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Backscatter radio communication for IoT applications

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***Abstract*— The so called Internet of Things (IoT) is progressively becoming a normal thing in everyone daily lives. The desire of connecting everyday objects to the internet and to each other, to interact with other users and machines, is increasingly becoming a reality. In this context, where billions of connected objects are expected to be ubiquitously deployed worldwide, the frequent battery maintenance of wireless nodes is undesirable or even impossible. The growth of the devices will be made possible only if the sensors battery needs are eliminated or reduced significantly. For low power sensors and devices, careful power management and power conservation are critical to device lifetime and effectiveness. One of the possible solutions is to change completely the paradigm of the radio transceivers in the wireless nodes of the IoT system. The new paradigm should be able to communicate and to enhance the power to the sensor by using only electromagnetic waveforms transmitted over the air, in order to make the Wireless Power Transfer (WPT) concept a reality.**

Keywords: Backscatter communication, Internet of Things, Wireless power transmission.

I. Introduction

Passive Radio Frequency Identification (RFID) tags use the Radio Frequency (RF) power, from the reader, to energize the digital part of the tag, which is responsible for the modulation of the incoming wave. To enable the possibility of having a totally passive RFID tag with data logging and advanced computing a more careful and detailed Wireless Power Transmitters (WPTs) should be designed and optimized to power the intelligent tags. This integration of passive RFID, passive sensing and increased computing capabilities have enabled the interest in the concept of passive wireless sensors. The concept of having passive wireless sensors with data logging and advanced computing capabilities will play an important role in the IoT context, where a lot of sensors can be connected, deployed anywhere, and give information about environment without the need of batteries. Nonetheless, the increase of IoT sensors will imply the heighten of batteries to be deployed, which will have a negative ambient impact. The battery-powered tags can improve the distance of communication but have some limitations when referring to the battery cost and its replacement. Thus, the alternatives to the battery systems are based on Energy Harvesting (EH) technology or other different sources (solar [1], motion or vibration [2], ambient RF [3]). To overcome the drawbacks employed from the EH and batteries, the concept of WPT was explored to supply the tags with power.

In [4], a solution using inductive WPT and Ultra High Frequency (UHF) RFID was presented. The work proves that combining the inductive WPT with the UHF RFID increments the tag sensitivity in 21 dB, which increases the Interrogation Zone (IZ). However, the use of inductive WPT requires proximity between the tag and the power source. Regarding electromagnetic WPT, a comparison between different rectifier topologies and different stage levels was presented in [5]. The obtained results show a high dependence between the received power and the most efficient topology. A structure with a two-tone signal at 1.8 GHz and 2.4 GHz was shown in [6]. The results present a voltage output 20% higher in average when comparing with a single-tone input. The work in reference [7] begins with a reader that is configured to transmit power in Continuous Wave (CW). After rectification, the power charges the storage capacitor to 5.5 V. The storage capacitor, once charged, powers the tag that performs sensing and communication, reflecting the carrier wave. This entire process occurs at a distance of 1 m between the reader and tag. The same principle is used in [8]. The work in [9], [10] presents a solution using dual band wireless power and data transfer. One frequency is exclusively used to transmit energy to the sensor, and the other is fully dedicated to communication through backscatter. A similar approach, using different frequencies for transmitted energy and communication was presented in [11]. In that work, a differentiated circuit for the RF-DC conversion is used for each frequency. The work in [12] uses two different bands for RF communication and for WPT. The authors used 5.8 GHz to power up a portion of radio that is connected to a battery with an RF-DC converter. This path is only to turn the battery ON for the main transceiver as a wake up radio, and the link for the power up is no longer needed once the main transceiver is turned ON. The system is not passive and uses the WPT link to activate the main transceiver. Nevertheless, despite of having passive systems for communication, it is utmost important to improve the data rate in order to reduce on-chip power consumption and extend read range.

Nowadays the wireless sensing devices are growing at a phenomenal rate, with billions of wireless sensors reaching a much larger proportion than the world's population. However, this rapid increase presents two main issues: increased use of batteries and energy consumption. In the IoT context, passive backscatter radios will certainly play a crucial role due to their low cost, low complexity and battery-free operation. Therefore, there is a significant need to design novel wireless communication techniques to achieve higher data rates while simultaneously minimizing energy consumption. In

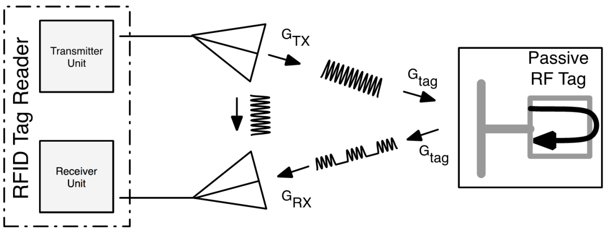


Fig. 1. Conventional backscatter system.

the backscatter communication the tag reflects a radio signal transmitted by the reader, and modulates the reflection by controlling its own reflection coefficient.

A simple and conventional scheme of the backscatter system is shown in Fig. 1. Backscattering radio frequency identification is a type of RFID technology employing tags that do not generate their own signals but reflect the received signals back to the readers. Conventional backscatter systems always use a single continuous carrier to emit between the RFID tag reader and the passive tag (Fig. 1). In traditional backscatter communication (e.g., RFID), a device communicates by modulating its reflections of an incident RF signal.

In most RFID systems and passive sensors, the reader to tag communication is an Amplitude Shift Keying (ASK) or Phase Shift Keying (PSK) that modulates either the amplitude, or both the amplitude and phase, of the reader's transmitted RF carrier. The use of this technology entails a number of advantages over barcode technologies such as tracking people, items, and equipment in real time, non-line of sight requirement, long reading range, and standing harsh environment. However, the work [13] has shown that modulated backscatter can be extended to include higher order modulation schemes, such as Four-state Quadrature Amplitude Modulation (4-QAM). While ASK and PSK transmit 1 bit of data per symbol period, 4-QAM based can transmit 2 bits per symbol period, thus increasing the data rate and leading to reduced on-chip power consumption and extended read range. The work presented in [13], [14] refers to a 4-QAM backscatter in semipassive systems, by using a coin cell battery as a power source for the modulator and a microcontroller that needs 3 V of supply. This way, the authors proved the Quadrature Phase Shift Keying (QPSK) modulator and battery powered system, by using an approach with a four lumped impedances connected to a RF switch that is controlled by a microcontroller. The same authors developed a 16-QAM modulator for UHF backscatter communication with a consumption of 1.49 mW at a rate of 96 Mbps only in the modulator (not the overall system with data generation logic feeding the modulator) [15].This modulator was implemented with 5 switches with lumped terminations as a 16-to-1 multiplexer to modulate the load between 16 different states.

In [16], the authors presented an I/Q backscatter modulator that use bias currents to change the impedance of two PIN diodes. The circuit comprises a Wilkinson power divider, two filters (low pass and high pass) to guarantee symmetrical paths on the board, one in each branch, and one PIN diode for each branch. The bias consumption of the circuit is 80 mW

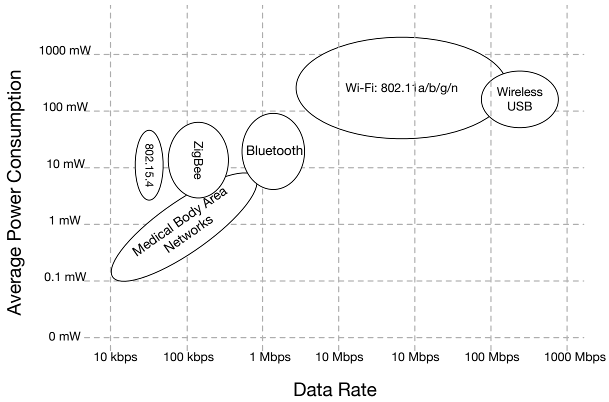


Fig. 2. Comparison of wireless technology average consumption and data rates.

(excluding Digital-to-Analog Converters (DACs) and Field-Programmable Gate Array (FPGA) logic), which imposes high power consumption and data rate limitations. The use of this circuit for a low power sensor is not feasible. Another approach by using the PIN diodes was presented in [17]. Pozar presented a reflection type phase shifter using a quadrature hybrid and two PIN diodes. By biasing the diodes to the ON and OFF state it was possible to change the total path length for both reflected waves, producing a phase shift at the output. However, the consumption of the PIN diodes is not suitable for low power sensors. One different solution to obtain a Binary Phase Shift Keying (BPSK) modulation was presented in [18]. The authors presented a phase-shift modulator with two switches that are connected to each other by a 90°delay line or 0°delay line. The phase-shift modulator was implemented as a two-port device that selectively delays the signal by 90°between port 1 and port 2, or passes the signal from port 1 to port 2 with no delay, achieving a BPSK modulation.

In [19], two multi-antenna technologies were used. The authors presented an energy harvester (Staggered-Pattern Charge Collector (SPCC)) that has two independent antenna arrays and harvests power to supply a microcontroller. They also present a Retrodirective Array Phase Modulator (RAPM) that backscatters the signal from the reader to the reader. The RAPM comprises two switches that are controlled by a microcontroller. The four switching states are connected through coplanar waveguides of different wavelengths, each separated by 90°. The RAPM can be used for QPSK modulation by calibrating the phase offsets in the switches.

The existing standards consume much more power in comparison with the one proposed in this work. As shown in Fig.2, power levels are in the range of 800 mW for Wi-Fi, 100 mW for Bluetooth, 50 mW for Zigbee. The high data rate and long operating range of Wi-Fi and wireless USB technologies come at an increase in power consumption which is impracticable for low power and remote sensor applications that require high-bandwidth wireless communication. In order to overcome this issue, RFID backscattering systems are being explored with some advances in the type of modulations used. In [13], [20], [21], QPSK modulation was implemented at

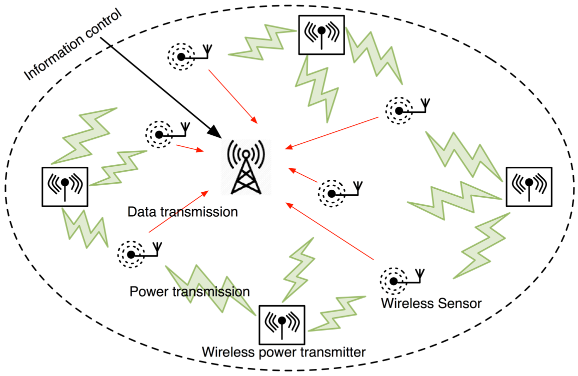


Fig. 3. Example of our proposed application using WPT combined with backscatter modulation.

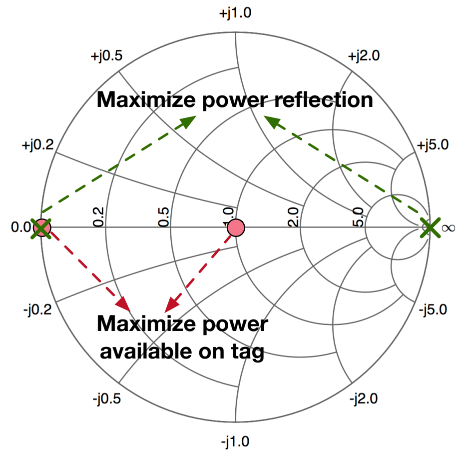


Fig. 4. Two different approaches of a binary ASK modulator.

900 MHz and 2.45 GHz, respectively. To increase the range of communication of backscattering systems, a 16-QAM [15] and a 32-QAM [22] were developed at 900 MHz and 5.8 GHz, respectively. These systems proved to be very suitable for low power communications due to the low energy per bit consumption and the achievable data rates. The authors in [23] presented a BPSK modulator with 330 Mb/s of data rate at 2.9 GHz.

II. IoT sensor Implementation

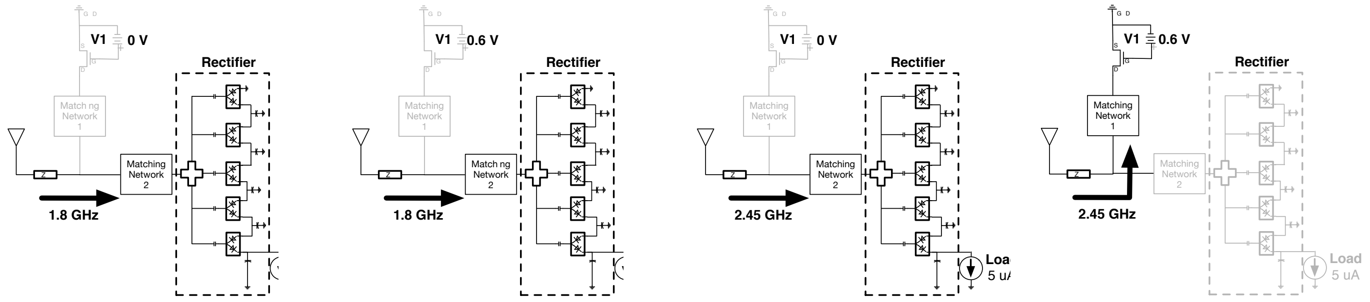
As illustrated in Fig. 3, we propose an example of application in wireless powered sensors combined with backscatter modulation. This solution presents a potential performance improvement when compared with conventional battery-powered wireless sensors network, since it eliminates the need of battery replacement or recharging. Nevertheless, the use of WPT reduces the operational cost and increases the communication performance. Wireless sensors need to harvest enough energy before transmitting data, and this novel solution intends to demonstrate the need of this work in achieving continuous power delivery to the passive backscatter WSNs, increasing the communication performance. It is important to denote that this solution uses two different frequencies for different purposes, one is used for WPT and the other for binary backscatter modulation.

Therefore, we envision that this solution will have an important role in many popular commercial and industrial systems in the future including IoT or space oriented WSNs systems.

In order to implement a binary ASK modulator it is necessary to understand the two different approaches that maximize the power available on the tag or the power reflection. In Fig. 4 it is shown the both possibilities that characterize a binary modulator. As it was said previously, the backscatter tag is composed by a semiconductor (switch) that will change the antenna's impedance by changing the voltages of the transistor (switch). To maximize the power reflection the modulator will act as a short and an open depending on two different voltages, which will penalize the power available on the tag. On the other hand, to maximize the power available on the tag, the modulator will act as a match load and a short, which will penalize the power reflection. In our approach, we combine both approaches by using two different frequencies.

The work proposed in [9] presents the capability of generating ASK backscatter modulation with a continuous flow of energy to supply the digital processing unit. This approach utilizes two different frequencies, one for the backscatter communication and the other for the WPT. The design follows the block diagram proposed in Fig. 6. It is composed by two matching networks, a backscatter modulator and a five-stage Dickson multiplier. The goal is to harvest electrical energy with one tone (1.8 GHz) and with the other tone (2.45 GHz) transfer data by backscatter means. The RF power harvester employs a receiving antenna, an impedance matching network, dc power conditioning, and the sensor to be powered. The backscatter modulator employs the receiving antenna, an impedance matching network, and a semiconductor device to control the reflection coefficient. The implemented prototype is shown in Fig. 7 and can be divided in three main sections. The first is the backscatter modulator, which is constituted by a switch transistor that modulate the impedance of the antenna, the second is the matching network that was designed for the load modulation in one frequency and to provide a continuous flow of WPT in other frequency. The third is the five-stage multiplier which allows the RF-DC conversion in order to provide sufficient DC power to supply the microcontroller.

A estimation of maximum sleep current consumption from all lower frequency circuits is needed, before simulating the RF front-end. A value of 5 μA was assumed to be the maximum sleep consumption of the microcontroller, a temperature sensor and ADC. After this assumption, all of the other circuits were replaced by an ideal current source that was placed in parallel with the storage capacitor with a value of 5 μA in the simulator. A harmonic balance simulation was performed in ADS to tune the matching network for the maximum DC output voltage with the ideal current. To provide both backscatter communication and wireless power transfer, a Large Signal SParameter (LSSP) simulation was performed with the objectives of matching the circuit in both states of



(a) (b) (c) (d)

Fig. 5. Different modes of operation with different frequencies (a) $V_{Gate} = 0$ V for 1.8 GHz (b) $V_{Gate} = 0.6$ V for 1.8 GHz. (c) $V_{Gate} = 0$ V for 2.45 GHz. (d) $V_{Gate} = 0.6$ V for 2.45 GHz.

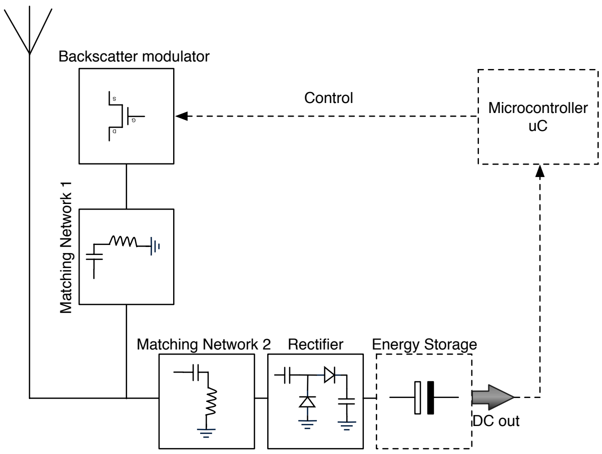
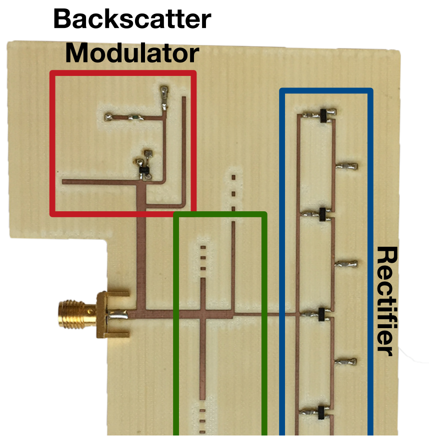


Fig. 6. Block diagram for a passive sensor.



the transistor at 1.8 GHz, matching the system at 2.45 GH one state and mismatching at the other state. This change the antenna's impedance at 2.45 GHz provides the backsca communication.

Fig. 5 illustrates the two different states of the gate volt of the transistor for two different frequency tones. Dur the OFF-state and ON-state of the switching transistor at GHz, the circuit was designed to have almost zero reflect coefficient, as shown in Fig. 5a and Fig. 5b. The sa reflection coefficient is achieved during the OFF-state of switching transistor when the frequency is 2.45 GHz, as sho in Fig. 5c. During the ON-state of the switching transi at 2.45 GHz, the circuit was designed to have the reflect coefficient different from 0 (ideally equal to 1), as illustra in Fig. 5d. Moreover, with the circuit presented in Fig. 7 v 0 dBm of input power we could measure the S_{11} and ve the different modes presented in Fig. 5. The measured S_1 presented in Fig. 8.

We conducted an experience with this implemented des powering a temperature sensor at a distance of 3 m from reader/transmitter. The tag turns ON at 26 dBm, as can seen in Fig. 9, and then starts the backscatter communication process (changing the impedance by switching ON and OFF the transistor) with the temperature information, which will be demodulated in the reader.

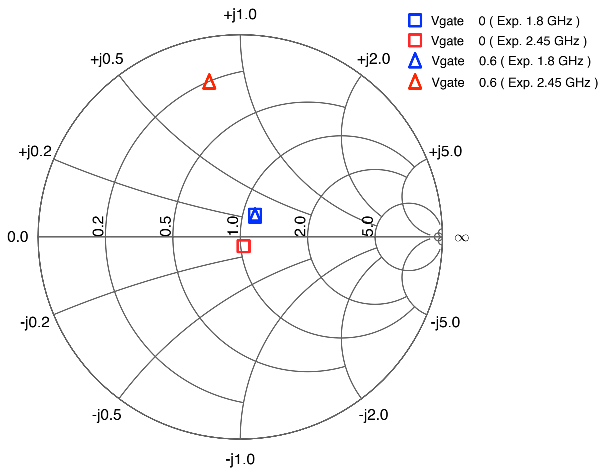


Fig. 8. S_{11} parameter as function of frequency for two different values of transistor's gate voltage with 0 dBm of input power.

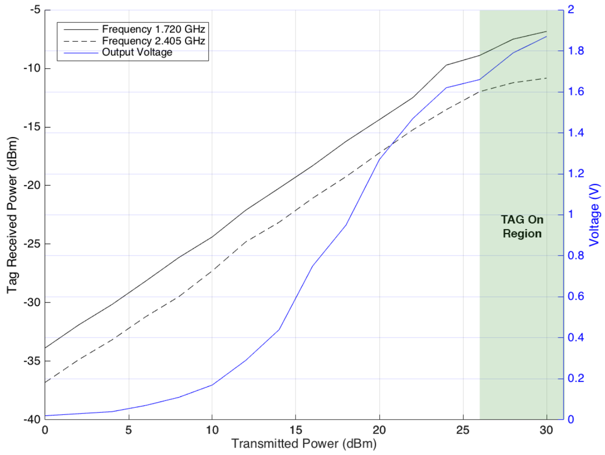


Fig. 9. Passive sensor with WPT at a distance of 3 m.

III. Conclusions

The manuscript explained the backscatter communication as a solution for passive sensors. The presented circuit was designed to operate at two different frequencies (1.8 GHz and 2.45 GHz), one for the data modulation and the other for WPT. With the proposed circuit and scheme it was shown that it is possible to supply a continuous power flow to the wireless sensor combined with backscatter communication with a distance of 3 m. This way the sensors can be continuously powered during the operation mode without requiring any battery.

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