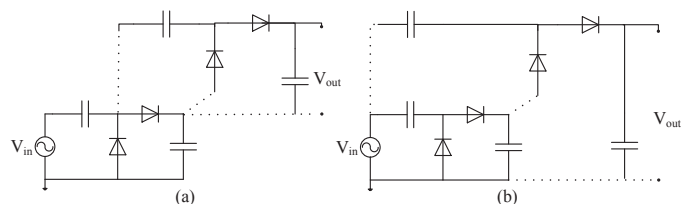


Figure 7. Voltage multiplier circuits with two stages: a) Cockcroft–Walton and b) Dickson.

In order to have a self-sustainable WBAN, energy efficient harvesting and management techniques must be considered. However, one of the drawbacks of wireless sensor devices is the finite battery capacity, as well as the voltage generated by the RF energy circuit, since it may be insufficient to drive the *motes* (i.e., at least 1.8V for the IRIS *mote*). Therefore, by means of simulation, we address the main aspects and parameters that influence the performance of the Dickson voltage multiplier such as, e.g., the choice of diodes, the number of stages and the load impedance. We have used the Advanced Design System (ADS) [7] from Agilent by varying the RF received power, P_r , from -50 dBm to 20 dBm. The considered centre frequency is equal 945 MHz since, in the previous sections, we have identified the GSM 900 band as the most promising one for RF energy harvesting. The Dickson voltage multiplier presented in Fig. 7 b) is mainly formed by diodes and capacitors in parallel (instead of being in series, as for the Cockcroft–Walton voltage multiplier). As the input peak voltage from the antenna signal is usually much lower than the diode forward conduction voltage [6], diodes with low turn-on voltage have been considered. Therefore, we considered HSMS-2850 Schottky diodes from Avago Technologies optimized for low power applications (in our simulation).

The number of rectifier stages has a major impact on the output voltage of the Dickson voltage multiplier. According to [8], the output open circuit voltage (OCV) of an N -stage Dickson voltage multiplier is given as follows:

$$V_{out} = 2 \cdot N \cdot (V_{in} - V_T) \quad (5)$$

where N is the number of stages, V_{in} is the input voltage amplitude and V_T is the forward conduction voltage of diodes. As shown in equation (5) the output voltage is directly proportional to the number of stages. However, practical restrictions (e.g., conversion efficiency) limit the number of permissible stages.

Figures 8 and 9 analyse the impact of the number of stages (3, 5 or 8) on the output voltage and conversion efficiency of the Dickson voltage multiplier, by assuming a load impedance of 100 k Ω . The effect was obtained through a harmonic balanced analysis (i.e., a frequency domain method) that evaluates the steady state solution of a nonlinear circuit.

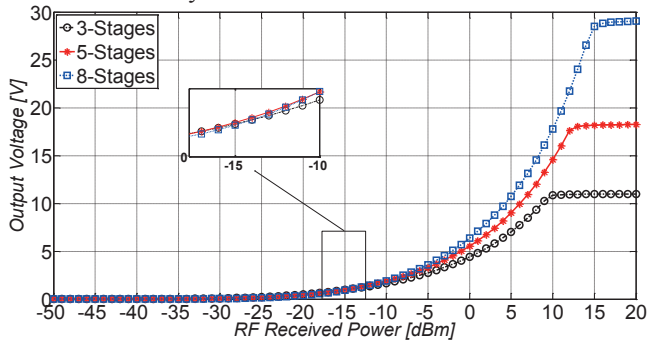


Figure 8. Impact of number of stages on the output voltage for an N -stage Dickson voltage multiplier.

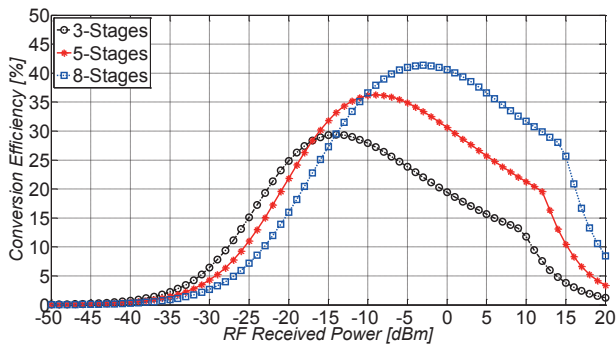


Figure 9. Impact of number of stages on the conversion efficiency for an N -stage Dickson voltage multiplier.

By analysing Fig. 8, we conclude that, by increasing the number of stages we increase the output voltage. The saturation values are theoretically obtained by multiplying the number of stages by the reverse breakdown voltage (i.e., 3.8V for HSMS-2850). By considering the number of stages equal to 3, 5 or 8 the maximum output voltage obtained by simulation is approximately 11, 18 and 29 V, respectively, which correspond to RF input received powers of 10, 12 and 15 dBm.

Figure 9 presents the effect of the RF received power on the conversion efficiency. By adding more stages, the peak of conversion efficiency curve shifts towards the higher received power region. These results are similar to the ones presented by the authors in [9]. Therefore, we have chosen the 5-stage Dickson voltage multiplier as the best circuit for RF energy harvesting for WBANs. This is explained by the fact that more than 5 stages will not bring substantial improvement for the power levels considered, due to energy losses along the chain [6]. Moreover, since the wireless sensor nodes need at least

1.8V for operation (i.e., approximately -10 dBm RF input power), the 5-stage Dickson voltage multiplier is the one who presents the best performance in terms of conversion efficiency.

Figure 10 presents the impact of the load impedance on the conversion efficiency of the 5-stage Dickson voltage multiplier. Based on the simulation results we can conclude that the optimal conversion efficiency is achieved when the load impedance is 50 k Ω . If the resistive load value is too low or too high, the conversion efficiency greatly decreases. In WBAN the nodes equivalent impedance is different for each radio operation state (i.e., RX, TX and SLEEP). According to [9], the value of the impedance from Mica2 in the deep sleep state is 100 k Ω . This value is considered as the impedance reference load for the IRIS *notes*.

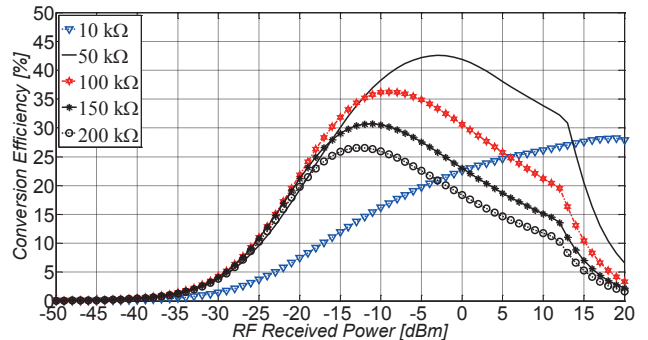


Figure 10. Impact of load impedance in the conversion efficiency for a 5-stage Dickson voltage multiplier.

V. RF WIRELESS CHARGING AND ENERGY HARVESTING

Nowadays, RF energy is being transmitted from billions of radio transmitters around the world, including mobile cell phones, handheld radios, mobile base stations, and television/radio broadcast stations. There are therefore plenty of opportunities for harvesting this RF energy for power supply nodes from WBANs. Although the opportunities for energy harvesting are vast, the amount of energy collected could not be enough for power supply the wireless nodes for a WBAN.

In previous sections, it has been shown that it is possible to harvest RF electromagnetic energy from multiple sources. However, nodes typically need to be power supplied by a source able to provide at least 1.8 V, i.e., -10 dBm by considering a 5-stage Dickson voltage multiplier like the one previously presented. Therefore, by combining the TX91501 Powercast[®] RF transmitter with a power output of 3W and the N -stage Dickson voltage multiplier, 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 battery-based systems. Figure 11 presents the available received power for RF energy harvesting by considering Equation (4), where the effective isotropic radiated power (EIRP), $P_t \cdot G_t$, is 3W, G_r is 3.98 and the operation frequency is 945 MHz. By analysing the obtained results, one may conclude that dedicated power transmitters can be used to wirelessly power the sensor nodes located at less than 9 m away from each other corresponding to the received power higher than -10 dBm.

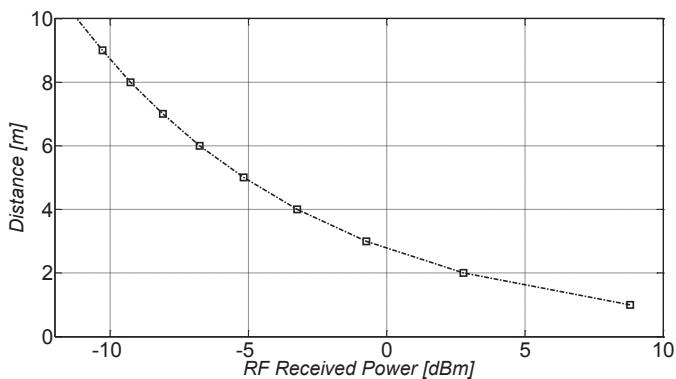


Figure 11. Distance between wireless sensors versus amount of power harvested by the 5-stage Dickson voltage multiplier.

By analysing Figs. 9 and 10 the range of power corresponds to values of the conversion efficiency in the descendent part of the curves (with load impedance of 100 k Ω). Besides, for short-range applications the 5-stage Dickson voltage multiplier could be used for store the RF energy directly into a battery. However, for longer-range applications, it is advised to accumulate the energy in a supercapacitor before directly powering up circuits or charging batteries, since we may only obtain intermittent pulses of energy. The use of supercapacitors allows faster charging times, better discharge performance and “unlimited” virtually life cycles. The choice of the supercapacitors is justified by the fact that batteries suffer from some non-linear characteristics, such as degradation and saturation (due to high constant current drain). Note however that the main disadvantage of supercapacitors is their high “self-discharge” characteristic. Based on the presented characteristics, a system is envisaged where both batteries and supercapacitors are used, enabling to overcome the saturation and degradation problem from the batteries, if they are only used during the mote’s sleep state (i.e., very low current drain), whilst the supercapacitors are being charged. During the active state, nodes can be power supplied by supercapacitors, turning off the batteries. This way, higher current consumptions will not degrade batteries, increasing the network lifetime. Moreover, we can also conclude that the spectrum opportunities presented in Section II may not be enough to power supply the current WBANs platforms. This is due to the insufficient energy available, which corresponds to powers in the range -27 dBm to -37 dBm. To mitigate this very low received power we envisaged the use of highly efficient DC-to-DC boost converter (e.g. BQ25504 highly efficient DC-to-DC boost converter) placed between the rectifying antenna circuit and the storage device. This device manages power from a variety of sources (such as solar, thermal electric, electromagnetic and vibration energy [10]) in the range between microwatts (μ W) and milliwatts (mW).

VI. CONCLUSIONS

In this paper we have identified 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). For the GSM (900/1800) frequency bands, a dual-band printed antenna has been proposed, with gains of the order of 1.8-2.06 dBi and 77.6-84% efficiency. The design of RF energy harvesting circuits and the choice of textile materials for a wearable antenna were also analysed. We also simulated the behaviour of a 5-stage Dickson voltage multiplier for power supplying an IRIS mote, which can perpetually operate if the RF received power is as least -10 dBm. However, the transmission opportunities must be carefully selected according to the estimated battery lifetime based on the electromagnetic RF energy harvested. A scenario where RF dedicated transmitters are used has briefly analysed in the PROENERGY-WSN [4]. It enables future WBAN to operate without the need of replacing batteries.

ACKNOWLEDGMENT

We would like to thank Prof. Luis M. Correia and Eng. Daniel Sebastião for making the NARDA-SMR spectrum analyser with measuring antenna available to us.

REFERENCES

- [1] H. Jabbar, Y. S. Song and T. T. Jeong, “RF energy harvesting system and circuits for charging of mobile devices,” *IEEE Transactions on Consumer Electronics*, vol. 56, no. 1, pp. 247-253, Feb. 2010.
- [2] N. Barroca, J. M. Ferro, L. M. Borges, J. Tavares and F. J. Velez, “Electromagnetic Energy Harvesting for Wireless Body Area Networks with Cognitive Radio Capabilities,” in *Proc. of URSI Seminar of the Portuguese Committee*, Lisbon, Portugal, Nov. 2012.
- [3] J. S. Bellon, M. Cabedo-Fabres, E. Antonino-Daviu, M. Ferrando-Bataller and F. Penaranda-Foix, “Textile MIMO antenna for Wireless Body Area Networks,” in *Proc. of the 5th European Conference on Antennas and Propagation (EUCAP)*, Rome, Italy, Apr. 2011, pp. 428-432.
- [4] PROENERGY-WSN, “Prototypes for Efficient Energy Self-sustainable Wireless Sensor Networks,” <http://www.e-projects.ubi.pt/proenergy-wsn>, Apr. 2013.
- [5] J. Tavares, N. Barroca, H. M. Saraiva, L. M. Borges, F. J. Velez, C. Loss, R. Salvado, P. Pinho, R. Gonçalves and N. B. Carvalho, “Spectrum Opportunities for Electromagnetic Energy Harvesting from 350 MHz to 3 GHz,” in *Proc. of The 7th International Symposium on Medical Information and Communication Technology (ISMICT 2013) - Special Session on Antennas and Propagation for Body Area Network*, Tokyo, Japan, Mar. 2013.
- [6] H. Yan, J. G. M. Montero, A. Akhnouk, L. C. N. de Vreede, and J. N. Burghart, “An integration scheme for RF power harvesting,” in *Proc. of The 8th Annual Workshop on Semiconductor Advances for Future Electronics and Sensors*, Veldhoven, Netherlands, Nov. 2005.
- [7] Advanced Design System software, <http://www.home.agilent.com/en/pc-1297113/advanced-design-system-ads?&cc=PT&lc=eng>, Jan. 2013.
- [8] U. Karthaus and M. Fischer, “Fully integrated passive UHF RFID transponder IC with 16.7 μ W minimum RF input power,” *IEEE J. Solid State Circuits*, vol. 38, no. 10, pp. 1602-1608, Oct. 2003.
- [9] P. Nintanavongsa, U. Muncuk, D. R. Lewis and K. R. Chowdhury, “Design Optimization and Implementation for RF Energy Harvesting Circuits,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, no. 1, pp. 24-33, Mar. 2012.
- [10] BQ25504, “Ultra Low Power Boost Converter with Battery Management for Energy Harvester Applications,” <http://www.ti.com/product/bq25504>, Apr. 2013.