Vector Backscattered Signal Analysis of Piggyback Modulation for Passive UHF RFID Tags

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Abstract — We describe a “piggyback modulation” technique to integrate sensing functions with existing standard passive UHF RFID tags through electromagnetic coupling. Instead of focusing on the scalar backscattered power that is proportional to the radar cross section (RCS), we present vector analysis and measurement for backscattered signals with piggyback modulation. Measuring both amplitude and phase of the backscattered wave makes advanced demodulations possible. Quasi-4-QAM demodulation is proposed to reduce the interferences between two independent data streams and improve the bit error rate. The measurement setup, experimental results, and demodulation analysis for the conventional ASK and quasi-4-QAM are presented.

Index Terms — piggyback modulation, UHF RFID, sensor, backscattering, vector signal analysis, ASK, quasi-4-QAM.

I. INTRODUCTION

Over the last decades, radio-frequency identification (RFID) technology has been developed to provide simple and economical solutions for wireless identification and data access. It is widely applied in diverse fields, such as supply chain, access and control, healthcare, and real time location system (RTLS) [1]. Recently, demands of wireless sensing and the success of RFID inspire attempts to integrate a variety of sensors and RFID technologies. Promising markets, like cold chain management, military surveillance and tracking, and environmental monitoring, make “RFID sensing” one of the most emerging RFID-based applications.

Piggyback modulation enables addition of small, inexpensive sensors to existing UHF RFID passive tags [2]. The RCS of a UHF RFID tag is used to measure the backscattered power from a tag and it has been commonly treated as a scalar parameter for amplitude shift keying (ASK) modulation. The viability of the piggyback modulation, the proof-of-principle experiments, and the transfer function connecting the sensing signal and the scalar backscattered signal strength were presented [3]. However, the input impedances of the ASIC and the PIN diode modulator are complex numbers and hence the piggyback sensor modulates both amplitude and phase of the signal. A quasi-4-QAM demodulation scheme is proposed to use both amplitude and phase to recovery signals modulated by two independent sources, a tag ASIC and a sensor.

In this paper, the vector backscattered signal is measured, analyzed, and demodulated in ASK and quasi-4-QAM. The principle and design of the piggyback modulation is illustrated in Section II. Section III addresses the basics of backscatter from a passive tag and address the analysis of backscattered signals with piggyback modulation. The measurement setup for both amplitude and phase of the backscattered signal and the experimental results of signals with piggyback modulation are presented in Section IV. The analysis and the BER performance comparison of the ASK demodulation and quasi-4-QAM demodulation are reported in Section V.

II. PIGGYBACK MODULATION

For a passive tag, the application-specific integrated circuit (ASIC) of the tag switches its input impedance between two states to modulate the RCS of the tag antenna. Piggyback modulation technique uses the same principle: the voltage controlled sensor coupling module manipulates the RCS by varying the effective input impedance of the tag antenna.

The two signal sources, a tag ASIC and a sensor, operate independently and simultaneously to modulate the backscattered wave through wireless coupling by simply attaching a sensor coupling module. Wireless sensing is realized to use the existing channel between RFID readers and tags by piggybacking the data from sensors on top of the identification data stream without any circuit-level integration.

The coupling mechanism that is the bridge for sensor data transmission is implemented by attaching the coupling loop to a tag with a small gap as shown in figure 1. The modulation is employed by two independent sources, the tag ASIC though a
conductive connection and the additional sensor through the piggyback modulator. RCS is a scalar value with dimension of area as a measure of how detectable an object is and it is used to detect the piggybacked signals in the traditional ASK demodulation scheme by differentiating four levels in amplitudes.

However, the bit error rate (BER) performance could be improved if the demodulation is performed by taking both amplitude and phase into account. Based on this idea, a quadrature amplitude modulation (QAM) backscatter method is proposed to reduce the BER, transmit more bits per symbol, and use the bandwidth more effectively [7].

Without attaching the sensor coupling module, the vector backscattered signal from a tag has two states representing bit ‘0’ ($V_0$) and ‘1’ ($V_1$), as shown in Fig. 3. Having the sensor coupling module on top of the tag adds four vectors representing the mixed bits, ‘11’ ($V_{S1[11]}$), ‘01’ ($V_{S2[01]}$), ‘10’ ($V_{S3[10]}$), and ‘00’ ($V_{S4[00]}$). Both the amplitude and phase of the backscattered signal are modulated by simultaneously switching the complex input impedances of the two independent sources. For example the received vector backscattered signal of state 1 is $V_1 + V_{S1[11]}$. Compared with the traditional ASK demodulation scheme for signal detection, employing quasi-4-QAM demodulation for the vector backscattered signal reduces the interferences between two independent data streams and improves the bit error rate.

### III. VECTOR BACKSCATTERED SIGNAL

The “vector backscattered signal” is used to describe the backscattered signals in both amplitude and phase. For most of the passive tags, either the ASK or the phase shift keying (PSK) is selected to modulate the backscattered wave, since Gen2 standard readers are regulated by the EPCglobal UHF Class-1 Generation-2 air interface protocol to fully perform demodulation for both of these two formats. To demodulate signals backscattered from tags that adopt ASK/PSK modulation, only the amplitude/phase is detected while the other one is discarded even though both of them are modulated by switching two complex input impedances of the tag ASIC.

Figure 2. Digital signal waveform from the ASIC and the sensor; each of the four states represent four different “mixed bits”.

### IV. MEASUREMENT SETUP AND EXPERIMENTAL RESULTS

The measurement setup and the experimental results for the vector backscattered signals with piggyback modulation are presented in this section.

#### A. Measurement Setup

To capture all of the four different vectors, the tag ASIC needs to be awakened by receiving a Gen2 standard forward link signal that contains request commands. In the previous measurement setup, a reader is used to awake and communicate with a tag attached with the sensor coupling module and an antenna of the vector signal analyzer (VSA) system receives both of the forward link and return link signals.

Figure 4. Schematic diagram of the measurement setup.
Nonetheless, what is measured is not backscattering because the reader antenna and the receiving antenna of the VSA system cannot be exactly collocated. In addition, it is difficult to measure signals at one fixed carrier frequency since readers are designed to produce carrier frequency hopping around within 902-928 MHz. The isolation and the synchronization between the RFID reader and the VSA system are needed but not usually provided.

The measurement setup is modified and the schematic diagram is indicated in Fig. 4. The key improvements are listed below:

- No RFID reader is needed; the “forward link” signal is generated by a vector signal generator to awaken the tags.
- It is a true backscattering measurement; one single antenna completes both signal transmission and reception.
- The carrier frequency is controllable and fixed to a specific one, 915 MHz in this case.
- The isolation between the RFID reader and the VSA system is around 25 dB which is determined by the reflection coefficient of the antenna.
- The forward link signal generator and the VSA system are well synchronized with rms phase error less than 1 degree; thus the phase measurement is viable.

B. Experimental Results

The experimental results of the vector backscattered signals with piggyback modulation in the time domain are encouraging. AD-222 is used as the commercial passive UHF RFID tag and it is attached with the sensor coupling module fed by an emulated sensor signal, \( V_s \), a 5 kHz square waveform between 0 and 600 mV. The carrier frequency is set at 915 MHz. Four states of the vector backscattered signal are represented by four magnitude levels of the amplitude and four locations in the constellation diagram, as shown in Fig. 5 (a) and (b).

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<tr>
<td>I [mV]</td>
<td>610</td>
<td>606</td>
<td>606</td>
<td>590</td>
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<tr>
<td>Q [mV]</td>
<td>-31</td>
<td>-7.5</td>
<td>-40</td>
<td>-39</td>
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Table 1. The measurement of the vector backscattered signal at 915 MHz.

V. ANALYSIS OF DEMODULATION SCHEMES

In this section, we present three demodulation schemes: the split two-level ASK demodulation, the four-level ASK demodulation, and the quasi-4-QAM demodulation.

In the split two-level ASK demodulation, the signal detection will be processed individually for the ASIC data stream and the sensor data stream. While performing the ASIC signal demodulation, a threshold is set to distinguish “high” and “low” and the sensor signal is treated as noise. Therefore the BER of the ASIC data stream is dramatically deteriorated when increasing frequency or amplitude of the piggybacking signal, as shown in [3]. Besides, a low pass filter is needed to recovery the waveform of the sensor signal, which normally has lower bit rate, before the demodulation.

The problem of the interference between two signals could be solved by performing the four-level ASK demodulation or the quasi-4-QAM demodulation. In these two demodulation schemes, signals are treated as a whole and categorized into one of the four states according to their amplitude or the locations in the constellation diagram without need for a low pass filter. To extract two data streams from the piggyback modulated signal using four-level ASK demodulation, only the amplitude detection is required. On the other hand, the quasi-4-QAM demodulation needs to acquire both of the amplitude and the phase of the piggyback modulated signal.
Figure 6. Monte-Carlo simulation of BER versus SNR for a coupled sensor tag. ASIC/sensor signal refers to demodulation of the ASIC/sensor signal part of the coupled sensor tag response. The bit rate ratio of the ASIC signal and the sensor signal is 5.

Typical digital modulation schemes, like 4-QAM, have all the symbols located around the origin of the constellation diagram while the backscattering modulation pulls the symbols far from the origin because its nature makes the strength of the return link signal diminutive compared with the leakage forward link signal. Therefore, to achieve the same BER performance, the backscattering modulation requires much higher SNR than other typical digital modulation schemes.

A BER performance comparison of these two demodulation schemes for the actual experimental results is done by Matlab simulations. The measured amplitude and the coordinate for each state, as listed in Table 1, are imported and used in the Monte-Carlo simulation. The AWGN channel model is used and minimum distance detection is applied. In the four-level ASK detection scheme, the decoded symbol is chosen as the symbol which has the closest amplitude to the received signal. In the proposed quasi-4-QAM demodulation scheme, the distance is measured in the two dimensional complex domain which exploits both magnitude and phase information.

In Fig. 6, the simulation result shows that the BER performance of the quasi-4-QAM demodulation is better than that of the four-level ASK demodulation for both signals. The bit rate ratio of the ASIC signal and the emulated sensor signal is set as 5 in this case. As a result, the emulated sensor signal is superior to the ASIC signal in terms of BER no matter which demodulation scheme is used. In general, RFID tag reply error rate below 20% requires BER less than $10^{-3}$ [8], and for typical systems achieve 99% reliability with BER of $10^{-5}$ [9]. The quasi-4-QAM demodulation scheme provides sufficient BER for common applications, while the BER performance of the four-level ASK demodulation is inferior.

VI. CONCLUSION

In this paper, the vector backscattered signal is measured, analyzed, and demodulated in both ASK and quasi-4-QAM schemes. The principle of the piggyback modulation and the basics of the backscatter from a passive tag are addressed. The measurement setup for both amplitude and phase of the backscattered signal is modified. Based on the experimental results, we demonstrate the analysis and BER performance comparison of the ASK demodulation and quasi-4-QAM demodulation in Matlab simulations.

ACKNOWLEDGEMENT

The authors acknowledge support from the NSF-PFI grant (0650321) “PFI Partnership for Innovation in Wisconsin’s Packaging and Printing Industry Cluster.”

REFERENCES