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Evolution of Simultaneous Wireless Information and Power Transfer (SWIPT) for the IoT World

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Introduction

In these past few years, many interesting approaches have been studied and designed to advance the practical implementation of the concepts of wireless information and power transfer (WIPT) [1] and simultaneous wireless information and power transfer (SWIPT) [2], [3] in the contexts of everyday life, academic research, and industry.

The ever-growing array of internet of things (IoT) technologies presents a tangible answer to the need for modern densely populated networks of wirelessly connected devices. In this context, node maintenance is a challenging task given both the enormous size of these networks and the location of the devices, which can be spread over difficult-to-reach areas.

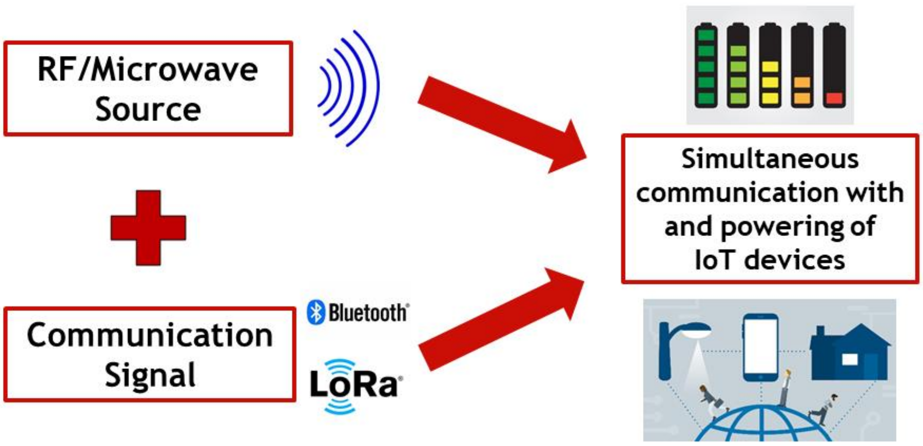


Fig. 1. Envisioned scenario for SWIPT applications: the combination of RF energy sources and communication signals allows the implementation of networks composed of battery-less IoT devices.

In particular, the paradigm of SWIPT [4] is currently being investigated in a wide range of different systems for industrial applications combined with emerging technologies typical of the industrial internet of things (IIoT), namely wireless sensor networks (WSN) that enable unlimited and uninterrupted connectivity in generic industrial environments. The main goal is to continuously monitor key components of the equipment with smart sensors that are able to track, in almost real-time rotation, position, speed, temperature, acceleration, and all the other vital parameters of the devices that have to be monitored [5].

One of the more urgent features desired in the wireless sensor nodes is the ability to autonomously operate through energy harvesting (EH) techniques rather than to be plugged-in with obstructive cables, or to depend on batteries which have a limited lifetime. Moreover, batteries are less reliable at high temperatures and might require multiple replacements over the node's lifespan, thus dramatically increasing the maintenance cost. Several implementations of sensors of this kind have been presented in the literature (e.g., relying on light [6], [7], wind [7], kinetic [8], thermoelectric [9], or piezoelectric [10] energy harvesting). But they all are limited by the frequent unavailability of the corresponding energy source. On the other hand, electromagnetic (EM) energy is always available in humanized environments, and plenty of solutions for its exploitation are present in the literature [11]–[14]. In this case, the limit consists of the low level of energy to be harvested [15].

In Fig. 1, an envisioned scenario for a typical SWIPT application is represented: the basic element is the simultaneous presence of RF/microwave power sources and communication signals, which could also coincide in some cases, allowing both the interconnection of IoT devices and their energetic support without the need for cables or batteries.

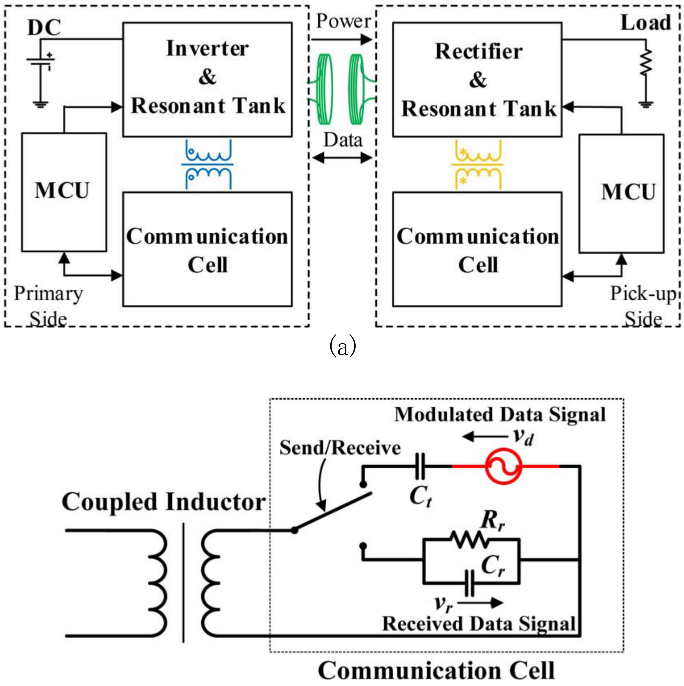
The development of wireless power transfer (WPT) solutions that exploit intentional sources [16], and the reduction of node-power-consumption enabled unconstrained sensor powering with a reliable and well-controlled energy source, have the two-fold advantage of achieving the archetype of "green power" by getting rid of batteries, and reducing the need for maintenance of the hardware devices [17]–[20]. For the latter, predictive maintenance is becoming increasingly important, because of the need for continuous monitoring of the equipment's most critical parts in order to prevent damage in a timely manner [21].

Great emphasis has been laid on solutions that exploit radiofrequency (RF) waves to power sensor nodes which monitor key objects, with the additional intention to significantly reduce the use of cables in the nearby area. For this purpose, near-field inductive solutions have been adopted [22], [23], as well as prototypes exploiting far-field radiative WPT [24]. Having said that, one of the obstacles concerns the fact that these sensors are most frequently placed inside or in the vicinity of metallic environments where the antenna (and the sensing circuitry) can come in close contact with metal tools. Indeed, the application scenario needs to be well characterized from the EM point of view, because of possible multiple reflections, detuning, fading, and shadowing effects that can occur; as an example, the challenge of RFID tags over metallic plates is described and dealt with in [25].

This article reviews some recent promising solutions in both near- and far-field applications, where SWIPT becomes a reality thanks to challenging design choices.

Reactive SWIPT for Power Electronics in Industry 4.0

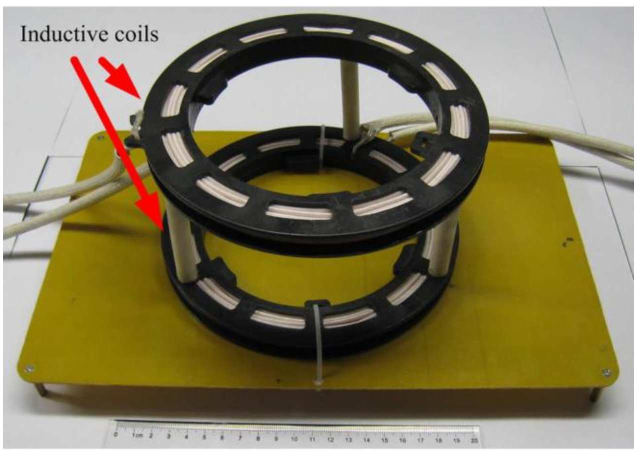
The first solutions for wireless power and data delivery that are covered in this work exploit the near (or reactive) EM field which is provided by nearby sources in the low (LF: 30–300 kHz) [26] or high (HF: 3–30 MHz) [27] frequency range, to realize so-called near-field SWIPT (NF-SWIPT). This particular case does not imply EM wave propagation, but it is just a matter of EM reactive coupling with coils (involving magnetic fields) or electrodes (involving electric fields) acting as transmitters and receivers. In most cases, the power level of these systems goes from a few W to kW, for power transmission, but still involving low powers (μW or mW) for communication purposes.



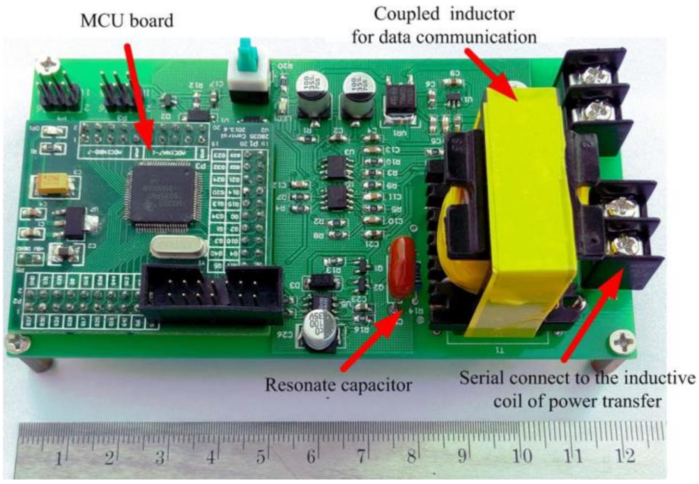
(b)

Fig. 2. Block schematic of (a) a system for near-field wireless power and data transfer, and (b) a typical structure of the communication cell [28].

A typical example for explaining the overall working principles and the architecture of a NF-SWIPT system is represented in Fig. 2(a) [28]: this work proposes a system consisting of a single inductive link enabling wireless power and data transmission with multiple carriers. This method can be applied for high-power WPT operating in the kHz range, and the selected data-carrier frequency is at least one order of magnitude higher than the power frequency; in this way, a frequency division multiplexing technique can be applied, transmitting power and data by employing different carrier frequencies and controlling them independently.



(a)



(b)

Fig. 3. Picture of (a) the inductive coils and (b) the communication board presented in [28].

One can say that the integration between bidirectional data communication and a high-power WPT system is proposed here: in fact, the power and data transfer share the same inductive link between coreless coils (Fig. 3(a)). The communication cells schematized in Fig. 2(b) and represented in Fig. 3(b) feature transmitter and receiver operation modes: for the first, a signal amplifier is used as a source to transmit data, whereas for the second, the rectifier and its matching network are designed to receive from the transmitter side the data carrier which is demodulated and read by a microcontroller unit (MCU).

A similar solution is presented in [29], where the same pair of inductive coils is adopted both for NF-WPT and for communication purposes. The main problem is, also in this case, to transmit simultaneously data with low-power protocols and a strong energy signal. It has been demonstrated by means of simulations and measurements of the overall system, that a robust data transmission system achieving a large signal-to-noise ratio (SNR) is possible even in the presence of a simultaneous power transfer of several kW.

The approach followed in [29] previews the communication carrier at the frequency of 8 kHz, which is lower than the energy transfer (150 kHz, with power transmission of 3 kW). With this method, the harmonics generated by the electronic power supply switching circuit will be outside of the communication band. The measurements revealed an SNR of 51.1 dB without power transfer and 39.7 dB with simultaneous energy transmission of 3 kW adopting a binary phase-shift keying (BPSK) modulated signal with a data rate of 1 kbps; this means that communication is very tolerant of interference that can be created by the simultaneous presence of energy transfer in the near-field.

In [30], a typical structure for a multiple input-multiple output (MIMO) system for SWIPT at 13.56 MHz is presented, using signal transmission based on magnetic inductances for supporting one data and multiple parallel power flows, as depicted in Fig. 4. One of the possible applications of this approach is an NFC-based access point. The overall system has been optimized to guarantee a sufficient quality-of-service (QoS) level (SNR greater than or equal to 10 dB for the data stream in this case), as well as maximum overall power received at the three reception coils.

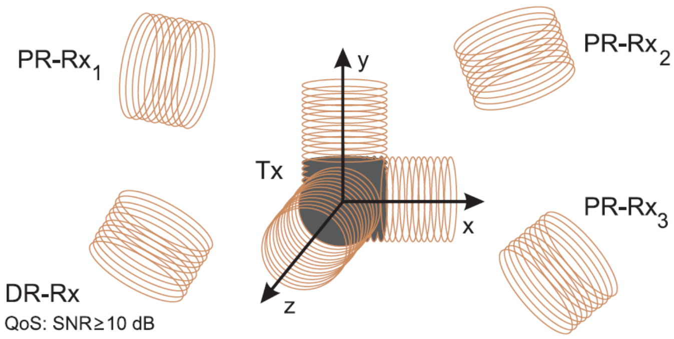
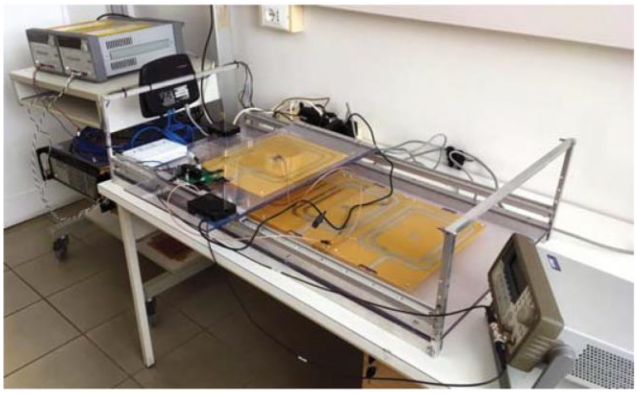


Fig. 4. Example of an NF-SWIPT system making use of a tri-dimensional inductive coil for transmission (Tx), three single-coils for power reception (PR-Rx1, PR-Rx2, PR-Rx3), and a single coil for data reception (DR-Rx) [30].

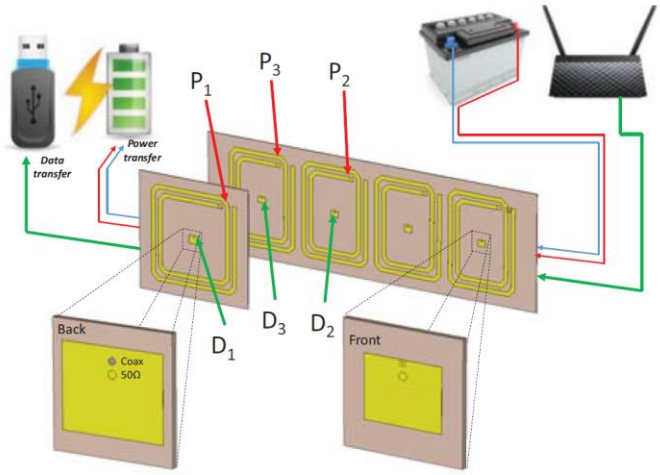
The theme of simultaneous near-field WPT and communication data transfer for industrial applications (e.g., in the automotive and railway sectors) is also developed in [31]; here, a series connection of sliding resonant coils at 100 kHz has been designed and employed to maintain constant coupling along the entire track, therefore guaranteeing constant link and power-rectifying performances. This was done using a couple of transmitting coils and a geometrically optimized receiver. A photograph and the general representation of the entire system are reported in Fig. 5(a) and 5(b), respectively.

The goal of [31] was to develop a system that is able to simultaneously transfer power and data, independent of its position and of the misalignment of the facing coils, thanks to a constant coupling factor. A simultaneous implementation of a multiple-input single-output (MISO) communication link was realized in the microwave range through co-localized patch antennas operating in the mid-field region.

In particular, the system is composed of a single (bigger) receiving coil separated at a distance of 6 cm from four (smaller) transmitting coils. In Fig. 5(b), the power (P1, P2, P3) and data transfer ports (D1, D2, D3) are highlighted in red and green respectively. It is also possible to see in the picture the patch antennas that are incorporated inside the coils.



(a)



(b)

Fig. 5. (a) Photograph of the structure composed of inductive sliding coils and (b) schematical representation of the overall NF-SWIPT system [31].

For the information exchange, these patch antennas are placed at the center of each coil in order to enable Wi-Fi transmission at 5.24 GHz.

At this point, it is worth saying that in industrial scenarios that are typically harsh from the EM point of view, the communication link is very often deteriorated by electromagnetic interference (EMI); for example, if the system is located inside an environment full of metal parts. Putting a patch antenna at 5.24 GHz in each transmitting coil provides enough margin to overcome EMI with a power signal that is very robust. Validation measurements demonstrated that it is feasible to transfer 100 W of power to the load with the inductive NF-SWIPT coils, as well as to maintain a stable Wi-Fi connection at 100 Mbps with an attenuation of the signal that is low enough to provide integrity in very noisy industrial scenarios.

Finally, an interesting opportunity for practical implementation of NF-SWIPT in automatic machinery has been investigated and realized in [32]; moving to higher frequencies (i.e., 868 MHz in the ultra-high frequency (UHF) band), which is an uncommon choice for near-field designs. The system exploits a self-resonant capacitive near-field link for data communication combined with a compact standard inductive WPT system operating at 50 kHz. The design of the UHF link is motivated by the increase in the channel transfer efficiency obtained by exploiting two facing auto-resonant structures, split-ring resonators (SRRs), one at each end of the link, as shown in Fig. 6(a). The involved distance (*d*) is of a few (or a fraction of) millimeters, as in many industrial applications: in this case, free rotation of the SRRs is considered. Fig. 6(b) shows a view of one element of the SWIPT system, along with the co-location of the inductive windings for the power transfer. To conclude, this research proves that a reactive link at UHF can be successfully exploited in the near-field range for remote passive sensing purposes instead of employing conventional low-frequency RFID bands.

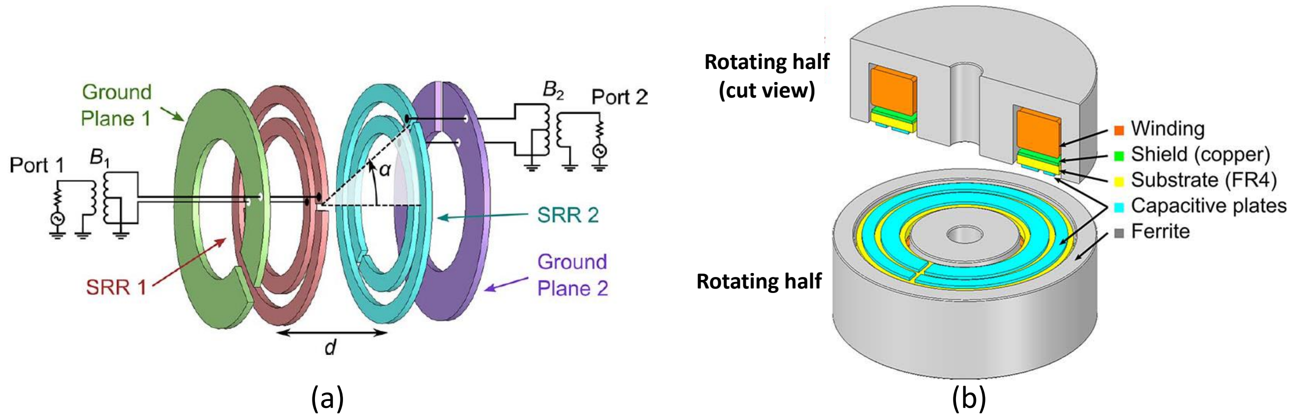


Fig. 6. (a) Representation of the entire stack-up of the SRR communication link. The distance d represents the clearance between two SRRs, and the angle α is the relative angular position of the outer strips' slot positions. (b) 3D view of the transmitting/receiving SWIPT element [32].

Far-Field SWIPT for Low-Power Wireless Sensor Networks in the IoT World

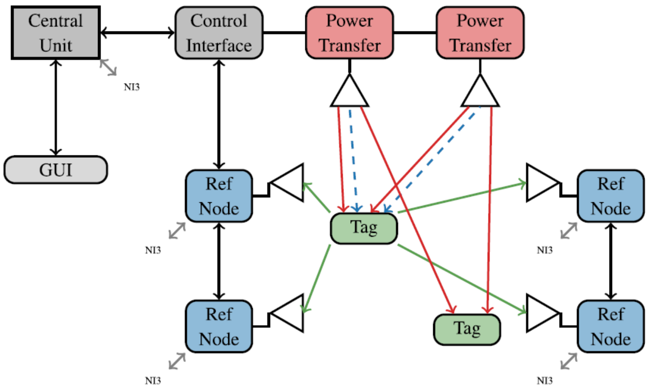
Nowadays, the exploitation of RF sources placed further from the receivers is the most common way to achieve far-field simultaneous wireless information and power transfer (FF-SWIPT). In this case, the involved frequencies are in the microwave (300 MHz – 30 GHz) [33] or millimeter wave (30 GHz – 300 GHz) [34] range.

One of the most common solutions adopted to achieve FF-SWIPT is to employ ultra-wide band (UWB) signals for communication or localization functions, at the same time allowing RF energy harvesting within the UHF band (300 MHz – 3 GHz) [35], [36].

An indoor positioning system (IPS) is a developing technology of the past few years, and several different methods have been adopted for its actuation. The use of UWB (typically backscattered) signals [37], [38] is advantageous because the exploitation of a very large range of frequencies avoids possible effects of fading and shadowing that can occur in indoor environments at certain frequencies. However, these procedures need a certain number of anchors inside the room under evaluation to become effective.

As an example, Figs. 7(a) and 7(b) represent the schematic diagram of the overall system and of the RFID passive tag for high-accuracy indoor localization presented in [36]. In this work, an UWB indoor positioning system enhanced with EH capabilities at 868 MHz has been realized, aiming at localization and tracking of floating objects inside space stations.

The batteryless tags schematically represented in Fig. 7(a) are powered by a power transfer unit (called an "energy shower"), which is basically an RF single tone transmitter in the upper UHF band with the function of feeding all the nearby tags. Moreover, these tags include a pulse generator in the 3-5 GHz UWB band that needs energy to make the localization possible. Validation measurements that have been carried out on the European Space Agency (ESA) Mars Rover showed a very satisfactory accuracy of about 1 cm with energization distances larger than 10 meter.



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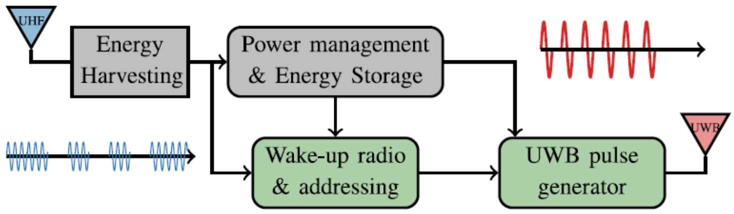

(b)

Fig. 7. (a) Schematic of a UWB/UHF system and (b) block diagram of the corresponding battery-less tag equipped with UWB pulse generator for passive localization in space environments [36].

Another very interesting SWIPT for space applications is introduced in [39], with higher WPT operating frequencies; the schematic of the wireless sensor system fed by a microwave power transfer (MPT) unit at 5.8 GHz for "Space-by-Wireless" purposes is described in Fig. 8.

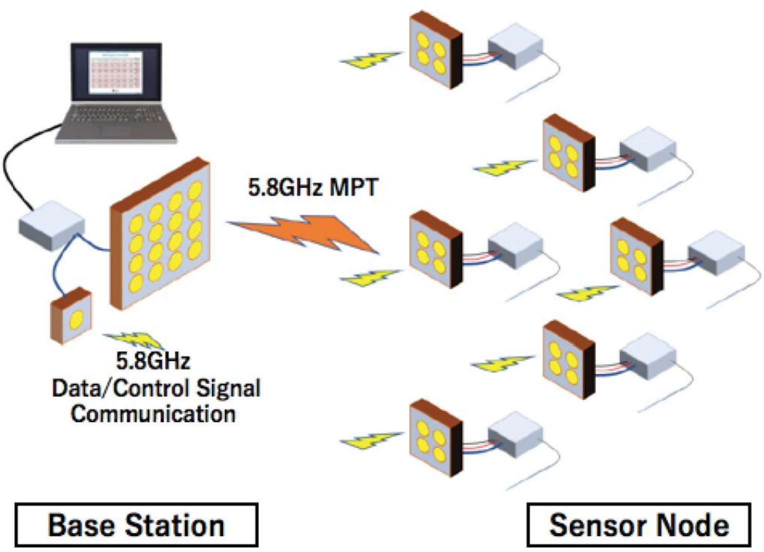

Fig. 8. Envisioned scenario for SWIPT at 5.8 GHz in a wireless sensor system for spacecraft health monitoring [39].

The wireless sensor node unit is primarily composed of an active integrated antenna (AIA) and a hybrid semiconductor integrated circuit (HySIC), combined with an energy harvester equipped with a selector which allows for a wide range of RF input powers and automatically switches the rectifiers to maximize the RF-to-DC power conversion efficiency (PCE) at the nodes. Six of the nodes are used for validation measurements and are equipped with thermocouples in order to send the temperature to the base station every second.

Moreover, the base station also acts as an MPT source working at the same frequency adopted for the transmission of communication beacons with an approach based on time division operations, as explained in Fig. 9.

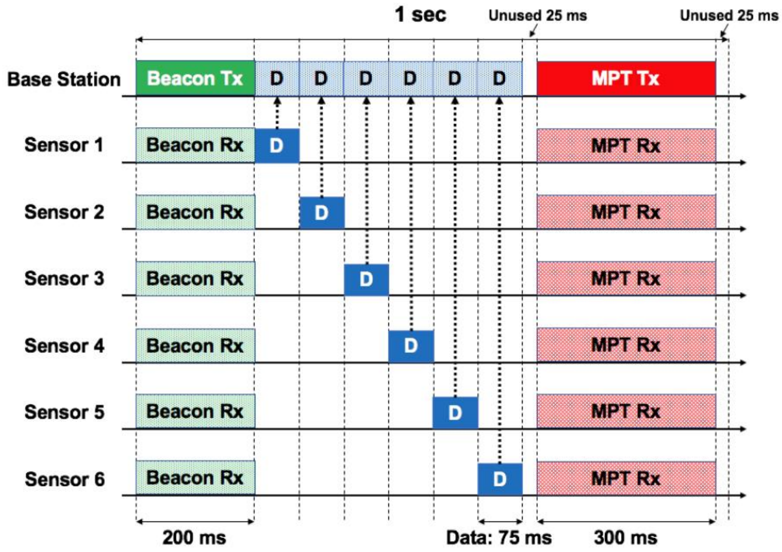

Fig. 9. Envisioned scenario for SWIPT at 5.8 GHz in a wireless sensor system for spacecraft health monitoring [39].

In [40], a WSN architecture for structural health monitoring (SHM) in harsh environments has been realized. It consists of a meshed grid architecture composed of wirelessly powered and battery-free sensing and communicating nodes. The sensing nodes are used to sense the physical world; they are battery-free and wirelessly powered by a dedicated radiofrequency source via a far-field wireless power transmission system. The data collected by the sensing nodes are sent to the communicating nodes that interface the physical world with the digital world through the Internet.

The prototype of the sensing node (Fig. 10) using long range wide area network (LoRaWAN) uplink wireless communication has been assembled with temperature and relative humidity sensors, and experiments have been performed to specifically characterize it.

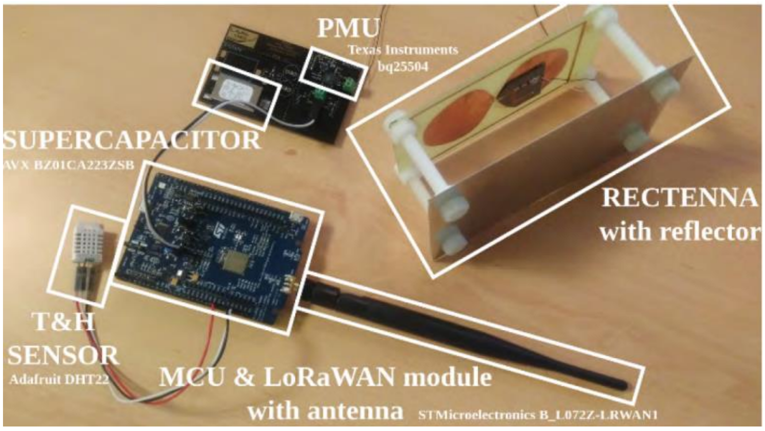

Fig. 10. Picture of the components of the sensing node prototype realized in [40].

A further step forward is provided in [41] - [43], where original circuits are realized for WPT enhanced with backscatter demodulation of amplitude-shift keying (ASK) and quadrature amplitude modulation (16-QAM) signals.

The first prototype presented in [41] is composed of the RF power harvester employing a receiving antenna, an impedance matching network, a power management unit (PMU), and the sensor to be powered; as well as the backscatter modulator which has its receiving antenna, an impedance matching network, and a switch to control the reflection coefficient.

From the energy harvester point of view, the aim is to store RF energy at 1.8 GHz and to transfer data at 2.45 GHz with passive backscattering techniques. A dual-band matching network is employed to match the two different impedances in order to achieve better efficiency at the frequencies of 1.8 GHz for WPT and 2.45 GHz for the implementation of the backscattering approach.

On the other side, a pseudomorphic high electron mobility transistor (pHEMT, Avago ATF-54143, acting as a switch) modulates the impedance of the antenna of the circuit for backscatter modulation, causing a change in the amount of energy reflected by the antenna itself.

Finally, an integration of backscattering and energy harvesting circuits is achieved (Fig. 11), with the final goal of obtaining, for different states of the transistor (0 and 0.6 V at the gate) and for the two different frequencies, modulation combined with WPT. This work showed that it is possible to supply a wireless sensor together with backscatter communication that is continuously powered during the operation mode.

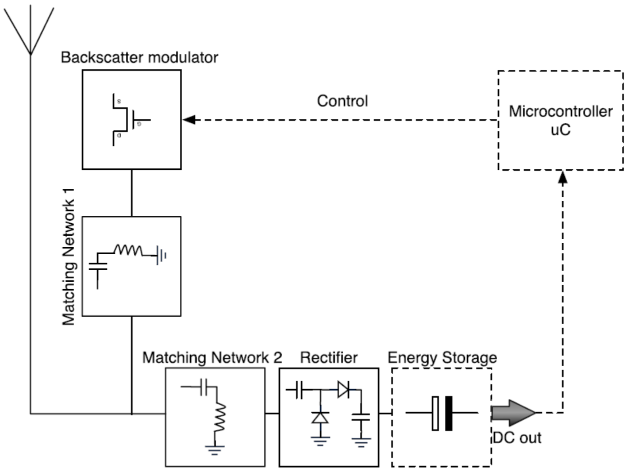

Fig. 11. Block diagram of the system proposed for RF energy harvesting and backscattering [41].

Subsequently, the same approach has been followed for including higher order modulation schemes, such as (4-QAM) [42]. However, the dimensions of the circuit are in this case too large and with the extension to higher order modulation, such as sixteen-state quadrature amplitude modulation (16-QAM), should be even larger. For this reason, a new implementation has been evaluated in [43] for 16-QAM modulation.

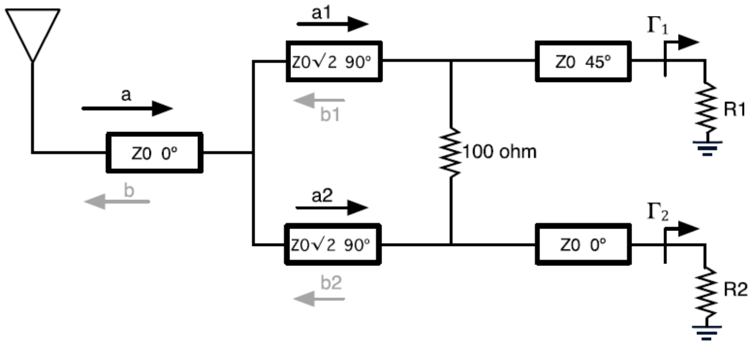

Fig. 12. Schematic implementation of 16-QAM demodulation [43].

As schematically represented in Fig. 12, this novel model employs a Wilkinson power divider, and each branch is terminated with a line and an ideal impedance. The lines present a 45° phase shift with respect to each other, to allow the reflected wave from each branch to be 90° shifted from its counterpart.

This solution allows a higher bit rate with a limited amount of RF power via the adoption of a modulation technique that enables a high-bandwidth wireless communication with very low power. This solution can be combined with WPT for ultralow-power wireless applications that require high bandwidth communication, such as the UWB indoor localization systems described above.

One method to achieve SWIPT from Gaussian frequency-shift keying (GFSK) modulated signals (i.e., the modulation adopted by Bluetooth low energy (BLE)) is explored in [44]. In this case, the circuit of the node, composed of a matching network and a voltage-doubler rectifier, was designed and realized to harvest energy from continuous wave (CW) sources, multitone signals (3-, 4-, and 5-tones), and frequency-modulated signals, such as FSK or GFSK.

However, at the same time, it is possible to exploit the same topology with the aim of achieving an FM-to-AM conversion, in order to recognize the stream of bits that is sent from a BLE transmitter, as depicted in Fig. 13. Attention must be paid to the correct choice of cut-off frequency at the output of the rectifier, which has to be set taking into account the bandwidth of the signal, its data-rate, and the deviation of the selected FSK modulation.

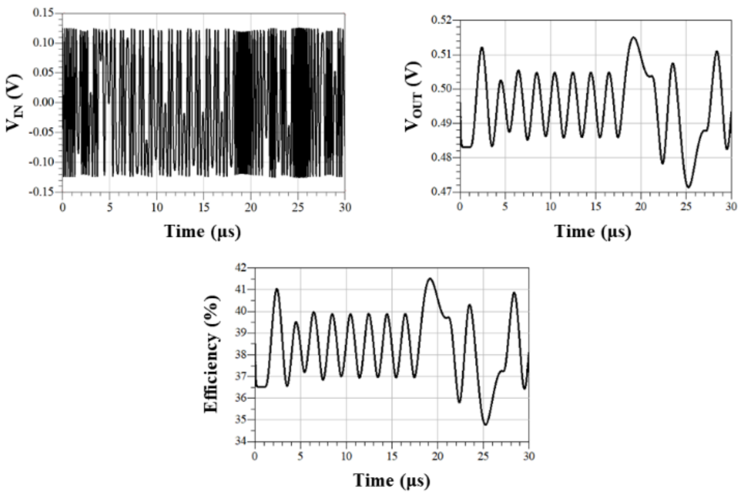

Fig. 13. Input voltage, output voltage, and efficiency for the presented rectifier, with the bandwidth of the output filter set at 2 MHz [44].

A further step to reach actual SWIPT with the same circuit can be achieved by adopting the same approach as in [38]. In particular, at the output of the voltage doubler acting as a rectifier (D1 and D2) with its matching network (MN), an additional inductor (L_1) can play the role of a diplexer: it can guide the DC current to the load (R_{L1}) for energy harvesting purposes and, at the same time, realize a path for the demodulation (FM-to-AM conversion) of the input signal's bits managed by an analog-to-digital converter (ADC, represented by the load R_{L2}), as shown in Fig. 14.

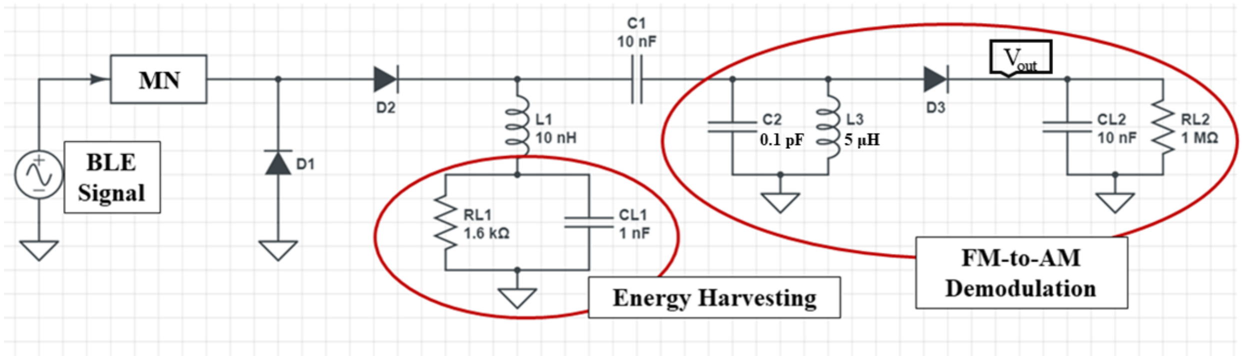

Fig. 14. Schematic of SWIPT (energy harvesting plus demodulation of FSK modulated signals) achieved within the same circuit for BLE inputs.

The results obtained for this layout are reported in Figs. 15. For these circuit simulations performed with Keysight ADS, a BLE signal with a frequency carrier at 2.426 GHz has been considered, with a bit rate of 1 Mbps (Fig. 15 (a)) and 125 kbps (Fig. 15 (b)). From these figures, it is possible to retrieve the input sequence of zeros immediately followed by ones at the output of the demodulation part of the circuit (V_{out}). For the energy harvesting path, for an input power of 0 dBm, an average RF-to-DC PCE of 47% is guaranteed.

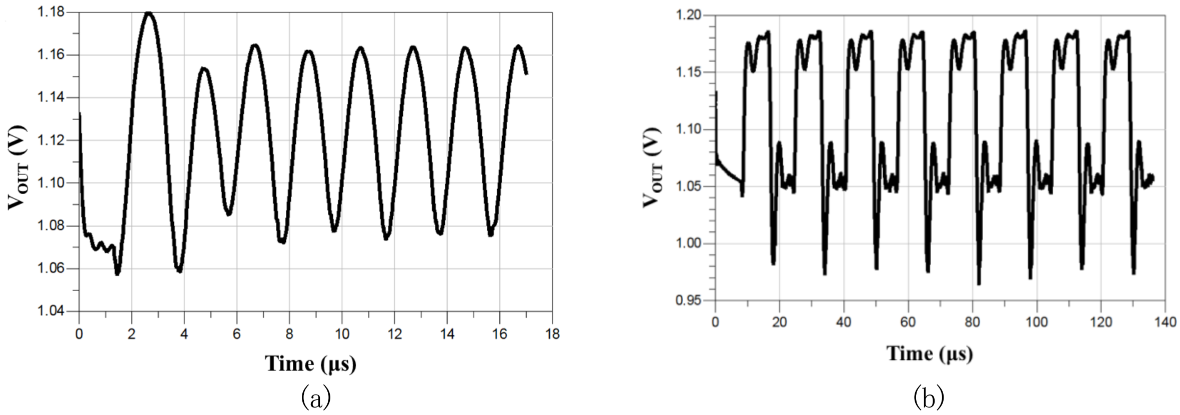

Fig. 15. Output voltage V_{OUT} at the demodulator path for BLE at (a) 1 Mbps and (b) 125 kbps.

Another important aspect to be considered for SWIPT is the optimization of modulated signals for achieving both higher PCEs and, at the same time, correct data transfer without loss of information. The main objective is to design and employ waveforms that increase the DC output power for EH, while enhancing the information rate, which is also the maximization problem of the rate-power (RP) region, by reaching a trade-off between data rate and delivered power [45].

In that sense, in [46] two novel FSK modulation schemes are presented: the first one makes use of waveforms suitable for improving WPT conversion efficiency by optimizing the peak-to-average power ratio (PAPR), in particular by adopting uniform multitone FSK signals.

On the other hand, the proposed non-uniform multitone FSK modulation technique employs multitone signals, but with different frequency spacings between the tones within one symbol with the aim of increasing the amount of information per symbol, thus improving spectral efficiency and wireless information transmission (WIT) performance.

Moreover, here the signal can be decoded thanks to the nonlinear characteristics of the diode(s) that are present in the EH part. Then, it is possible to decode the information by means of the same rectifying circuit without the need for a power-consuming local oscillator (LO).

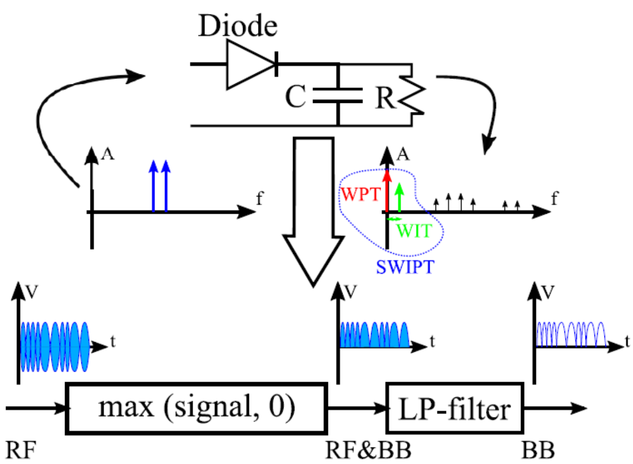

Fig. 16. Schematic and system model for a single-wave rectifying circuit, showing the coexistence at the output of DC (from WPT) and baseband (BB, for wireless information transfer, WIT) signals [46].

Conclusion

This article reviews of recent techniques and possible solutions for simultaneous wireless communication and powering of IoT devices, in both reactive and radiative conditions. Many solutions have been implemented through near-field approaches for feeding power electronics applications (automotive, packaging, railway services) combined with communication protocols optimized for sensing vital parameters of the devices under test. Much larger is the research literature with respect to far-field applications, that need radiative elements (antennas, or rectennas) to operate. Moreover, a new approach to SWIPT of GFSK modulated signals (e.g., BLE) is proposed, with the aim of exploiting the same circuit for WPT and data communication; the final goal is to create a wireless sensor node that can be fully autonomous from the energy point of view, with all the ensuing consequences (i.e., removal of batteries and limited (or nearly removed) maintenance time with economical effort).

However, near-field prototypes are more mature from a technological and industrial perspective; conversely, radiative solutions in far-field are still developing and need further validation before entering the market, as well as regulatory evaluation.

These interesting topics and challenges should provide a boost for future research studies and practical applications in industry 4.0 and in general in the IoT world, with the aim of developing an adequate response for the always increasing demand of wirelessly connected devices, preferably without the need for energy from batteries.

Acknowledgement

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References

[1] B. Clerckx, R. Zhang, R. Schober, D. W. K. Ng, D. I. Kim, and H. V. Poor, "Fundamentals of Wireless Information and Power Transfer: From RF Energy Harvester Models to Signal and System Designs," IEEE Journal on Selected Areas in Communications, vol. 37, no. 1, pp. 4-33, Jan. 2019. doi: 10.1109/JSAC.2018.2872615.

[2] B. Clerckx, A. Costanzo, A. Georgiadis, and N. Borges Carvalho, "Toward 1G Mobile Power Networks: RF, Signal, and System Designs to Make Smart Objects Autonomous," IEEE Microwave Magazine, vol. 19, no. 6, pp. 69-82, Sept.-Oct. 2018. doi: 10.1109/JSAC.2018.2872615.

[3] L. Ji, L. Wang, C. Liao, and S. Li, "Simultaneous Wireless Power and Bidirectional Information Transmission With a Single-Coil, Dual-Resonant Structure," IEEE Transactions on Industrial Electronics, vol. 66, no. 5, pp. 4013-4022, May 2019. doi: 10.1109/TIE.2018.2831196.

[4] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless Networks With RF Energy Harvesting: A Contemporary Survey," IEEE Communications Surveys & Tutorials, vol. 17, no. 2, pp. 757-789, Second quarter 2015. doi: 10.1109/COMST.2014.2368999.

[5] G. Paolini, M. Guermandi, D. Masotti, M. Shanawani, F. Benassi, L. Benini, and A.

Costanzo, “RF-Powered Low-Energy Sensor Nodes for Predictive Maintenance in Electromagnetically Harsh Industrial Environments,” Sensors, vol. 21, no. 2, pp. 386-403, Jan. 2021. doi: 10.3390/s21020386.
[6] X. Yue, M. Kauer, M. Bellanger, O. Beard, M. Brownlow, D. Gibson, C. Clark, C. MacGregor, and S. Song, ″Development of an Indoor Photovoltaic Energy Harvesting Module for Autonomous Sensors in Building Air Quality Applications,″ IEEE Internet of Things Journal, vol. 4, no. 6, pp. 2092-2103, Dec. 2017. doi: 10.1109/JIOT.2017.2754981.
[7] M. Magno, D. Boyle, D. Brunelli, B. O’Flynn, E. Popovici, and L. Benini, ″Extended Wireless Monitoring Through Intelligent Hybrid Energy Supply,″ IEEE Transactions on Industrial Electronics, vol. 61, no. 4, pp. 1871-1881, Apr. 2014. doi: 10.1109/TIE.2013.2267694.
[8] M. Magno, D. Kneubühler, P. Mayer, and L. Benini, ″Micro Kinetic Energy Harvesting for Autonomous Wearable Devices,″ Proc. 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, Italy, 2018, pp. 105-110. doi: 10.1109/SPEEDAM.2018.8445342.
[9] G. Verma and V. Sharma, ″A Novel Thermoelectric Energy Harvester for Wireless Sensor Network Application,″ IEEE Transactions on Industrial Electronics, vol. 66, no. 5, pp. 3530-3538, May 2019. doi: 10.1109/TIE.2018.2863190.
[10] Y. Ma, Q. Ji, S. Chen, and G. Song, “An experimental study of ultra-low power wireless sensor-based autonomous energy harvesting system,” Journal of Renewable and Sustainable Energy, vol. 9, Oct. 2017. doi: 10.1063/1.4997274.
[11] M. Pizzotti, L. Perilli, M. Del Prete, D. Fabbri, R. Canegallo, M. Dini, D. Masotti, A. Costanzo, E. Franchi Scarselli, and A. Romani, “A Long-Distance RF-Powered Sensor Node with Adaptive Power Management for IoT Applications,” Sensors, vol. 17, no. 8, 2017, pp. 1732- 1752, Jul. 2017. doi: 10.3390/s17081732.
[12] A. Okba, A. Takacs, and H. Aubert, ″Compact Rectennas for Ultra-Low-Power Wireless Transmission Applications,″ IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 5, pp. 1697-1707, May 2019. doi: 10.1109/TMTT.2019.2902552.
[13] V. Palazzi, J. Hester, J. Bito, F. Alimenti, C. Kalialakis, A. Collado, P. Mezzanotte, A. Georgiadis, L. Roselli, and M. Tentzeris, ″A Novel Ultra-Lightweight Multiband Rectenna on Paper for RF Energy Harvesting in the Next Generation LTE Bands,″ IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 1, pp. 366-379, Jan. 2018. doi: 10.1109/TMTT.2017.2721399.
[14] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, ″Recycling ambient microwave energy with broad-band rectenna arrays,″ IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 3, pp. 1014-1024, March 2004. doi: 10.1109/TMTT.2004.823585.
[15] M. Piñuela, P. D. Mitcheson, and S. Lucyszyn, ″Ambient RF Energy Harvesting in Urban and Semi-Urban Environments,″ IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 7, pp. 2715-2726, July 2013. doi: 10.1109/TMTT.2013.2262687.
[16] A. Costanzo and D. Masotti, ″Smart Solutions in Smart Spaces: Getting the Most from Far-Field Wireless Power Transfer,″ IEEE Microwave Magazine, vol. 17, no. 5, pp. 30-45, May 2016. doi: 10.1109/MMM.2016.2525119.

[17] H. Hayashi and T. Ueda, "Requirements and considerations of energy harvesting for industrial wireless transmitter," Proc. 2012 SICE Annual Conference (SICE), Akita, Japan, 2012, pp. 1414-1415.
[18] C. Viehweger, T. Keutel, and O. Kanoun, "Energy harvesting for wireless sensor nodes in factory environments," Proc. 2014 IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14), Barcelona, Spain, 2014, pp. 1-4. doi: 10.1109/SSD.2014.6808913.
[19] S. Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, and M. Tentzeris, "Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms," Proc. of the IEEE, vol. 102, no. 11, pp. 1649-1666, Nov. 2014. doi: 10.1109/JPROC.2014.2357031.
[20] A. Berger, L. B. Hörmann, C. Leitner, S. B. Oswald, P. Priller, and A. Springer, "Sustainable energy harvesting for robust wireless sensor networks in industrial applications," Proc. 2015 IEEE Sensors Applications Symposium (SAS), Zadar, Croatia, 2015, pp. 1-6. doi: 10.1109/SAS.2015.7133585.
[21] B. Luo, H. Wang, H. Liu, B. Li, and F. Peng, "Early Fault Detection of Machine Tools Based on Deep Learning and Dynamic Identification," IEEE Transactions on Industrial Electronics, vol. 66, no. 1, pp. 509-518, Jan. 2019. doi: 10.1109/TIE.2018.2807414.
[22] R. Trevisan and A. Costanzo, "A 1-kW Contactless Energy Transfer System Based on a Rotary Transformer for Sealing Rollers," IEEE Transactions on Industrial Electronics, vol. 61, no. 11, pp. 6337-6345, Nov. 2014. doi: 10.1109/TIE.2014.2311395.
[23] G. He, Q. Chen, X. Ren, S. Wong, and Z. Zhang, "Modeling and Design of Contactless Sliprings for Rotary Applications," IEEE Transactions on Industrial Electronics, vol. 66, no. 5, pp. 4130-4140, May 2019. doi: 10.1109/TIE.2018.2860529.
[24] Z. Popovic, "Far-field wireless power delivery and power management for low-power sensors," Proc. 2013 IEEE Wireless Power Transfer (WPT), Perugia, Italy, 2013, pp. 1-4. doi: 10.1109/WPT.2013.6556867.
[25] K. Zannas, H. E. Matbouly, Y. Duroc, and S. Tedjini, "Flipping a Coin, Heads or Tails. Flipping an RFID Tag on Metal, ETSI or FCC Bands," Proc. 2019 IEEE MTT-S International Microwave Symposium (IMS), Boston, MA, USA, 2019, pp. 283-285. doi: 10.1109/MWSYM.2019.8700808.
[26] S. Mao, J. Zhang, K. Song, G. Wei and C. Zhu, "Wireless power transfer using a field-enhancing coil and a small-sized receiver with low coupling coefficient," IET Power Electronics, vol. 9, no. 7, pp. 1546-1552, Aug. 2016. doi: 10.1049/iet-pel.2015.0457.
[27] K. F. Warnick, R. B. Gottula, S. Shrestha and J. Smith, "Optimizing Power Transfer Efficiency and Bandwidth for Near Field Communication Systems," IEEE Transactions on Antennas and Propagation, vol. 61, no. 2, pp. 927-933, Feb. 2013. doi: 10.1109/TAP.2012.2220325.
[28] J. Wu, C. Zhao, Z. Lin, J. Du, Y. Hu, and X. He, "Wireless Power and Data Transfer via a Common Inductive Link Using Frequency Division Multiplexing," IEEE Transactions on Industrial Electronics, vol. 62, no. 12, pp. 7810-7820, Dec. 2015. doi: 10.1109/TIE.2015.2453934.
[29] M. Trautmann, C. Joffe, F. Pflaum, B. Sanftl, R. Weigel, T. Heckel, and A. Koelpin, "Implementation of simultaneous energy and data transfer in a contactless connector," IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet), 2016, pp. 101-104. doi: 10.1109/WISNET.2016.7444333.

[30] S. Kisseleff, I. F. Akyildiz, and W. H. Gerstacker, "Magnetic Induction-Based Simultaneous Wireless Information and Power Transfer for Single Information and Multiple Power Receivers," IEEE Transactions on Communications, vol. 65, no. 3, pp. 1396-1410, March 2017. doi: 10.1109/TCOMM.2016.2646684.
[31] A. Pacini, F. Berra, D. Masotti, and A. Costanzo, "Uniform sliding system for Simultaneous WPT and Communication Data Transfer," IEEE Radio and Wireless Symposium (RWS), 2019, pp. 1-3. doi: 10.1109/RWS.2019.8714337.
[32] R. Trevisan and A. Costanzo, "A UHF Near-Field Link for Passive Sensing in Industrial Wireless Power Transfer Systems," IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 5, pp. 1634-1643, May 2016. doi: 10.1109/TMTT.2016.2544317.
[33] P. Xu, D. Flandre, and D. Bol, "Analysis, Modeling, and Design of a 2.45-GHz RF Energy Harvester for SWIPT IoT Smart Sensors," IEEE Journal of Solid-State Circuits, vol. 54, no. 10, pp. 2717-2729, Oct. 2019. doi: 10.1109/JSSC.2019.2914581.
[34] L. Tu and M. Di Renzo, "Analysis of millimeter wave cellular networks with simultaneous wireless information and power transfer," International Conference on Recent Advances in Signal Processing, Telecommunications & Computing (SigTelCom), 2017, pp. 39-43. doi: 10.1109/SIGTELCOM.2017.7849792.
[35] C. C. Cruz, J. R. Costa, and C. A. Fernandes, "Hybrid UHF/UWB Antenna for Passive Indoor Identification and Localization Systems," IEEE Transactions on Antennas and Propagation, vol. 61, no. 1, pp. 354-361, Jan. 2013. doi: 10.1109/TAP.2012.2220112.
[36] D. Dardari N. Decarli, A. Guerra, M. Fantuzzi, D. Masotti, A. Costanzo, D. Fabbri, A. Romani, M. Drouguet, T. Feuillen, C. Raucy, L. Vandendorpe, and C. Craeye, "An Ultra-Low Power Ultra-Wide Bandwidth Positioning System," IEEE Journal of Radio Frequency Identification, vol. 4, no. 4, pp. 353-364, Dec. 2020. doi: 10.1109/JRFID.2020.3008200.
[37] N. Decarli, F. Guidi, and D. Dardari, "Passive UWB RFID for Tag Localization: Architectures and Design," IEEE Sensors Journal, vol. 16, no. 5, pp. 1385-1397, March1, 2016. doi: 10.1109/JSEN.2015.2497373.
[38] N. Decarli, M. Del Prete, D. Masotti, D. Dardari, and A. Costanzo, "High-Accuracy Localization of Passive Tags with Multisine Excitations," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 12, pp. 5894-5908, Dec. 2018. doi: 10.1109/TMTT.2018.2879806.
[39] D. Kobuchi, K. Matsuura, Y. Narusue, S. Yoshida, K. Nishikawa, and S. Kawasaki, "Smart Wireless Sensor System by Microwave Powering for Space-by-Wireless," IEEE MTT-S International Microwave Symposium (IMS), 2019, pp. 1144-1147. doi: 10.1109/MWSYM.2019.8701077.
[40] G. Loubet, A. Takacs, and D. Dragomirescu, "Implementation of a Battery-Free Wireless Sensor for Cyber-Physical Systems Dedicated to Structural Health Monitoring Applications," IEEE Access, vol. 7, pp. 24679-24690, 2019. doi: 10.1109/ACCESS.2019.2900161.
[41] R. Correia, N. Borges Carvalho, and S. Kawasaki, "Continuously Power Delivering for Passive Backscatter Wireless Sensor Networks," IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 11, pp. 3723-3731, Nov. 2016. doi: 10.1109/TMTT.2016.2603985.
[42] R. Correia and N. B. Carvalho, "Design of high order modulation backscatter wireless

sensor for passive IoT solutions," 2016 IEEE Wireless Power Transfer Conference (WPTC), 2016, pp. 1-3. doi: 10.1109/WPT.2016.7498833.
[43] R. Correia, A. Boaventura, and N. Borges Carvalho, "Quadrature Amplitude Backscatter Modulator for Passive Wireless Sensors in IoT Applications," IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 4, pp. 1103-1110, April 2017. doi: 10.1109/TMTT.2017.2661262.
[44] G. Paolini, Y. Murillo, S. Claessens, D. Masotti, S. Pollin, A. Costanzo, and D. Schreurs, "RF Energy Harvesting from GFSK-Modulated BLE Signals," 2021 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNeT), 2021, pp. 27-29. doi: 10.1109/WiSNeT51848.2021.9413780.
[45] M. Varasteh, J. Hoydis, and B. Clerckx, "Learning to Communicate and Energize: Modulation, Coding, and Multiple Access Designs for Wireless Information-Power Transmission," IEEE Transactions on Communications, vol. 68, no. 11, pp. 6822-6839, Nov. 2020. doi: 10.1109/TCOMM.2020.3017020.
[46] S. Claessens, N. Pan, D. Schreurs, and S. Pollin, "Multitone FSK Modulation for SWIPT," IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 5, pp. 1665-1674, May 2019. doi: 10.1109/TMTT.2019.2908645.