

Base-Station Design for Passive UHF RFID Tags with Pulse-Width Modulated Backscattering

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Abstract—In this work, a base-station design is proposed for passive UHF RFID tags that use pulse-width modulation (PWM) in backscattering communication. The theoretical analysis of the PWM backscattering is presented along with the challenges it creates in the base-station design. The self-jamming issue in the base station is analyzed with a numerical case study. The theoretical analysis of the reverse communication channel is presented. A method is proposed for wired backscattering measurements, which models the path loss and reflection from the tag eliminating the need for wireless measurements in an anechoic chamber. It is shown by measurements that the base-station is capable of measuring the pulse-width of the backscattered signal with an error less than 1% at a distance of 2 meters.

Index Terms—Radio frequency identification (RFID), passive RFID, remote powering, UHF, backscattering, base-station

I. INTRODUCTION

The integration of sensors with passive UHF RFID tags extends the application of RFID technology to many new fields such as environmental monitoring, healthcare, and food quality monitoring [1]. It has been shown that phase-locked loop (PLL) based sensor interfaces can be used in RFID tags with capacitive sensors to reduce the power consumption of the tags [1].

In [1], a novel method is proposed for tag-to-reader communication, where the backscattering signal is pulse width modulated. The duty-cycle of the pulse-width modulated signal carries the information about the capacitance value of the sensing element on the tag. This type of RFID tag requires a dedicated base-station design.

The biggest issue in RFID base-station design for passive tags is the carrier leakage from transmit to receive path. In order to have a long operating range, the transmitter emits the maximum power that is allowed by the regulations. This full-power carrier creates a self-jamming signal at the center of the receiver bandwidth, which is much more powerful compared to the received back-scatter signal from the RFID tag.

In order to overcome the self-jamming problem, one approach is to separate the transmit path from the receive path by using two antennas [2]. The transmit-receive isolation depends on the coupling between the two antennas. It is obvious that in order to have a better isolation, the antennas should be placed

far away from each other. The separation should be more than two wavelengths to eliminate near-field coupling.

Another approach to overcome the self-jamming problem is to use an isolating element between the transmit and receive paths, while using a single antenna. The isolating element can be a circulator or a directional coupler. In this work, the aim is to design a base-station for passive UHF RFID tags with sensors, which use pulse-width modulation (PWM) for tag-to-reader communication. In order to have a more compact base-station, the single antenna approach is chosen. A circulator is used to isolate the transmit path from the receive path. Section II gives an overview and theoretical analysis of the PWM based backscattering communication. The self-jamming issue and the reverse communication link is explained along with the design of the base station in Section III. The implementation is explained and the measurement results are presented in Section IV and the results are discussed in Section V.

II. PWM BASED BACKSCATTERING

In [1], a PLL-based capacitive sensor interface is used. The output of the sensor interface is a pulse train whose duty cycle is proportional to the variation in the sensor capacitance value. The pulse train signal controls the backscattering switches that short the antenna terminals. This way the sensor value information is pulse-width modulated and sent to the base-station (reader) by backscattering. In contrast to the standard RFID systems where the information is digitized for tag-to-reader communication, PWM approach is analog in nature.

Figure 1 shows a pulse train, in other words, a square wave of amplitude A with arbitrary duty cycle, $d = k/T$, with the pulse width k , and period $T = 1/f$. This pulse train can be stated as a sum of sine and cosine waves using the well-known Fourier synthesis equation:

$$x(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(2\pi ftn) + \sum_{n=1}^{\infty} b_n \sin(2\pi ftn) \quad (1)$$

The dc component a_0 , and the amplitudes of the cosine and

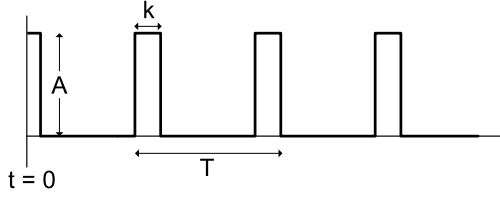


Fig. 1. The pulse-train, i.e., a square wave with an arbitrary duty-cycle $d = k/T$, period T , and amplitude A .

sine waves, a_n and b_n , can be calculated as:

$$a_0 = Ad \quad (2)$$

$$a_n = \frac{2A}{n\pi} \sin(n\pi d) \quad (3)$$

$$b_n = 0 \quad (4)$$

Consider two pulse trains with duty cycles d and $1-d$ (e.g. 20% and 80%), the amplitudes of the cosine waves for the two signals will be:

$$a_n(d) = \frac{2A}{n\pi} \sin(n\pi d) \quad (5)$$

$$a_n(1-d) = \frac{2A}{n\pi} \sin[n\pi(1-d)] \quad (6)$$

Rearranging (6) using the trigonometric identity yields:

$$a_n(1-d) = \begin{cases} \frac{2A}{n\pi} \sin(n\pi d) & \text{if } n \text{ is odd,} \\ -\frac{2A}{n\pi} \sin(n\pi d) & \text{if } n \text{ is even.} \end{cases} \quad (7)$$

$$(8)$$

$$= \begin{cases} a_n(d) & \text{if } n \text{ is odd,} \\ -a_n(d) & \text{if } n \text{ is even.} \end{cases} \quad (9)$$

This shows that, in order to discriminate between square waves with complementing duty cycles, e.g. 20% and 80%, we need to have the second and even the fourth harmonics in the receiver. That condition puts forward a larger bandwidth requirement for the receiver. Note that the dc component cannot be used due to the transmit leakage.

III. BASE-STATION DESIGN

The base-station for passive RFID systems has three main functions: 1) remote powering the passive RFID tags, 2) sending the commands, i.e., reader-to-tag communication, 3) receiving the backscattered information from the RFID tags, i.e., tag-to-reader communication. In this work, the tags are "always ON," i.e., they start operating and sending back the sensor readout as long as there is enough power at the tag. Hence, the reader-to-tag communication is out of the scope of this work.

In order to have a compact base-station, the single antenna approach is chosen in this work. The transmit and the receive paths are isolated by using a circulator. The circulator is a critical component in the base-station because the amplitude of the self-jamming signal depends on the isolation performance of the circulator.

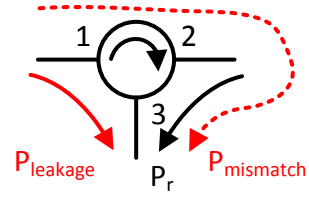


Fig. 2. The components of self-jamming signal shown around the circulator. $P_{leakage}$ is the signal power leaked through the isolation path of the circulator, $P_{mismatch}$ is the signal power that is reflected back from the base-station antenna due to mismatch, and P_r is the power of the received modulated wave backscattered from the tag.

A. Self-jamming

Figure 2 shows the two components of the self-jamming. First one is the power leaked through the isolation path of the circulator, denoted as $P_{leakage}$. The second one is due to the mismatch between the circulator and the antenna. The carrier wave that is reflected back from the antenna input port passes through the circulator, whose power is denoted as $P_{mismatch}$. These two self-jamming components are added to the received signal (received modulated signal power denoted by P_r) and fed into the receiver.

Commercial antennas have reflection coefficients between -10 dB and -20 dB, which results in a relatively large $P_{mismatch}$. The reflection coefficient of the base-station antenna used in this work is -24 dB at 866 MHz [3].

The signal power at the input of the receiver can be written as:

$$P_{in} = P_r + P_{leakage} + P_{mismatch} \quad (10)$$

If we denote the output power of the power amplifier as P_{PA} and the reflection coefficient of the antenna in dB as $S_{11,ant}$, the leakage and mismatch components can be expressed in dB as:

$$P_{leakage} = P_{PA} - |S_{31,circ}| \quad (11)$$

$$P_{mismatch} = P_{PA} - |S_{11,ant}| - |S_{32,circ}| \quad (12)$$

where $S_{31,circ}$ is the isolation of the circulator from port 1 to port 3 and $S_{32,circ}$ represents the loss in the circulator from port 2 to port 3, i.e., the insertion loss. The insertion loss of the circulator can be neglected since it is generally very small.

B. The reverse link

The power received at the base-station scattered from an RFID tag in the far-field can be written using the classical radar equation as [4]:

$$P_{received} = P_{eirp} G_b \frac{\lambda^2}{(4\pi)^3 r^4} \sigma \quad (13)$$

where P_{eirp} is the radiated power from the base-station antenna, G_b is the base-station antenna gain, λ is the wavelength, and r is the distance between the base-station and the RFID tag, and σ is the radar cross-section of the RFID tag. In this formulation, the polarization losses and the multi-path effects are ignored.

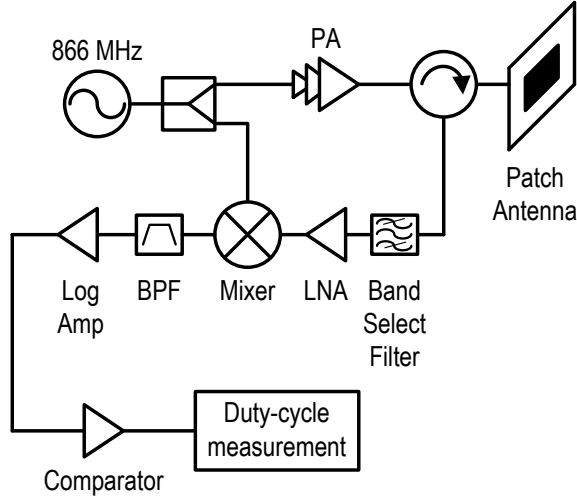


Fig. 3. The block diagram of the base-station.

If the RFID tag is backscattering by modulating the impedance at the antenna inputs, the modulated power received at the base-station can be expressed as:

$$P_r = P_{eirp} G_b \frac{\lambda^2}{(4\pi)^3 r^4} \Delta\sigma \quad (14)$$

where $\Delta\sigma$ is the differential radar cross-section of the tag.

The radar cross-section of the tag can be expressed by using the Thevenin equivalent circuit of the RFID tag as [5]:

$$\sigma = \frac{\lambda^2 G_t^2 R_a^2}{\pi |Z_a + Z_c|^2} \quad (15)$$

where G_t is the gain of the tag antenna, $Z_a = R_a + jX_a$ is the complex antenna impedance, and $Z_c = R_c + jX_c$ is the complex input impedance of the tag chip.

The power radiated from the base-station, P_{eirp} , can be calculated as:

$$P_{eirp} = P_{PA} (1 - |S_{11,ant}|^2) G_b \approx P_{PA} G_b \quad (16)$$

neglecting the insertion loss of the circulator. For a well matched antenna ($|S_{11,ant}| < -20 \text{ dB}$), the $1 - |S_{11,ant}|^2$ term might be omitted for simplification. Thus, inserting (16) in (14) yields:

$$P_r = P_{PA} G_b^2 \frac{\lambda^2}{(4\pi)^3 r^4} \Delta\sigma \quad (17)$$

C. Case study

The maximum allowed power in the 865.6-867.6 MHz European ISM band is 3.3 W e.i.r.p (35.2 dBm). and the base-station antenna is a 50 Ω planar patch antenna with 3.6 dBi gain at 866 MHz [3]. Hence, the output of the power amplifier is 31.6 dBm when the maximum allowed power is transmitted from the base-station. Commercially available circulators can achieve 30 dB isolation. Putting in the values for the circulator

isolation and the reflection coefficient of the antenna yields:

$$P_{leakage} = 31.6 \text{ dBm} - 30 \text{ dB} = 1.6 \text{ dBm} \quad (18)$$

$$P_{mismatch} = 31.6 \text{ dBm} - 24 \text{ dB} = 7.6 \text{ dBm} \quad (19)$$

The larger of these two components will be dominant in the self-jamming signal: in this case $P_{mismatch}$ is dominant. In other words, the circulator isolation itself doesn't guarantee low self-jamming signal if the antenna input reflection coefficient (S_{11}) is not low enough.

D. Transmit

The block diagram of the base-station is given in Fig. 3. The transmit section of the base-station consists of the signal source, the power splitter, the power amplifier, the circulator, and the antenna. The signal source generates the carrier signal at 866 MHz. The signal is then split into two by the power splitter, one half being fed to the power amplifier while the other is fed to mixer in the receiver. The base-station antenna emits the electromagnetic wave for the RFID tags. The passive RFID tags are powered up by the electromagnetic wave power emitted by the base-station. The regulations put a limit on the maximum RF power that can be emitted from the base-station. The phase noise of the signal source is also a critical parameter that affects the quality of reverse communication link.

E. Receive

The receive section of the base-station consists of the antenna, the circulator, the band-select filter, the low-noise amplifier (LNA), the down-converting mixer, the bandpass filter, and the logarithmic amplifier. The modulated backscattering signal from the tag is collected by the base-station antenna and fed into the receiver through the circulator. In order to filter out the unwanted parts of the electromagnetic spectrum, a band-select filter is used, which helps preventing the LNA from saturation. The filtered signal is amplified by the LNA and down-converted to DC by the mixer, in a direct conversion fashion. The reason to use this architecture is the large self-jamming signal present in the receiver. The log-amp saturates due to the self-jamming signal if it is used directly after the LNA. It is easier to filter out the self-jamming signal at the output of the mixer, since it basically creates a DC offset. A band-pass filter (BPF) filters out the DC offset, passing the wanted part of the signal to the log-amp, whose output is amplified by a comparator. Finally, the duty-cycle of the signal is measured.

The large self-jamming signal creates problems in this architecture. The LNA and the mixer can saturate due to the self-jamming signal. One method to decrease the amplitude of the self-jamming signal is to use a high-gain antenna and decrease the output power of the PA.

IV. IMPLEMENTATION AND MEASUREMENTS

The base-station is implemented according to Fig. 3 using commercially available components. Figure 4 shows the circuit that is used in the measurements to model the path loss and the

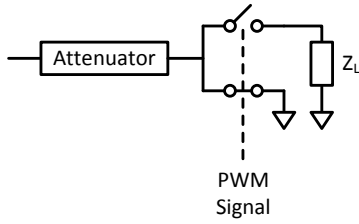


Fig. 4. The circuit that is used in measurements to model the path loss and the backscattering from the tag.

backscattering from the tag. An attenuator is used to mimic the path loss.

The value of attenuation is selected to model the path loss at 2 meters, taking into account the gain of the base-station antenna. As seen in (17), the received power is a function of the square of the base-station antenna gain. Hence, the value of attenuation can be calculated in dB as:

$$P_{att} = P_{Loss} - 2 \cdot G_b \quad (20)$$

where P_{att} is the value of the attenuation, and P_{Loss} is the path loss in free space. The required attenuation is calculated to be 30 dB.

The backscattering from the tag is modeled using a waveform generator and an RF switch. The PWM signal from the waveform generator controls the RF switch, which changes the load seen by the cable between short circuit and the impedance Z_L . The difference in the electromagnetic power reflection from the tag for the high and low states of the PWM signal is calculated and the value of Z_L is adjusted accordingly so that the change in the power reflection from the circuit between the two states is the same as the difference in the electromagnetic power reflected from the tag.

The duty-cycle of the PWM signal controlling the RF switch is swept from 20% to 80% with 5% steps and the duty-cycle is measured five times at each step at the base-station. Figure 5 shows the error in each measurement and the average measured duty-cycle at each step plotted with respect to the actual duty-cycle of the control signal. Measurements show that the base-station can measure the duty-cycle with an error less than 1%.

Figure 6 shows example voltage waveforms recorded during the measurements for a 100 kHz PWM signal with 35% duty cycle. The output of the logarithmic amplifier is shown along with the output of the comparator.

V. CONCLUSION

A base-station design is proposed for passive UHF RFID tags that use pulse-width modulation (PWM) in backscattering communication. The self-jamming problem is critical in the base-station design. It is shown theoretically that amplitude of the self-leakage signal depends on the circulator isolation and the reflection coefficient of the base-station antenna. The architecture of the proposed base-station which is designed for a single-antenna is presented. A circuit based on an attenuator

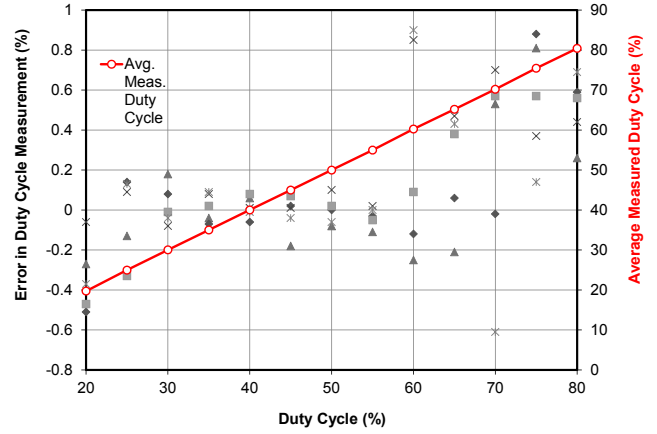


Fig. 5. The results of the duty-cycle measurements. The error in each measurement and the average measured duty-cycle are plotted with respect to the actual duty-cycle of the control signal which is swept from 20% to 80% with 5% steps.

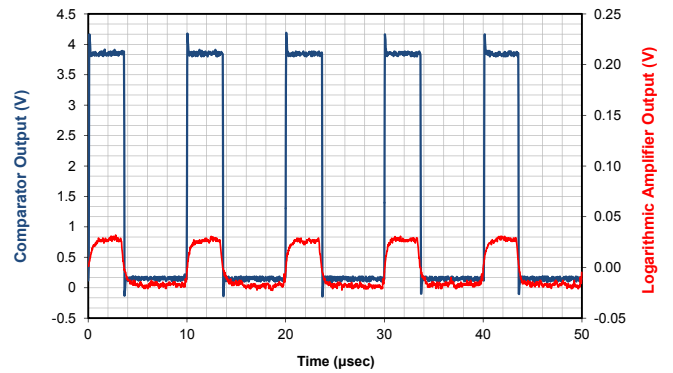


Fig. 6. The measured voltage waveforms at the output of the log-amp (red) and at the output of the comparator (blue) for a 100 kHz PWM signal with 35% duty-cycle. The 50 mV_{p-p} signal at the output of the logarithmic amplifier is amplified to a rail-to-rail signal by the comparator.

and an RF switch is used in measurements to model the path loss and reflection from the tag. Measurement results show that the base-station is capable of measuring the pulse-width of the backscattered signal with an error less than 1% from a distance of 2 meters.

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