Quadrature Amplitude Modulation Backscatter for Passive Wireless Sensors

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Abstract

Backscatter RFID sensors are beneficial for sensing applications where small, low-maintenance and no-battery sensor’s nodes are needed. In this work two different approaches for battery free sensors are presented. The first approach is based on ASK backscatter modulation and a prototype is presented and measured. With this circuit it is shown that is possible to have a complete passive WSN by combining backscatter modulation with WPT. In order to increase the data rate of the sensors, a new approach based on QAM modulation was implemented. A backscatter modulator based in a Wilkinson power divider was proposed which contains a delay in one of the design branch and two transistors acting as switches to generate M-QAM backscatter modulation. It is foreseen that the modulator is the basis for a truly passive WSN.

Index Terms

Wireless sensor network, backscatter communication, wireless power transfer, quadrature amplitude modulation, amplitude shift keying, internet of things.

I. INTRODUCTION

Radio Frequency Identification (RFID) technology has been used for logistical purposes as a replacement for bar codes so as to improve reliability and speed of item identification, as well as enabling additional features such as enhanced inventory management. The promise of RFID and its eventual widespread successful deployment within a commercial supply chain is predicated on low cost, passive tags that support reliable, fast reading of tag IDs by readers. Along with this price reduction, advances in semiconductor technology have allowed the possibility of passive RFID enabled sensors to be integrated in wireless sensor networks (WSNs) [1]. However,
Fig. 1. Traditional RFID system with load modulation

ultra-cheap tags and a reliable, efficient system are very difficult to combine, due to extreme limitations on tag capabilities. This includes very limited memory and on-tag data processing, and (most relevant for our purposes), seriously constrained power availability. Nevertheless, RFID tag designs are being continually improved on various fronts - via improved circuitry and energy management approaches, among others. The major advantage of passive RFID-enabled sensors over traditional sensors is their low cost and the maintenance free. These advantages are only possible due to the use of backscattered radio waves.

In most commonly deployed RFID systems, the backscatter link uses a simple modulation scheme, such as amplitude shift keying (ASK) or phase shift keying (PSK) backscatter generated by a two-state modulation of the impedance presented to a transponder’s antenna (Fig. 1). Since tag to reader distance is generally unknown, most readers employ homodyne I/Q demodulation. In the case the reader rotate the received constellation until it falls on the real axis before demodulation as if the signal were ASK regardless of whether the tag’s modulator is configured to generate ASK or PSK modulation. The reflected portion of the carrier signal incident on the tag antenna is impressed with an envelope (altering amplitude, phase, or both) carrying the binary backscatter data. Backscatter radio technology has grown is the last decade because the applications that do not require battery have increased. Using backscatter communication allows for extremely low power dissipation for remote devices, which enables new areas of sensor development. The backscatter tags, by receiving the local oscillator over the air, do not need their own radio frequency (RF) oscillator or phase-locked loop (PLL). By removing these
circuits, one reduces the power consumption and the cost of a tag chip [2]. Nevertheless, the backscattered signal received by the readers is weak, thus limiting communication range. In conventional backscatter communication, the tags must harvest enough power from the reader to turn on and modulate data, and the readers must receive strong backscattered signal to operate.

A recent work [3] has shown that modulated backscatter can be extended to include higher order modulation schemes, such as 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 [3], [4] 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 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) [5]. This modulator was implemented with 5 switches with lumped terminations as a 16-to-1 Mux to modulate the load between 16 different states.

Some recent work [6], [7] show the possibility of using one frequency to continuously power the wireless sensor and other to transfer data by backscatter means with ASK modulation. Fig. 2 presents a potential solution presented in [6], [7] for this implementation. An energy harvester and power management circuitry are responsible for collecting sufficient energy to power the tag and any additional sensor. As previously mentioned, this energy can come from a variety of sources but is typically reader-delivered RF power. Over the last years, RF energy harvesting, which is the capability of converting RF signals into DC energy, has gained a lot of interest [8] and resulted in some commercial solutions. Thus, there is a strong motivation to enable a WSN with wireless power transmission (WPT) in order to afford all the operational costs.

As illustrated in Fig. 3, without the need to replace energy depleted sensors in conventional WSNs, a passive WPT WSN can achieve a continuous operation with a large number of sensors powered by fixed energy transmitters used for both wireless charging and data collection. Nevertheless, due to the more ample power supply from WPT, RFID devices can now expect much longer operating lifetimes, and afford to transmit actively at a much larger data rate and from a longer distance than conventional backscatter based RFID communications. Therefore, we
envision that a WSN with WPT will be an important building block of many popular commercial and industrial systems in the future, including the upcoming Internet of Things/Everything (IoT/IoE) systems consisting of millions of sensing/RFID devices as well as large-scale WSNs.

In this article we first provide an overview of state-of-the-art in WPT and backscatter modulation in order to face the above technical challenges. Section II highlights the definition and the importance of backscatter. Section III shows the first approach for the passive sensor
using ASK modulation with measured results. Section IV describes the approach used for the
16-QAM RF circuit design and the final solution for the QAM backscatter implementation.
Section V presents the simulated and experimental results as well as the achievable data rates
obtained for the implemented backscatter modulator. Finally, we conclude the work in Section
VI.

II. BACKSCATTER CIRCUITS REVISITED

The idea of communication by means of reflected power was revisited in development of
an animal tracking system that involved into a robust design for automated tracking of railway
trains [9]. The use of backscatter as a low-power communication means is possible due to the
capability of supplying the remote device by the continuous wave (CW) signal emitted from the
reader.

Backscatter systems were first used in the late 1990s-early 2000s with the advent of single-
chip UHF RFID tags. The first designs were battery-free devices that used RF-to-DC converters
to supply system DC power and employed modulated backscatter to transfer ID information
[10]. Some recent work, shows the possibility to transfer data and continuously deliver power to
the sensor by using two different frequencies, one to supply the sensor and the other to transfer
data by backscatter means [7].

To understand the principle of backscatter, a schematic is shown in Fig. 4 where a current
flowing on a transmitting antenna leads to a voltage induced on a receiving antenna. In the
figure there are two different cases to analyse. In the first case, the smallest possible load (short
circuit), is shown that connecting the antenna to a load leads to an induced current on the
receiving antenna. The radiated wave can make its way back to the transmitting antenna, induce
a voltage, and therefore, produce a signal that can be detected: a backscattered signal. In the
second case, the largest possible load (open circuit), is shown that little or no induced current
will result, that leads to negligible backscattered wave. Therefore, the signal on the transmitting
antenna depends on the load connected to the receiving antenna [11].

A backscatter RFID system relies on the wireless communication between an RFID reader
and a backscatter tag [12]. A schematic of the backscatter communication system with emphasis
on the RFID tag is depicted in Figure 1. The wireless communication link between the RFID
reader and the backscatter tag can be divided into a forward link and a backward link. In the
forward link, the RFID reader transmits RF power and data to the tag. In the backward link,
whenever a reader command requires a tag’s response, the tag starts its data transfer using a modulated backscatter signal, i.e., the signal from the reader is reflected by the tag depending on the transmitted data. Typically, some tags achieve their data transmission by changing the properties of the tags themselves, while others switch a load resistor in and out of the antenna circuit and the reflected signal switches between two states, representing a logical ‘0’ and ‘1’.

Over short ranges, the amount of power reaching the tag from the reader is sufficient to allow operation of small low current circuits within the tag. This can be used to drive an electronic switch, e.g. a FET that can switch an antenna load resistor in and out of circuit. This will effectively modulate the returned signal and allow data to be passed back to the reader.

The limitation of such a system is that the read range is reduced and the data rate is low. In this work, an high order backscatter modulator is implemented in order to overcome these limitations.

### III. Passive Sensor with ASK Modulation Backscatter Capabilities

Fig. 2 presents the block diagram of the proposed system. This system is composed by two main blocks, which are the backscatter modulator (switch transistor) and the RF harvesting circuit with a power management unit. The main objective of the RF harvesting block is to generate
Our proposed system was based on the circuit presented in [6] and it is illustrated in Fig. 5. The circuit includes a switch transistor to modulate the impedance of the antenna and causes a change in the reflection coefficient. It also includes a five-stage Dickson multiplier to maximize the dc output voltage collected and RF Schottky diodes (SKYWORKS, SMS7630-006LF) were used to obtain a sufficient dc output power to supply the microcontroller to modulate the information acquired from an external sensor, by means of switching ON and OFF the transistor (ASK modulation).

Fig. 5. a) Configuration of the proposed system. b) Photograph of the proposed system.

Fig. 6. Block diagram of the measurement setup
employed. The designed matching network has an important role in this circuit, since it needs to be designed for the backscatter load modulation in one frequency and for the continuous energy beam for the WPT in other frequency. The frequency selected for the communication was 2.3 GHz and for the WPT was 1.6 GHz.

Fig. 6 presents the block diagram of the measurement setup used to acquire the reflection wave from our proposed circuit. We used a vector signal generator (ROHDE&SCHWARZ, SMW200A) to generate 1.6 GHz and 2.3 GHz. At the output of the vector signal generator we used a power combiner (Mini-Circuits, ZFRSC-183-S+) to combine 1.6 GHz and 2.3 GHz to the input of the power amplifier. A coupler (Marki, CBR16-0012) was used to measure the reflected backscattered
signal, using a signal analyzer (ROHDE&SCHWARZ, FSQ). A waveform generator (Agilent, 3325OA) was used to switch the transistor’s gate voltage to provide the backscatter modulation.

Fig. 8 represents the distance at which it is possible to supply the microcontroller and the sensors for different values of transmitted power. The reflected wave from the backscattered wave is illustrated in Fig. 7, which is the sensor subcarrier. The measures were made for the frequency of 1.6 GHz (WPT) and 2.3 GHz (Backscatter).

IV. QAM BACKSCATTER MODULATOR

In most RFID systems and passive sensors, the reader to tag communication is an 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 proposal presented in this manuscript follows the same approach as in [6] and Fig. 2, combining WPT with a higher order backscatter modulation format, by designing an RF circuit that is able to be replicated to include more modulation levels. In this work a novel strategy will be proposed in order to increase the modulation order to 16-QAM, by using the transistor model to create different backscatter impedances.

Backscatter radios are based on the reflected waveform that should switch between a fully matched and short circuit solution built on a switch that is directly connected to the receiving/transmitting antenna of the sensor. For a higher level modulation format, the number of different backscattered waves should change among several states, thus the switch combinations should clearly create a specific impedance for that symbol combination.

Fig. 9 presents the design for the 16-QAM solution. This 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 respect to each other, so as to allow that the reflected wave from each branch has 90° phase difference from the other. Equation 1 shows the reflected wave as a sum of both reflected waves from each branch. Using (2) and (3) is possible to determine the reflection coefficient of the model for different impedances.

\begin{equation}
    b = \frac{b_1}{\sqrt{2}} + \frac{b_2}{\sqrt{2}} = \frac{a_1 \Gamma_1 e^{j \frac{\pi}{2}}}{\sqrt{2}} + \frac{a_2 \Gamma_2}{\sqrt{2}}
\end{equation}

\begin{align}
    \Gamma_1 &= \frac{R_1 - Z_0}{R_1 + Z_0}; \quad \Gamma_2 = \frac{R_2 - Z_0}{R_2 + Z_0}
\end{align}
\[ \Gamma = \frac{b}{a} = \frac{\Gamma_1}{\sqrt{2}} e^{j \frac{\pi}{4}} + \frac{\Gamma_2}{\sqrt{2}} \Rightarrow \Gamma = \frac{\Gamma_2}{2} + j \frac{\Gamma_1}{2} \] (3)

Considering two different values for each resistance (0 or \( \infty \)) we obtain four different combinations with four different reflection coefficients:

- \( R_1 = 0 \) and \( R_2 = 0 \) \( \Rightarrow \Gamma = -\frac{1}{2} - j \frac{1}{2}; \)
- \( R_1 = 0 \) and \( R_2 = \infty \) \( \Rightarrow \Gamma = \frac{1}{2} - j \frac{1}{2}; \)
- \( R_1 = \infty \) and \( R_2 = 0 \) \( \Rightarrow \Gamma = -\frac{1}{2} + j \frac{1}{2}; \)
- \( R_1 = \infty \) and \( R_2 = \infty \) \( \Rightarrow \Gamma = \frac{1}{2} + j \frac{1}{2}. \)

Fig. 10 presents the previous reflection coefficients in the smith chart.

A similar reasoning can be used to create any type of multi-level higher order modulation. In order to do that, arbitrary real impedances could be used, instead of the 0 and \( \infty \) impedance. Thus different impedances are implemented using an active load based on a transistor, one example is presented in Fig. 11, where different impedances were used in the scheme presented in Fig. 9, the impedances were 0 \( \Omega \), 10 \( \Omega \), 100 \( \Omega \) and 300\( \Omega \).

The last approach can be extended, where the load presents different impedance values, consider for instance a, b, c and d real impedances. The impedances are then matched with the overall circuit using a two branch approach and a microstrip line scheme, were each branch imposes a specific delay. By combining these two degrees of freedom, 16 impedance levels can be created. Equation 4 was deduced, where R represents the four different impedances in one branch and Q represents the four impedances in the other branch. It was based on Fig. 12 and presents sixteen possibilities of impedances from \( a/\phi + a/\theta \) to \( d/\phi + d/\theta \), using all combinations.
Fig. 10. Simulation of the model for 4-QAM solution

Fig. 11. Simulation of the model for 16-QAM solution

\[ X = R \phi + Q \theta \] (4)
Fig. 12. Block diagram for different impedance terminations

Fig. 13. Photograph of the QAM backscatter circuit

Fig. 13 illustrates the differences of line length in each branch, which are related to 45° phase shift. By using this approach, the circuit in Fig. 13 was designed and each transistor is switched for different voltage levels to achieve different reflection coefficients.

V. RESULTS

Fig. 14 presents the photograph of measurement setup used to acquire the reflection coefficient from our proposed circuit, illustrated in Fig. 13. We used a power supply and a Performance Network Analyzer (PNA) (E8361C, from Agilent Technologies) that was calibrated at 0 dBm for the frequencies from 2 GHz to 3 GHz. The results of the simulations and measurements are presented in Fig. 15 and in Table I are presented the different reflection coefficients for different voltages at the transistor. Table I shows also the simulated and experimental voltage levels used to obtain the matching between the reflection coefficients. The switches were changed according to the simulated results, with different voltage levels at each gate of transistor. Table I shows different voltage levels for simulated and measured results, due to the models used for the transistor.
Fig. 14. Photograph of measurement setup

Fig. 15. Simulated and measured S11 for different voltage levels at the gate of each transistor for 2.45 GHz at 0 dBm
Fig. 16. Simulated S11 for different voltage levels (from 0 V to 0.6 V with a step of 0.01 V) at the gate of each transistor for 2.45 GHz (a) Pin = -10 dBm. (b) Pin = 0 dBm. (c) Pin = 5 dBm.

In order to give more precise and accurate results in real scenario applications we present Fig. 16, which can be seen that for higher input power levels the constellation will be more
difficult to implement. For lower input powers it is possible to obtain 16-QAM as in Fig. 16b. Fig. 16 presents the simulated results optimized for 0 dBm. The results could be improved for higher input power levels if the circuit was optimized for that levels.

A. Demodulation and potential data rates

![Diagram](image)

Fig. 17. Block diagram of measurement setup for demodulation and achievable data rates.

The maximum data rate of the communication on the modulator link was studied and evaluated by using the measurement setup presented in Fig. 17. This measurement setup was used to view the received constellation at multiple transmission rates. A vector signal generator (ROHDE& SCHWARZ SMJ 100A) to generate the transmitter signal at 2.45 GHz was used. An arbitrary waveform generator (TEKTRONIX AWG5012C) was used to generate the different voltage levels at the gate of each transistor. The voltage levels presented in Table I were applied into the gate of each transistor and 16 different impedances were generated and analyzed in the signal & spectrum analyzer. The received constellations are shown in Fig. 18 for bit rates of 8 Mb/s, 24 Mb/s and 80 Mb/s. The constellation points lie in the appropriate quadrants, and each point is clearly visible. In order to perform better results, the system can be calibrated by changing the gate voltage level.
Fig. 18. Received 16-QAM constellation for a center frequency of 2.45 GHz for different data rates. (a) 8 Mb/s. (b) 24 Mb/s. (c) 80 Mb/s.
Fig. 19 shows the final implementation of the system, combining the QAM backscatter modulator with WPT. This solution presents a potential performance improvement when compared with conventional battery-powered wireless sensors network, because it eliminates the need of battery replacement or recharging. Using WPT reduces the operational cost and increase the communication performance. Since the wireless sensors need to harvest enough energy before sending data, with this solution it is possible to overcome these limitations by achieving continuous power delivery and increase the communication performance. The solution uses two different frequencies, one for WPT and the other for the QAM backscatter modulation and therefore it will have an important role in many popular commercial and industrial systems in the future of IoT systems.

![Fig. 19. Final block diagram of WPT with 16-QAM backscatter modulator](image)

VI. CONCLUSIONS

Tags employing vector backscatter modulations guarantee higher data throughput while running at a lower on-chip clock frequency, reducing on-chip power consumption and extending read range. Tags that employ an M-ary modulation can achieve $\log_2 M$ higher data throughput at essentially the same dc power consumption as an ASK or PSK tag.

With the solution proposed it was shown that the combination of WPT and backscatter can provide a continuous power flow to the wireless sensor. This way the sensors can be continuously powered during the operation mode.
The solution now presented combined with a WPT scheme can actually be used to increase bit rate in fully passive WSN and be one of the enablers of the IoT paradigm. It was described a modulation technique that enables a high-bandwidth wireless communication while requiring very low power demands. This solution can be combined with WPT for ultra low-power wireless applications requiring high bandwidth communications such as remote camera sensors or wireless audio.

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