An Overview of SWIPT Circuits and Systems

Ricardo TORRES[1,2], Diogo MATOS[1,2],
Felisberto PEREIRA[2,5], Ricardo CORREIA[2,3,4],
Nuno Borges CARVALHO[1,2]

(1. Department of Electronics, telecommunications and information, University of Aveiro, Aveiro 3810, Portugal;
2. Institute of Telecommunications, Aveiro 3800, Portugal;
3. CISeD-Research Center in Digital Services, Polytechnic of Viseu, Viseu 3500, Portugal;
4. Sinuta SA., Estarreja 3860, Portugal;
5. AlmaScience Colab, Madan Parque, Caparica 2829–516, Portugal)

DOI: 10.12142/ZTECOM.202202003

https://kns.cnki.net/kcms/detail/34.1294.TN.20220518.0925.002.html, published online May 19, 2022

Manuscript received: 2022-04-18

Abstract: From a circuit implementation perspective, this paper presents a brief overview of simultaneous wireless information and power transmission (SWIPT). By using zero-power batteryless wireless sensors, SWIPT mixes wireless power transmission with wireless communications to allow the truly practical implementation of the Internet of Things as well as many other applications. In this paper, technical backgrounds, problem formation, state-of-the-art solutions, circuit implementation examples, and system integrations of SWIPT are presented .

Keywords: simultaneous wireless information and power transmission (SWIPT) systems; backscatter communication; low power communication

Citation (IEEE Format): R. Torres, D. Matos, F. Pereira, et al., "An overview of SWIPT circuits and systems," *ZTE Communications*, vol. 20, no. 2, pp. 13 – 18, Jun. 2022. doi: 10.12142/ZTECOM.202202003.

1 Introduction

In addition to radio frequency (RF) waves' ability to transmit information, a viable energy source for powering low-power devices used in wireless sensor networks (WSN) or Internet of Things (IoT) applications should also be considered. The scientific community has explored this characteristic of radio waves, resulting in the proposal of a simultaneous wireless information and power transmission (SWIPT) system.

A careful design that incorporates wireless power transfer (WPT) capabilities should be considered to improve the devices' data storage or increase computing capabilities. This integration has facilitated the interest in the concept of passive wireless sensors, which may play an important role in an IoT scenario with sensors without batteries deployed everywhere sensing the environment. Nowadays, more IoT sensors bring the increase of batteries to be deployed, which will have a negative ambient impact. Battery-powered tags can improve communication distance but have limitations in battery cost and replacement. Thus, the alternatives to the battery systems are based on the energy harvester (EH) technology or other different sources (solar[1], motion or vibration[2], and ambient RF[3]). To overcome the problems from the EH and batteries, the concept of WPT has been explored to supply the tags with power.

In Ref. [4], a solution combining inductive WPT and ultra-high frequency (UHF) radio frequency identification (RFID) was presented, and by combining these two technologies it was possible to increase the tag sensitivity by 21 dB. However, with inductive WPT, the proximity of the tag to the power source is a huge obstacle to those systems, and to overcome the problem created by the short distance required in inductive wireless power transfer, electromagnetic wireless power transfer has emerged. It consists in using the power contained in RF waves and, through conditioning circuits such as RF to (direct current) DC converters, transforming this power into the current.

Regarding electromagnetic WPT, a comparison between different rectifier typologies and different stage levels was presented in Ref. [5]. The results show a high dependence between the received power and the most efficient topology. In Ref. [6], the authors presented a structure with a two-tone

This work is funded by FCT/MCTES through national funds and EU funds under the project UIDB/50008/2020-UIDP/50008/2020.

signal at 1.8 GHz and 2.4 GHz, which improved the voltage output by 20% higher on average than a single-tone input. The authors in Ref. [7] presented a reader which was configured to transmit power in continuous waves (CW). The tag used a storage capacitor that could charge up to 5.5 V after the rectification. After the storage capacitor was charged, it powered the tag that performed sensing and communication, reflecting the carrier wave. This process was proven at 1 m between the reader and the tag. The same principle was used in Ref. [8].

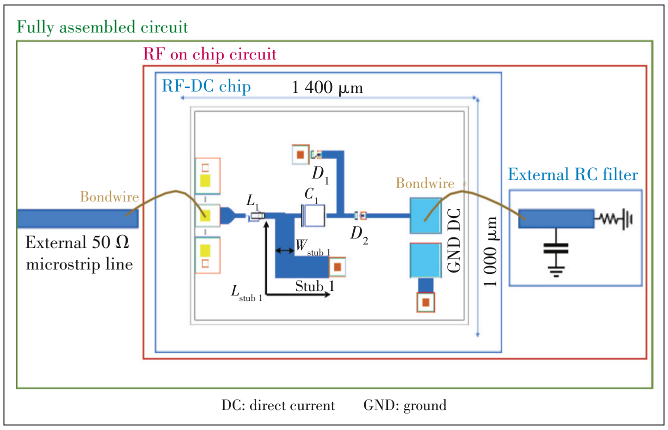
This paper describes the works presenting SWIPT systems or devices that are part of SWIPT systems, power conditioning circuits such as RF-DC converters, or backscatter communication circuits.

This paper is organized as follows. Section 2 presents some examples of work in the WPT area, Section 3 exposes backscatter communication systems, SWIPT systems are presented in Section 4, and the conclusions are drawn in Section 5.

2 Wireless Power Transfer Energy Harvesters

As mentioned previously, the increase of IoT devices raises the need for power and EH is a clean solution to that. Moreover, with new 5G bands (above 20 GHz), new opportunities emerge, due to the possibility of developing compact devices, using higher transmitted power, and using antenna arrays instead of single elements. Integrated circuits (IC) are also a solution to developing compact and quite cheap circuits, and Gallium Arsenide (GaAs) technology has evolved in recent years, making it a suitable technology for low-power systems.

In Ref. [9] the authors presented a hybrid solution combining an RF-DC converter chip, based on a 2-stage Dickson charge pump/voltage multiplier that was developed by resorting to a 100 μm GaAs technology foundry. In contrast to conventional circuits developed with IC technologies, the authors in Ref. [9] developed a DC low-pass filter externally to the chip, using a conventional microstrip substrate connected by bond wires, as shown in Fig. 1. The chip is composed of a matching network (values are shown in Fig. 1) that matches the input impedance to the diode's impedance. The external RC filter will allow tuning the circuit for different scenarios and frequencies. For example, when measuring the chip using a probe station, the RC network is not the same if the circuit is connected to an antenna, since the 50 Ω microstrip line and bond-wire would influence the chip response. This enables optimization of the circuit for different scenarios and different frequencies of operation. The substrate used is the Rogers RO4003C, with ϵ_r=3.48 and h=0.508 mm. With this circuit, for the case of on-chip measurement, 51 % efficiency is achieved for an input power of 15 dBm. In the fully assembled prototype, some de-



▲**Figure 1. RF-DC block diagram circuit for different scenarios, where L_1=0.12 nH, C_1=2.7 pF , $L_{stub\,1}$=372 μm, $W_{stub\,1}$=90 μm, W_{D1}=W_{D2}=10 (Nº of fingers), with the chip area of 1 400 μm×1 000 μm[9]**

viation is found, and the peak of efficiency appears at 23 GHz with efficiency of 54% and the input power of 13 dBm. Moreover, both circuits present promising results at other frequencies.

Using this approach, it is possible to power up a sensor even without the use of a battery pack, allowing the possibility of maximizing the service time of IoT sensors.

3 Wireless Information

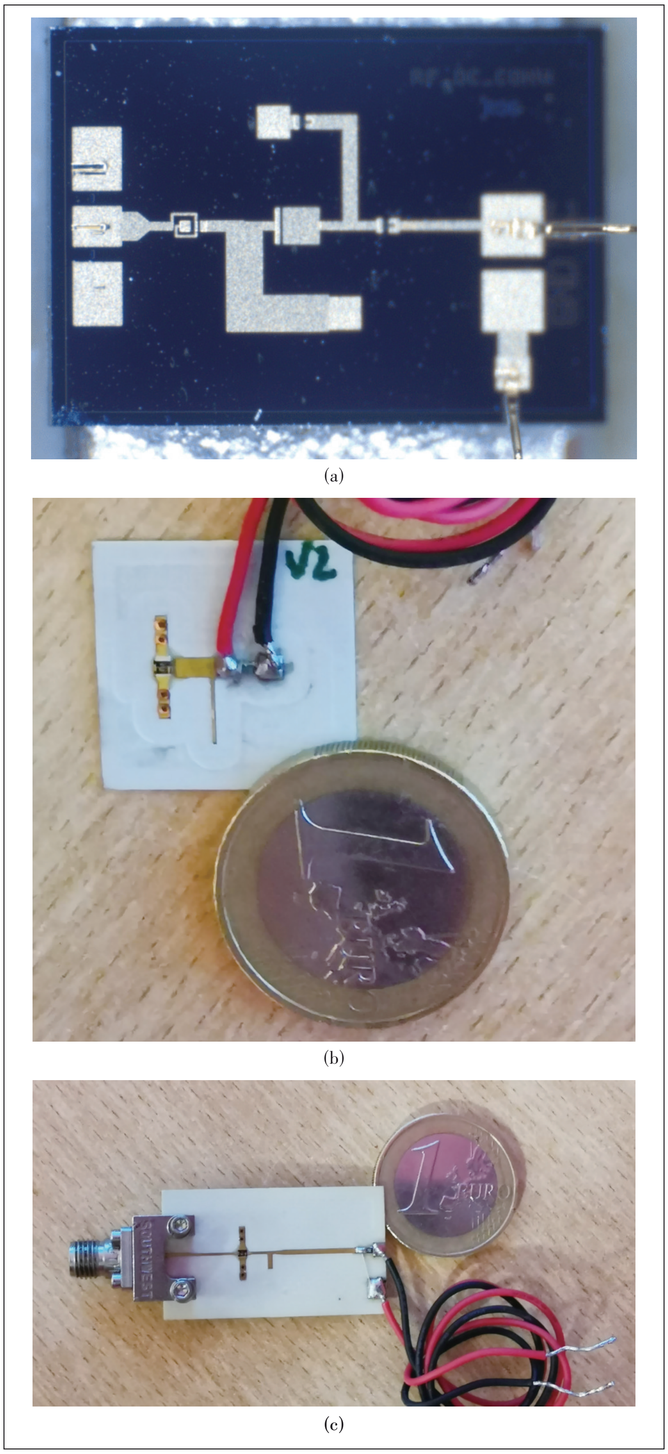
3.1 High Order Backscatter Communication

If the objective is to create an information layer on top of the power layer for the IoT sensors, the wireless communication layer should consume the minimum amount of energy possible. Traditional super-heterodyne approaches are not a viable solution in this scenario, since the energy cost is high for these approaches. One of the alternatives proposed by the authors in Ref. [10] is to use backscatter systems combined with WPT.

Backscatter systems are normally low bit-rate solutions, because they operate in amplitude shift keying, or binary phase shift keying modulation formats, creating different impedances at the antenna plane for the generation of such modulation schemes. Nevertheless, it is possible to combine some basic modulations to obtain better modulation formats for IoT applications, like the quadrature amplitude modulation (QAM) which combines the amplitude and phase modulation.

This technique uses the combination to change the antenna impedance, and each impedance will correspond to a symbol used to transmit the digital message. DASKALAKIS et al.[11] presented a low-power sensor tag. The tag could create up to 4 different antenna impedances, modulate data using four-pulse amplitude modulation (PAM) to increase the transmitted bit rate, and send it to a low-cost software-defined radio (SDR) reader. The tag requires no batteries and is supplied with an energy harvester, consuming only 27 μW.

In Ref. [12], the authors presented a novel modulator that



▲Figure 2. (a) Microscopic photograph of the chip, (b) on-chip scenario prototype, and (c) fully assembled circuit prototype[9]

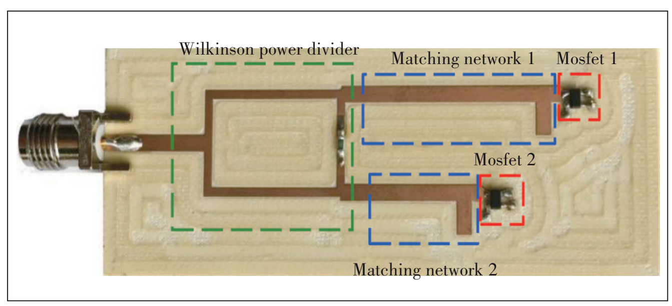
worked with a Wilkinson power divider with a phase shift and two transistors working as switches to generate M-QAM, as can be seen in Fig. 3. This modulation technique permits high-bandwidth and low-power wireless communications. The presented circuit has an energy consumption as low as 6.7 pJ/bit for a bit rate of 120 Mbit/s.

In Ref. [13], the authors implemented the same approach presented previously, but in this case, they used a 130 nm BiCMOS foundry technology. The objective was to achieve a low-power and high-speed M-QAM backscatter modulator for millimeter wave frequencies, as shown in Fig. 4. The authors showed that the modulator presented the lowest dynamic power consumption reported at the time, which was 6.96 μW, and could achieve 16, 32, and 64-QAM modulations in a range of 20 GHz to 28 GHz with a low value of error vector magnitude (EVM).

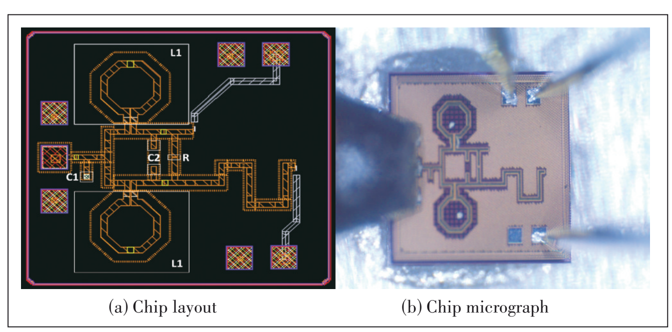
Moreover, backscatter could also be used with ambient electromagnetic waves, as in Ref. [14], which was based on the circuit of Ref. [13] and was possible to perform PAM modulation. In this case, the authors were interested in signal bands that are usually found on our daily basis, such as frequency modulation (FM)-100 MHz, industrial, scientific and medical (ISM)-400 MHz, digital video broadcasting-terrestrial (DVB-T)-700 MHz, or global system for mobile communications (GSM)-900 MHz. To demodulate the received signal, the authors have used a low-cost SDR that covers the bands of interest. The authors demonstrated that their system could demodulate signals in an extensive range of input power (−10 dBm to −60 dBm) and several data rate values (5 kbit/s to 50 kbit/s) in the mentioned frequencies.

3.2 All Digital Backscatter Communication

To minimize the costs of producing backscatter tags and increase the microcontroller unit (MCU) capability to receive and store data from the sensor networks, TORRES et



▲ **Figure 3. Photograph of the 16-quadrature amplitude modulation (QAM) backscatter circuit[12]**



▲ **Figure 4. BiCMOS high-order backscatter modulator, in which C_1= 385.117 fF, L_1 = 0.3 nH, C_2 = 30.012 fF, R = 100 Ω, with the chip area of 0.92 mm^2[13]**

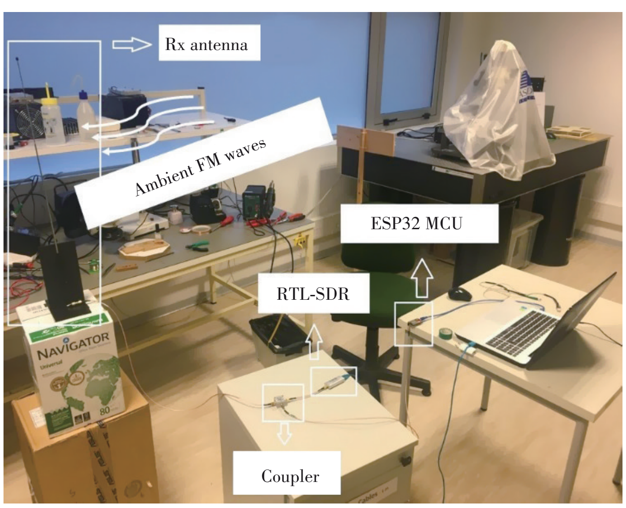
al.[15] showed a fully digital ambient backscatter system that operates with ambient FM sources, with a power of approximately −70 dBm. In this system, the backscatter module uses an ESP32 MCU and a telescopic monopole as an antenna. The variation of a digital I/O pin causes an impedance variation in the connected antenna reflecting the incoming FM waves with an amplitude shift keying (ASK) modulation and can be demodulated by a low-cost RTL-SDR USB dongle, as shown in Fig. 5.

The solution presented enables a large number of applications that can benefit from the different technologies used with the commercial modules tested, such as Wi-Fi, Bluetooth, and ambient backscatter communications.

In Ref. [16], the authors produced a digital backscatter tag connecting a dipole, the two red wires in Fig. 6, to a digital I/O pin of the PIC16 MCU, presenting a digital backscatter tag.

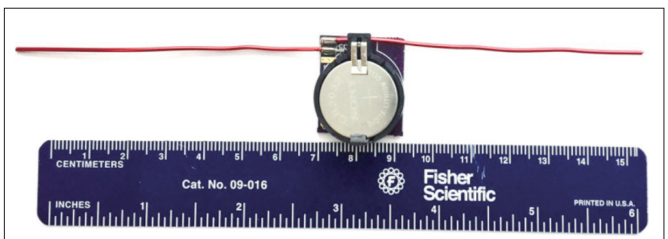
4 SWIPT System

The authors in Refs. [10] and [17], as shown in Fig. 7, presented a solution using dual-band wireless power and data transfer, a system with a backscatter modulator combined with WPT. In this solution, two frequencies were considered: one was used to power the tag and the other to perform the communication through backscatter. In this circuit, it is possible to find three main blocks. In the communications part, the red square in Fig. 7, the backscatter modulator will vary the impedance seen by the antenna, causing a reflection or absorption of the incident wave. The matching network is presented in green in Fig. 7, which is designed to provide backscatter load modulation at one frequency and continuous flow of WPT at other frequencies, and the five-stage Dickson multiplier provides sufficient DC power to supply the micro-controller. A similar approach, using different frequencies for energy and communication, was presented in Ref. [18], in which a different circuit for the RF-DC conversion was used for each frequency. The authors in Ref. [19] used two different frequencies for RF communication and WPT. They also used 5.8 GHz to power up a portion of radio connected to a battery with an RF-DC converter, and a wake-on radio (WOR) will only activate the battery for the primary transceiver. Nevertheless, the system is not passive and uses the WPT to activate the primary transceiver. Despite having passive tags for communication, it is of utmost importance to improve the data rate in the sensors in

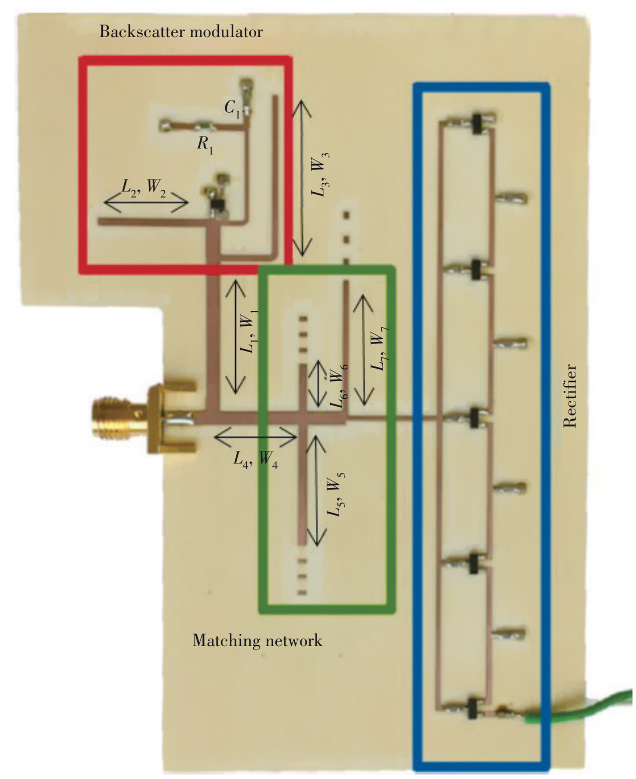


FM: frequency modulation
MCU: microcontroller unit
SDR: software defined radio
Rx: receiver

▲**Figure 5. Real ambient FM measurements setup**[15]



▲**Figure 6. Photo of digital backscatter prototype**[16]



▲ **Figure 7. Photograph of implemented system with backscatter modulator combined with wireless power transfer (WPT), element values of which are L_1 = 21.2 mm, W_1=1.87 mm, L_2=15.1 mm, W_2=1.0 mm, L_3=21.9 mm, W_3=0.8 mm, L_4=11.3 mm, W_4=1.87 mm, L_5=17.1 mm, W_5=1.2 mm, and L_6=6.7 mm**[17] order to reduce the power consumption and extend the read range.

5 Conclusions

In this paper, a brief review of SWIPT systems is presented, especially the combination of wireless power transmission and backscatter communications. The use of higher order modulation formats allows the implementation of such systems, reducing significantly the need for batteries in these sensors and paving the path for Internet of Everything in the future.

Acknowledgement:

Felisberto PEREIRA would like to thank to Lisboa 2020 Programme, Centro 2020 programme, Portugal 2020, European Union, through the European Social Fund who supported LISBOA-05-3559-FSE-000007 and CENTRO-04-3559-FSE-000094 operations as well as to Fundação para a Ciência e Tecnologia (FCT) and Agência Nacional de Inovação (ANI).

References

[1] SAMPLE A, SMITH J R. Experimental results with two wireless power transfer systems [J]. 2009 IEEE radio and wireless symposium, 2009: 16 – 18. DOI: 10.1109/RWS.2009.4957273

[2] ROUNDY S, WRIGHT P K, RABAEY J. A study of low level vibrations as a power source for wireless sensor nodes [J]. Computer Communications, 2003, 26(11): 1131 – 1144

[3] SAMPLE A, SMITH J R. Experimental results with two wireless power transfer systems [C]//IEEE Radio & Wireless Symposium. IEEE, 2009:16 – 18

[4] KRACEK J, ŠVANDA M, MAZANEK M, et al. Implantable semi-active UHF RFID tag with inductive wireless power transfer [J]. IEEE antennas and wireless propagation letters, 2016, 15: 1657 – 1660. DOI: 10.1109/LAWP.2016.2520663

[5] BORGES L M, CHÁVEZ-SANTIAGO R, BARROCA N, et al. Radio-frequency energy harvesting for wearable sensors [J]. Healthcare technology letters, 2015, 2(1): 22 – 27. DOI: 10.1049/htl.2014.0096

[6] KUHN V, SEGUIN F, LAHUEC C, et al. A multi-tone RF energy harvester in body sensor area network context [C]//Proceedings of 2013 Loughborough Antennas & Propagation Conference (LAPC). IEEE, 2013: 238 – 241. DOI: 10.1109/LAPC.2013.6711891

[7] YEAGER D J, HOLLEMAN J, PRASAD R, et al. NeuralWISP: A wirelessly powered neural interface with 1-m range [J]. IEEE transactions on biomedical circuits and systems, 2009, 3(6): 379 – 387. DOI: 10.1109/TBCAS.2009.2031628

[8] SAMPLE A P, YEAGER D J, POWLEDGE P S, et al. Design of an RFID-based battery-free programmable sensing platform [J]. IEEE transactions on instrumentation and measurement, 2008, 57(11): 2608 – 2615. DOI: 10.1109/tim.2008.925019

[9] MATOS D, CORREIA R, Carvalho N B. Millimeter-wave hybrid RF-DC converter based on a Gaas chip for IoT-WPT applications [J]. IEEE microwave and wireless components letters, 2021, 31(6): 787 – 790

[10] CORREIA R, BORGES CARVALHO N, KAWASAKI S. Continuously power delivering for passive backscatter wireless sensor networks [J]. IEEE transactions on microwave theory and techniques, 2016, 64(11): 3723 – 3731. DOI: 10.1109/TMTT.2016.2603985

[11] DASKALAKIS S N, CORREIA R, GOUSSETIS G. Four-PAM modulation of ambient FM backscattering for spectrally efficient low-power applications [J]. IEEE transactions on microwave theory and techniques, 2018, 66 (12): 5909 – 5921

[12] CORREIA R, CARVALHO N B. Ultrafast backscatter modulator with low-power consumption and wireless power transmission capabilities [J]. IEEE microwave and wireless components letters, 2017, 27(12): 1152 – 1154

[13] MATOS D, DA CRUZ JORDÃO M D, CORREIA R, et al. Millimeter-wave BiCMOS backscatter modulator for 5 G-IoT applications [J]. IEEE microwave and wireless components letters, 2021, 31(2): 173 – 176. DOI: 10.1109/LMWC.2020.3042709

[14] MATOS D, TORRES R, CORREIA R, et al. Ultra-wideband 4-PAM backscatter modulator based on BiCMOS technology for IoT/WPT applications [C]//Proceedings of 2021 IEEE Wireless Power Transfer Conference. IEEE, 2021: 1 – 4. DOI: 10.1109/WPTC51349.2021.9458113

[15] TORRES R, CORREIA R, CARVALHO N B. All digital ambient backscatter system [C]//Proceedings of 2020 IEEE Wireless Power Transfer Conference. IEEE, 2020: 327 – 330. DOI: 10.1109/WPTC48563.2020.9295547

[16] DADKHAH A, ROSENTHAL J, REYNOLDS M S. ZeroScatter: zero-added-component backscatter communication using existing digital I/O pins [C]//Proceedings of 2019 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet). IEEE, 2019: 1 – 3. DOI: 10.1109/WISNET.2019.8711796

[17] PEREIRA F, CORREIA R, CARVALHO N B. Passive sensors for long duration internet of things networks [J]. Sensors, 2017, 17(10). DOI: 10.3390/s17102268

[18] JANKOWSKI-MIHUŁOWICZ P, WĘGLARSKI M. A method for measuring the radiation pattern of UHF RFID transponders [J]. Metrology and measurement systems, 2016, 23(2): 163 – 172. DOI: 10.1515/mms-2016-0018

[19] LERDSITSOMBOON W, KENNETH O K. Technique for integration of a wireless switch in a 2.4 GHz single chip radio [J]. IEEE journal of solid-state circuits, 2011, 46(2): 368 – 377. DOI: 10.1109/JSSC.2010.2090089

Biographies

Ricardo TORRES (ricardo.torres@ua.pt) received the MS degree in electronics and telecommunications engineering in 2020 from University of Aveiro, Portugal, where he is currently working towards the PhD degree. He has been a researcher with Institute of Telecommunications, Portugal since 2019 and his main research interest include microwave electronic circuits, backscatter communication, and software-defined radio.

Diogo MATOS received the MS degree in electronics and telecommunications engineering in 2018 from the University of Aveiro, Portugal, where he is working toward the PhD degree. He was a hardware electrical design engineer in EVOLEO Technologies, Portugal. His current research interests include wireless power transfer, energy harvesting, wireless passive sensors for space applications, backscatter communications, and MMIC design. He is a member of the IEEE Microwave Theory and Techniques Society. He is also a reviewer of *IEEE Transactions on Microwave Theory and Techniques*.

Felisberto PEREIRA received the MS and PhD degrees in electrical engineering from University of Aveiro, Portugal, in 2017 and 2021, respectively. Currently he works as a senior researcher at Almascience, Portugal, a company focused on paper electronics. From 2017 to 2021 he was a researcher at Institute of Telecommunications, Portugal. His research interests include the areas of

sensors, energy harvesting and backscatter communications. PEREIRA published more than 15 scientific works, including five publications in peer-reviewed international journals. He also won three awards in international conferences regarding wireless power transfer and backscatter technologies.

Ricardo CORREIA received the MS degree in electronics and telecommunications engineering from the University of Aveiro, Portugal in 2009, and the PhD degree in electrical engineering at University of Aveiro, Portugal in 2019. He was an automation and electrical engineer and a researcher in embedded systems and signal processing. He is currently a researcher at Sinuta SA, Portugal, where he works on the transmission and reception system of electronically oriented signals for next generation satellite constellations. He is also a collaborator at the Institute of Telecommunications, University of Aveiro. His current research interests include wireless power transfer, energy harvesting, wireless passive sensors for space applications, and low power communications. Mr. CORREIA is a member of the IEEE Microwave Theory and Techniques Society. He is also a reviewer for the *IET Microwaves, Antennas and Propagation, Wireless Power Transfer Journal* and the *IEEE Transactions on Microwave Theory and Techniques*. He was a recipient of the 2016 URSI/ANACOM Prize awarded by the URSI Portuguese Section and Portuguese National Authority of Communications. He won the second prize in the PhD category of 2019 Fraunhofer Portugal challenge.

Nuno Borges CARVALHO received the doctoral degree in electronics and telecommunications engineering from the University of Aveiro, Portugal in 2000, respectively. He is currently a full professor and a senior research scientist with the Institute of Telecommunications, University of Aveiro and an IEEE Fellow. He coauthored Intermodulation in *Microwave and Wireless Circuits* (Artech House, 2003), *Microwave and Wireless Measurement Techniques* (Cambridge University Press, 2013), *White Space Communication Technologies* (Cambridge University Press, 2014), and *Wireless Power Transmission for Sustainable Electronics* (Wiley, 2020). He has been a reviewer and author of over 200 papers in magazines and conferences. He is the editor in chief of the *Cambridge Wireless Power Transfer Journal*, an associate editor of the *IEEE Microwave Magazine* and former associate editor of the *IEEE Transactions on Microwave Theory and Techniques* and *IET Microwaves Antennas and Propagation Journal*. He is the co-inventor of six patents. His main research interests include software-defined radio front-ends, wireless power transmission, nonlinear distortion analysis in microwave/wireless circuits and systems, and measurement of nonlinear phenomena. He has recently been involved in the design of dedicated radios and systems for newly emerging wireless technologies. Dr. CARVALHO is a member of the IEEE MTT ADCOM, the past-chair of the IEEE Portuguese Section, MTT-20 and MTT-11 and the member ofthe technical committees, MTT-24 and MTT-26. He is also the Chair of the URSI Commission A (Metrology Group). He was the recipient of the 1995 University of Aveiro and the Portuguese Engineering Association Prize for the best 1995 student at the University of Aveiro, the 1998 Student Paper Competition (Third Place) of the IEEE Microwave Theory and Techniques Society (IEEE MTTS) International Microwave Symposium (IMS), and the 2000 IEEE Measurement Prize. He is a distinguished lecturer for the RFID-council and was a distinguished microwave lecturer for the IEEE Microwave Theory and Techniques Society. In 2022 he is the IEEE-MTT President-Elect.