

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

Alessandra Costanzo, Diego Masotti, Giacomo Paolini, Dominique Schreurs

Alessandra Costanzo (alessandra.costanzo@unibo.it), Diego Masotti (diego.masotti@unibo.it), and Giacomo Paolini (giacomo.paolini4@unibo.it) are with Alma Mater Studiorum – University of Bologna, DEI – Department of Electrical, Electronic and Information Engineering “Guglielmo Marconi,” – Bologna, Italy.

Dominique Schreurs (dominique.schreurs@kuleuven.be) is with KU Leuven, ESAT-WaveCore, Leuven, Belgium.

Introduction

In these ~~last~~ past few years, many interesting approaches have been studied and designed to ~~go towards~~ 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 ~~also industrial fields~~ industry.

The ever-growing array of internet of things (IoT) technologies presents a tangible answer to the need ~~of 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, ~~that which~~ can be ~~potentially~~ spread over difficult-to-be-reached areas.

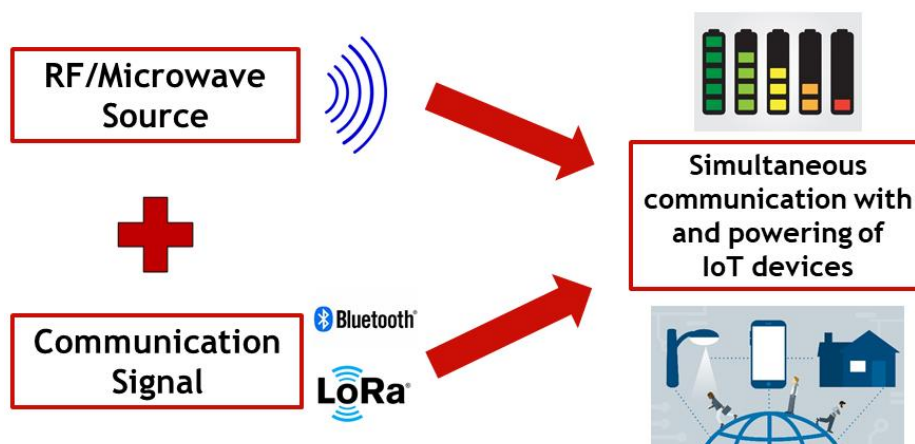


Fig. 1. Envisioned scenario for SWIPT applications: the combination of RF energy sources and communication signals allows the implementation of networks composed of battery-less IoT devices.

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) ~~enabling 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, ~~almost 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 ~~requested to desired in~~ the wireless sensor nodes is the ~~capability ability~~ to autonomously operate through energy harvesting (EH) techniques rather than to be plugged-in with ~~the presence of~~ obstructive cables, or to depend on batteries which ~~present have~~ a limited lifetime. Moreover, batteries are ~~not so less~~ reliable at high temperatures and might require multiple replacements over the node's ~~period of lifespan~~, thus ~~dramatically~~ increasing ~~dramatically~~ 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 ~~have to face the limit due are limited to by~~ the frequent unavailability of the corresponding energy source. ~~Vice versa~~ ~~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, ~~that which~~ could also coincide in some cases, allowing both the interconnection of IoT devices and their energetic support without the need ~~of for~~ cables or batteries.

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

Great emphasis has been laid on solutions ~~exploiting 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 ~~could~~ can occur; as an example, the challenge of RFID tags over metallic plates is described and dealt with ~~and described~~ in [25].

This article reviews some recent promising solutions in both ~~the~~ 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 ~~of~~ for wireless power and data delivery that are covered ~~by~~ in this work exploit the near (or reactive) EM field which is provided by near-~~located~~ by sources in the low (LF: 30–300 kHz) [26] or high (HF: 3–30 MHz) [27] frequency range, to realize ~~the~~ so-called near-field SWIPT (NF-SWIPT). This ~~very 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 ~~what concerns~~ power transmission, but still involving low powers (μW or mW) for communication purposes.

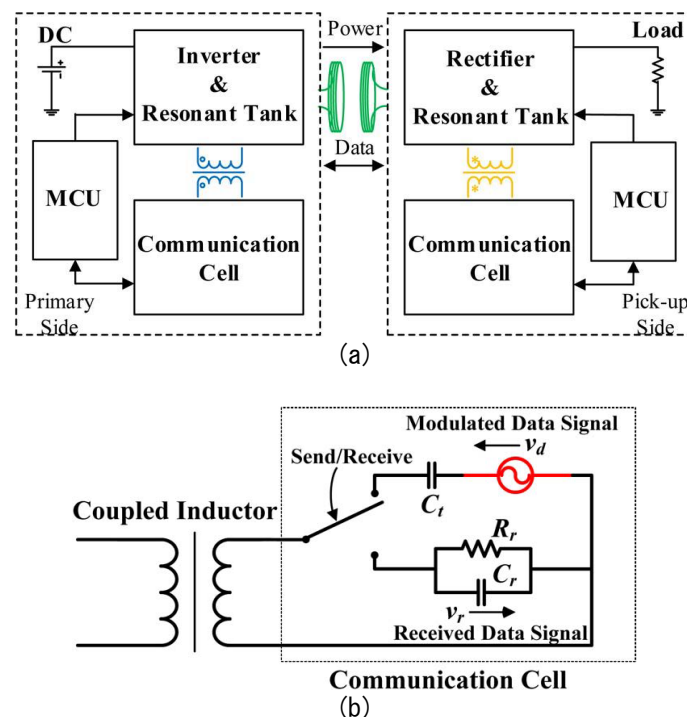


Fig. 2. Block schematic of (a) a system for near-field wireless power and data transfer, and (b) a typical structure of the communication cell [28].

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 selected 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. _

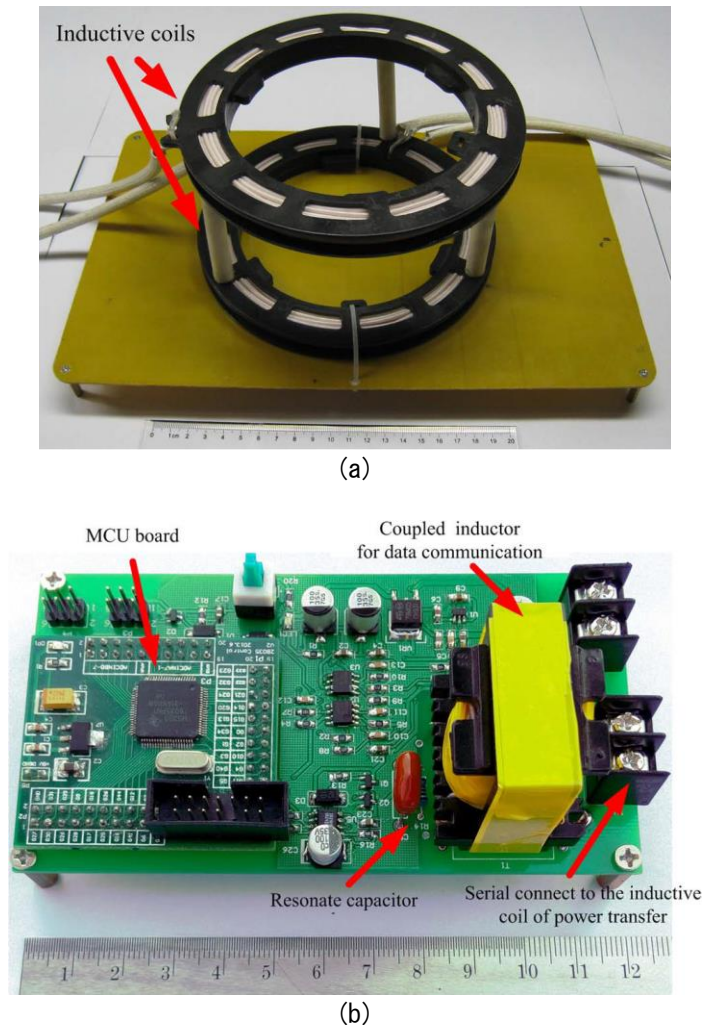


Fig. 3. Picture of ~~the~~ (a) the inductive coils and (b) the communication board presented in [28].

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 ~~one~~, 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 ~~to face~~ 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 with-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 ~~one~~ (150 kHz, with power transmission of 3 kW). ~~In-With~~ this ~~way~~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 against-of interferences that can be created by the simultaneous presence of energy transfer in the near-field.

In [30], a typical structure ~~of-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 ~~for this scheme 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.

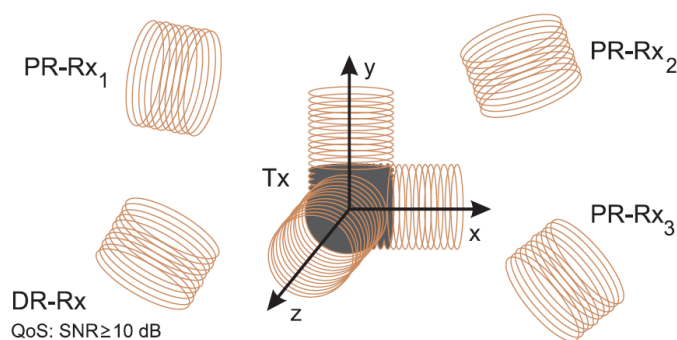
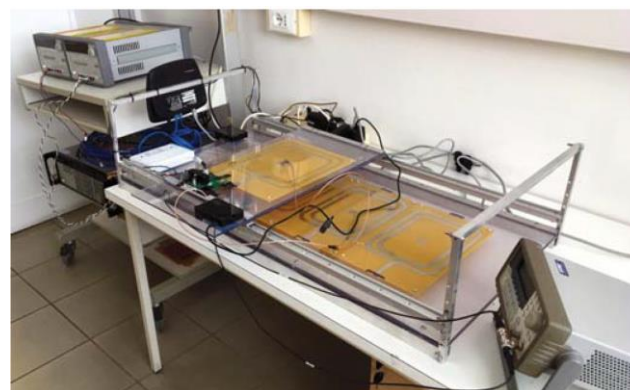


Fig. 4. Example of an NF-SWIPT system making use of a tri-dimensional inductive coil for transmission (Tx), three single-coils for power reception (PR-Rx1, PR-Rx2, PR-Rx3), and a single coil for data reception (DR-Rx) [30].

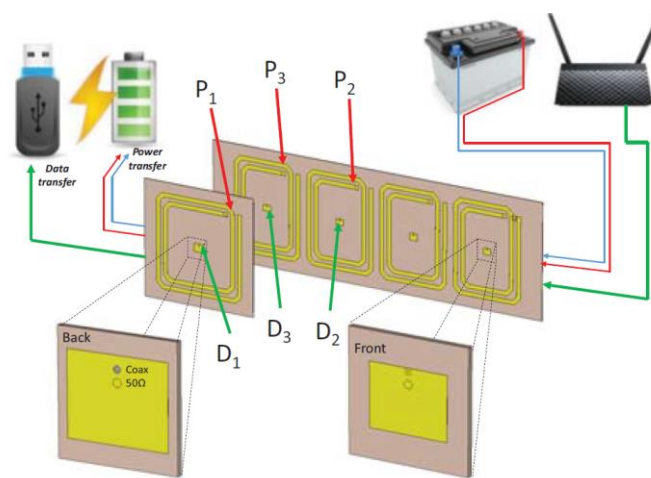
The theme of simultaneous near-field WPT and communication data transfer for industrial applications (e.i. ge., in the automotive and railway sectors) is also developed in [31]; here, a series connection of sliding resonant coils at 100 kHz has been designed and employed to maintain constant coupling along the entire track, and therefore guaranteeing constant link and power-rectifying performances. This ~~has been was~~ done using a ~~selected~~ couple of transmitting coils and a geometrically optimized receiver. ~~The 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~~ly~~ 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 ~~has been~~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 ~~notice~~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 ~~what concerns~~ 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. ~~The idea of p~~Putting a patch antenna at 5.24 GHz in each transmitting coil provides enough margin to

overcome EMI with ~~the~~ 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 ~~machineries~~ 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~~ 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 ~~of~~ in the channel transfer efficiency obtained by exploiting two facing auto-resonant structures, i.e., split-ring resonators (SRRs), one at each end ~~side~~ of the link, as shown in Fig. 6(a). The involved distance (d) is of a few (or a fraction of) ~~millimetres~~ millimeters, as in many industrial applications: in this case, free rotation of the SRRs is considered. Fig. 6(b) shows ~~the~~ a view of one element of the SWIPT system, ~~along~~ with the co-location of the inductive windings for the power transfer, ~~too~~. 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 ~~the~~ conventional low-frequency RFID bands.

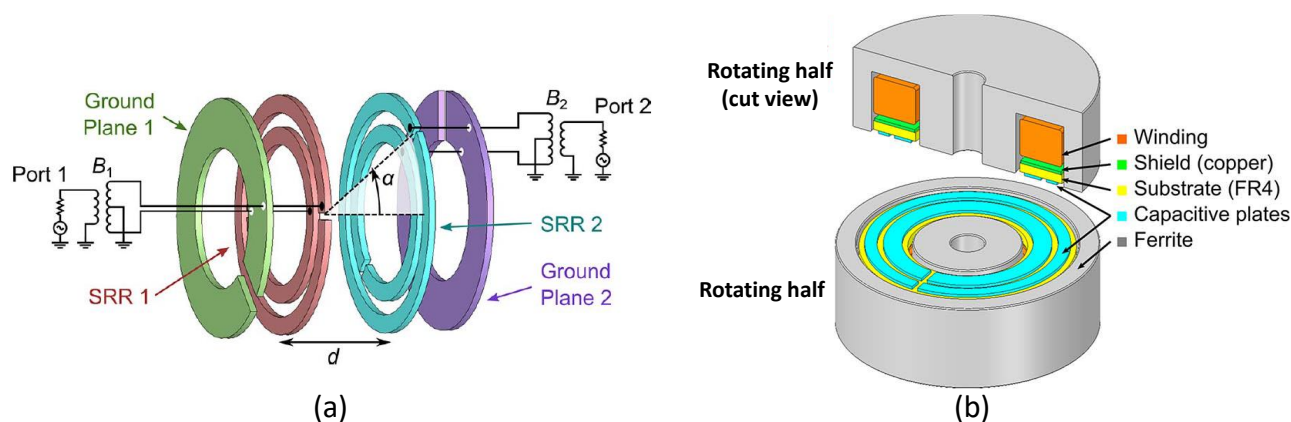


Fig. 6. (a) Representation of the entire stack-up of the SRR communication link. The distance d represents the clearance between two SRRs, and the angle α is the relative angular position of the outer strips' slots positions. (b) 3D view of the transmitting/receiving SWIPT element [32].

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]

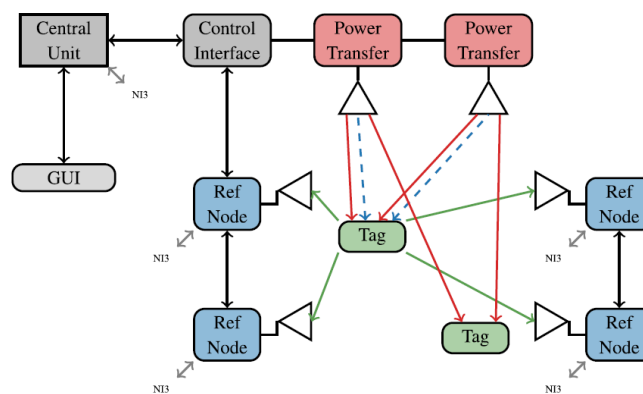
range.

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

An indoor positioning system (IPS) is ~~considered one of the new~~ developing ~~technologies~~ technology of the ~~last past few~~ years, and ~~the several different~~ methods ~~have been~~ adopted for its actuation ~~are several and different~~. In that sense, ~~t~~The use of UWB (typically backscattered) signals [37], [38] is advantageous because the exploitation of a very large range of frequencies ~~allows to avoids~~ possible effects of fading and shadowing that ~~could can~~ occur ~~with high probability~~ 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, ~~respectively~~, 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 battery-less tags schematically represented in Fig. 7(a) are powered ~~thanks to 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 ~~in the nearby~~. 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.



(a)

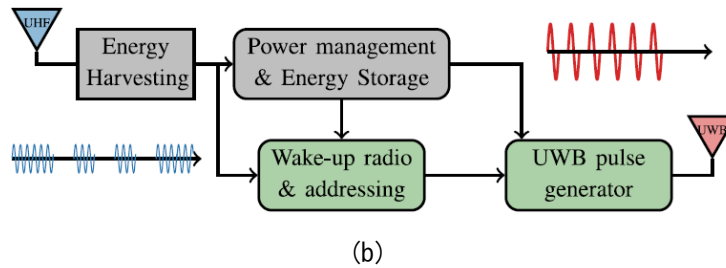


Fig. 7. (a) Schematic of a UWB/UHF system and (b) block diagram of the corresponding battery-less tag equipped with UWB pulse generator for passive localization in space environments [36].

~~Always considering~~ Another very interesting SWIPT for space applications, ~~a very interesting solution has been~~ introduced in [39], with higher WPT operating frequencies; the ~~scheme 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.

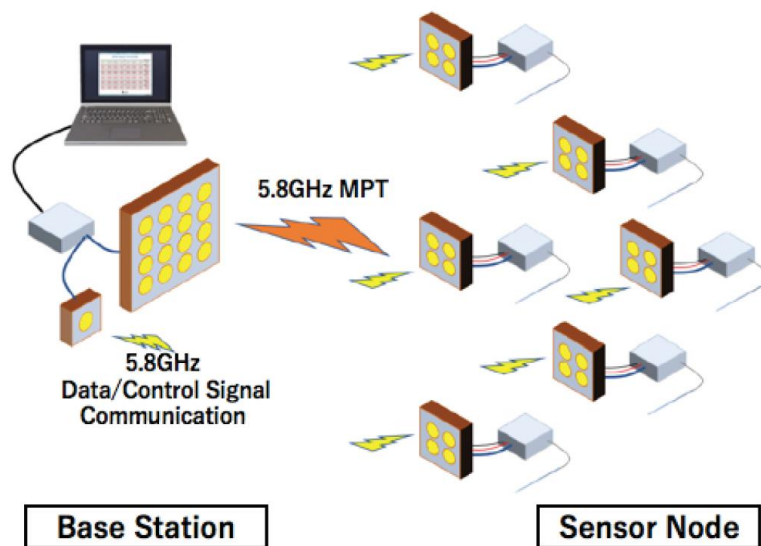


Fig. 8. Envisioned scenario for SWIPT at 5.8 GHz in a wireless sensor system for spacecraft health monitoring [39].

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

Moreover, the base station ~~also~~ acts ~~also~~ 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.

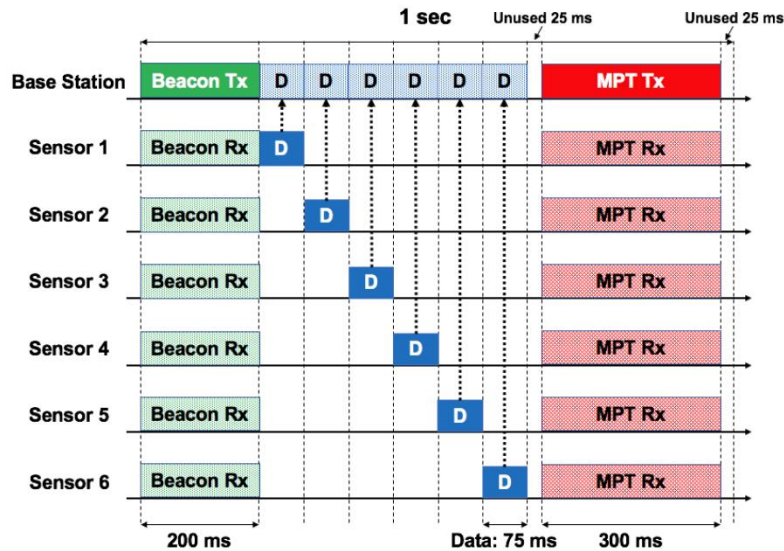


Fig. 9. Envisioned scenario for SWIPT at 5.8 GHz in a wireless sensor system for spacecraft health monitoring [39].

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.

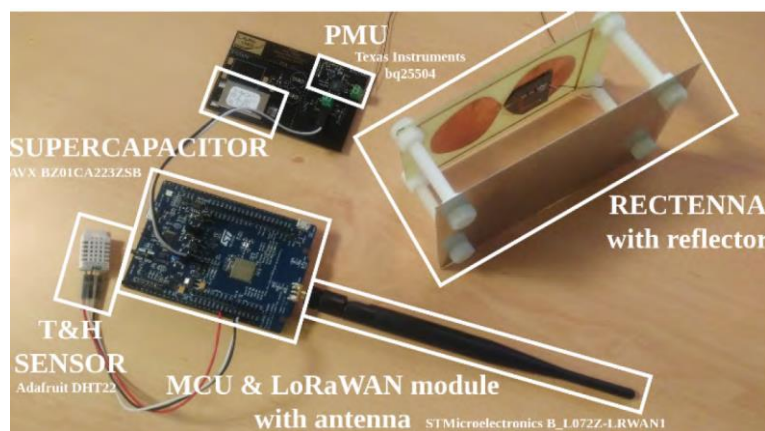


Fig. 10. Picture of the components of the sensing node prototype realized in [40].

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, ~~and of as well as~~ the backscatter modulator ~~that 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. ~~In that sense, 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 ~~to 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 communications ~~in order to be that is~~ continuously powered during the operation mode.

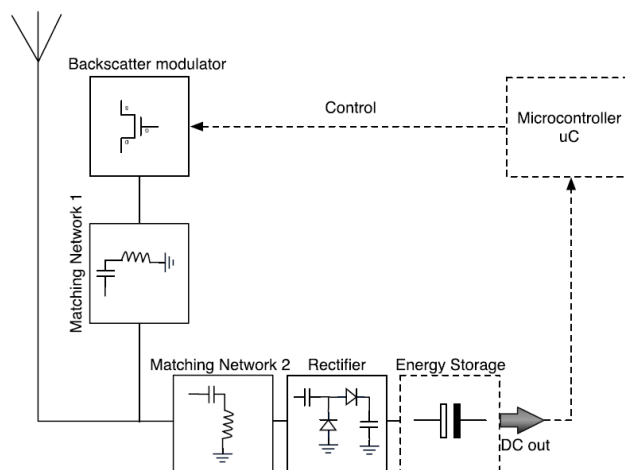


Fig. 11. Block diagram of the system proposed for RF energy harvesting and backscattering [41].

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.

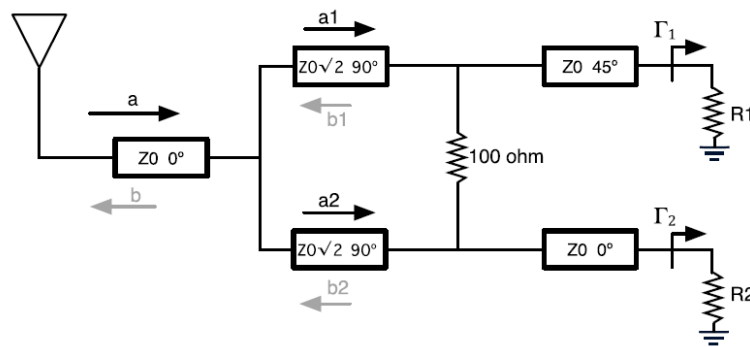


Fig. 12. Schematic implementation of 16-QAM demodulation [43].

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 ~~the other~~ its counterpart.

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

~~A One~~ method to achieve SWIPT from Gaussian frequency-shift keying (GFSK) modulated signals, ~~(i.e., the modulation adopted by Bluetooth low energy (BLE))~~), ~~can be the one that has been approached~~ is explored in [44]. In this case, the circuit of the node, composed of a matching network and a voltage-doubler rectifier, ~~has been~~ 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 ~~recognise~~ 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 ~~the~~ cut-off frequency at the output of the rectifier, ~~that which~~ has to be set taking into account the bandwidth of the signal, its data-rate, and the deviation of the selected FSK modulation.

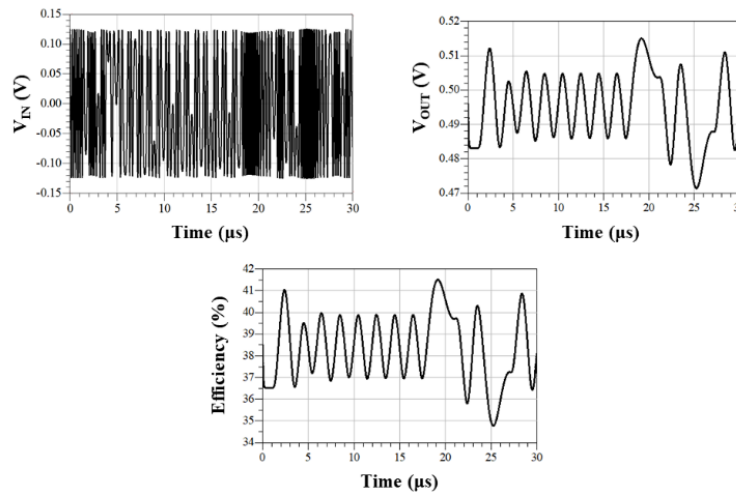


Fig. 13. Input voltage, output voltage, and efficiency for the presented rectifier, with the bandwidth of the output filter set at 2 MHz [44].

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 ~~de~~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 ~~schematized~~ shown in Fig. 14.

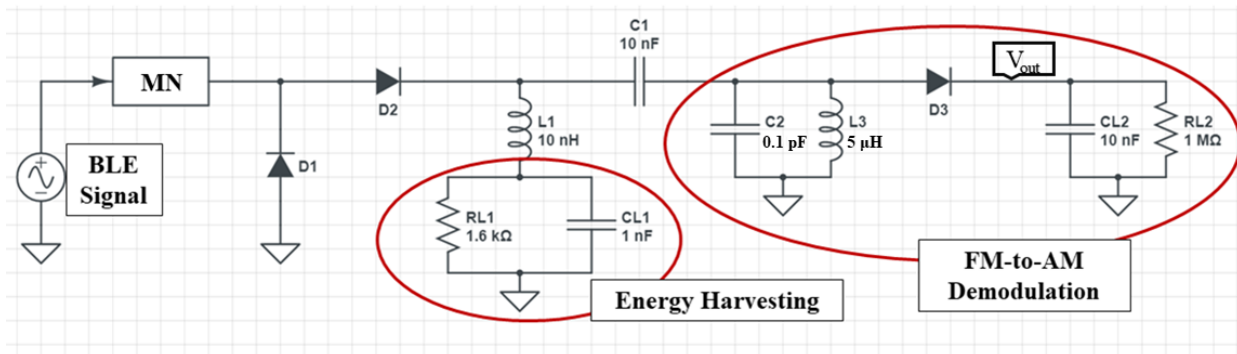


Fig. 14. Schematic of SWIPT (energy harvesting plus demodulation of FSK modulated signals) achieved within the same circuit for BLE inputs.

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 ~~what concerns~~ the energy harvesting path, for an input power of 0 dBm, an average RF-to-~~de~~DC PCE of 47% is guaranteed.

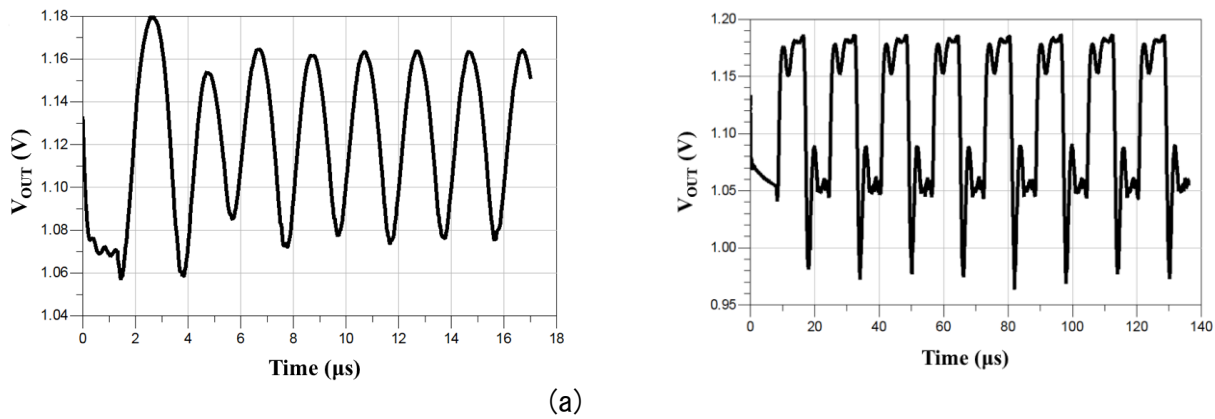


Fig. 15. Output voltage V_{OUT} at the demodulator path for BLE at (a) 1 Mbps and (b) 125 kbps.

Another important aspect to be considered for SWIPT purposes—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 ~~increasing that increase~~ the ~~de-DC~~ output power for EH, ~~but also while~~ enhancing the information rate, which is also ~~recognized as~~ 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 ~~also in this case~~, 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 non-linear 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 ~~of for~~ a power-consuming local oscillator (LO).

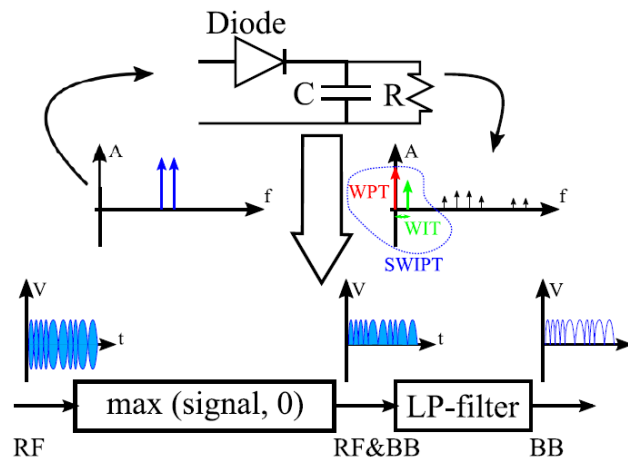


Fig. 16. Schematic and system model for a single-wave rectifying circuit, showing the coexistence at the output of ~~de-DC~~ (from WPT) and baseband (BB, for wireless information transfer, WIT) signals [46].

Conclusion

This article ~~features a reviews~~ of recent techniques and ~~different~~ possible solutions for simultaneous wireless communication and powering of IoT devices, ~~both 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 ~~important~~ 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 ~~for to~~ SWIPT of GFSK modulated signals (e.g., BLE) ~~has been 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., the~~ removal of batteries and ~~the~~ limited (or nearly ~~cancelled removed~~) maintenance time ~~and with~~ economical effort).

However, ~~it can be said that n~~near-field prototypes are ~~surely~~ more mature and ~~advanced~~ from a technological and industrial perspective; conversely, radiative solutions in far-field are still developing and need further ~~steps to be validated in order to be put on validation before entering~~ the market, ~~also with the requirement of an~~as well as ~~regulatory~~ evaluation ~~from the regulatory point of view~~.

These interesting topics and challenges ~~should provide a boost for can surely represent a booster in the future for the next~~ research studies and practical applications ~~to in~~ industry 4.0 and in general ~~to 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 ~~ef for~~ energy ~~sustainment coming~~ from batteries.

Acknowledgement

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