Channel Emulation for the Characterization of Wearable RFID Systems

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***Abstract*—Wearable sensors with RFID (Radio Frequency Identification) tags are considered to be an integral part of the upcoming revolution in the IoT (Internet of Things) sector. As with many deployed IoT sensor systems, dynamic environment conditions present challenges in reliably measuring system performance; this difficulty is enhanced due to proprietary details about the sensors, such as an RFID chip embedded within a novel knitted antenna acting as a passive sensor. A repeatable and scalable platform is necessary to evaluate the performance of the entire system in the pre-deployment stage in order to compare the predicted effects of varying components, design, and integration of sensors in an integrated IoT device. This paper demonstrates the development of an RFID channel emulation testbed in the United States ISM band (902-928 MHz). The testbed includes a commercial RFID interrogator, a custom-built circuit board housing a commercial passive RFID chip, and a dynamic spectrum environment emulator (DYSE) for wireless channel emulation. A single link scenario was considered where the DYSE emulates the antenna gain fluctuation due to the sensing of breathing with a fabric-based RFID. Two regular and one irregular breathing scenarios were emulated, and breathing rate or anomaly was detected from post-processed RSSI (Received Signal Strength Indicator) data received by the RFID interrogator.**

***Index Terms*—RFID channel emulation, RSSI (Received Signal Strength Indicator), DYSE (Dynamic Spectrum Environment Emulator)**

I. Introduction

RFID (Radio Frequency Identification) tags are an integral part of IoT (Internet of Things) systems. In general, Radio Frequency Identification (RFID) tags are characterized in an anechoic [1] or reverberation chamber [2]. However, an anechoic environment only allows the line-of-sight component of the radiated power. Although reverberation chambers offer multipath components, repeatability is still a matter of concern, mostly when the tag is in motion. Moreover, a large warehouse or hospital environment cannot be created in a reverberation chamber. This difficulty motivates the development of a repeatable, scalable, and compact method for the performance evaluation of RFID tags, even in the worst environments. While there has been some work in RFID channel emulation [3–5], previous testbeds are only capable of considering single tag and single interrogator environments with simple single-tap communication channels.

On-body wearable RFID presents a good opportunity for the use of channel emulation because while there have been prototypes reported in the literature; development of this technology is challenging due to the inability to separate out effects from the antenna, human body and underlying behavior being monitored, as well as the radio frequency propagation environment. For example, Patron et al. [6] and Liu et al. [7] presented wearable “bellyband” antennas for monitoring the breathing rate of an infant or uterine activity in a pregnant woman. Bellyband is a folded dipole structure made from knitted conductive yarns. A small PCB (Printed Circuit Board) equipped with an RFID chip is inserted into the pocket of the bellyband structure. The PCB helps to maintain a firm connection between the chip and the antenna. The bellyband antenna is designed in a way that its impedance is conjugate matched to the chip impedance when the flexible structure is stretched (100mm × 20mm). Moreover, the radiation efficiency of the antenna is higher in the stretched state [8]. On the other hand, the antenna has impedance mismatch with the chip at relaxed (81mm × 20mm) state and the radiation efficiency is comparatively lower. The dual effect of impedance mismatch and radiation efficiency is known as the “realized gain”:

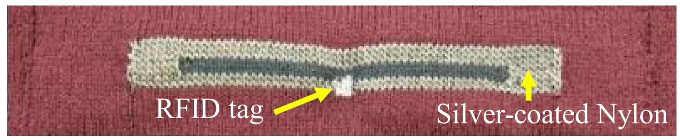

Fig. 1: Bellyband antenna [6]. The conductive part of the antenna is made from silver-coated nylon.

$$G_{\mathrm{r}} = \eta_{\mathrm{rad}}\ (1 - \Gamma^2) \tag{1}$$

where η_{rad} is the radiation efficiency (%) and Γ is the reflection coefficient due to the impedance mismatch between the chip and the antenna. The continuous stretching and flexing of the bellyband antenna results in a periodic realized gain, which in turn causes fluctuation in RSSI (Received Signal Strength Indicator). Raw RSSI shows the power level of the pulse train encoded by the chip. As a result, it is important to smoothen the raw RSSI using the moving average. The smoothed RSSI data can be used to determine breathing rate, uterine activity or unusual breathing pattern. As an on-body antenna, the bellyband is supposed to undergo dynamic environments (e.g. sweat, moisture, friction, elastic fatigue, etc.), and it is important to perform an experimental study of these scenarios. Machine learning and signal processing algorithms have been developed to extract and fuse features of the chip’s reflected RF [9]; however, it remains a challenge to compare learning and signal denoising approaches without a

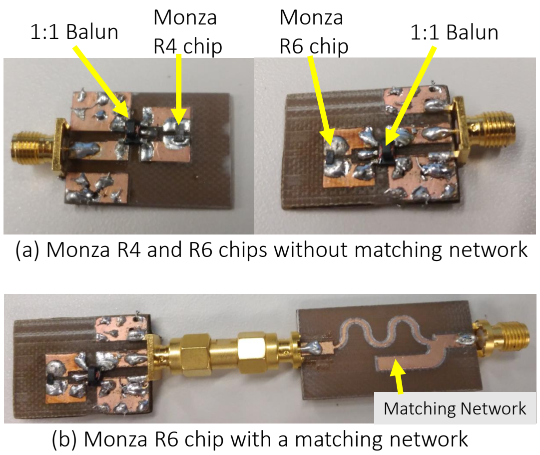

Fig. 2: Hardware setup of the emulation board, with and without a matching network.

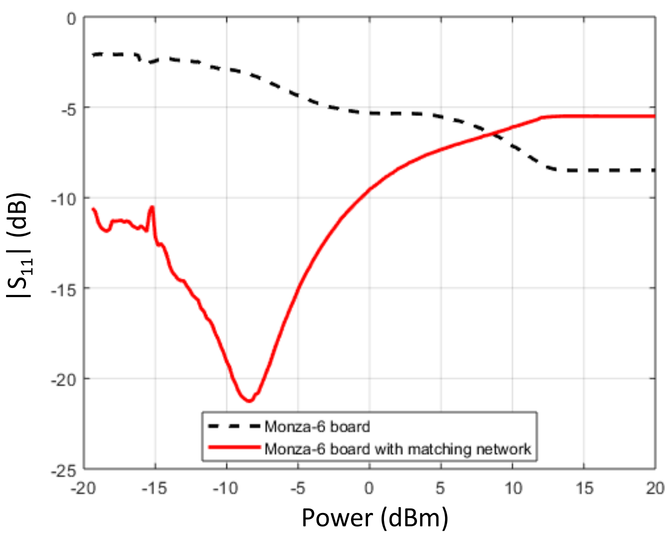

Fig. 3: S_{11} vs input power for monza-6 emulation board.

theoretical baseline signal under an idealized environment with the same biological processes. Moreover, It is not feasible to stretch the antenna by the same amount while experimenting with different tags. Channel emulation is a strong tool in this regard to evaluate tag performance and compare different tags under a completely repeatable channel. The emulation setup is easily scalable for emulating multiple readers and/or tag scenarios.

Winkler et al. [4] and Arthaber et al. [3] have developed a channel emulation system for the playback of measured link scenarios. They used an LC matching network at the wake-up power level of the chip. Abdelmalek et al. [5] proposed an RFID channel emulation platform to test the robustness of a system. To the authors' knowledge, our work is the first report of RFID channel emulation for wireless on-body sensors. Furthermore, our testbed is built on the flexibility of software defined radio (SDR) and is scalable to potentially enable testing of a multi-tag, multi-interrogator scenarios with multi-tap signal and interference channels. The paper is organized as below: section II shows the hardware and experimental testbed

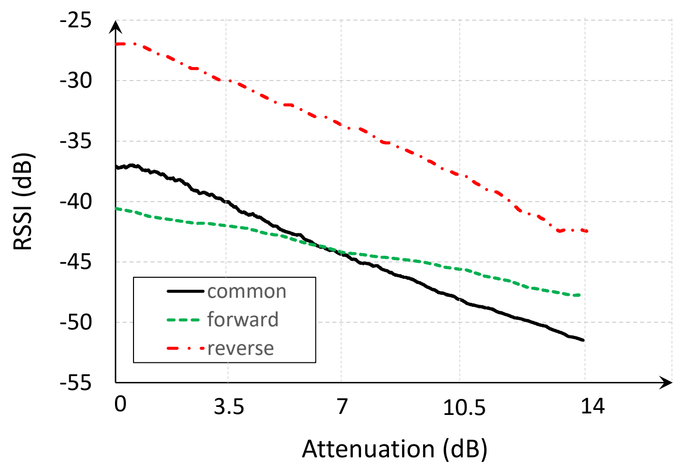

Fig. 4: RSSI vs attenuation in three channel configurations (forward, reverse, and common channel).

for channel emulation, section III explains the measurement results, and section IV concludes this work.

II. RFID Channel Emulation Testbed

A. DYnamic Spectrum Environment Emulator (DYSE)

Channel emulation enables unique real-world scenarios to be evaluated in a controllable and repeatable manner with physical hardware. The Echo Ridge DYnamic Spectrum Environment Emulator (DYSE) [10] is used to provide time-varying channel characteristics to the interrogator. DYSE allows for highly scalable studies, with up to 24 systems under test capable of being used as both transmitters and receivers as described in [11].

B. Emulation Board Hardware

The RFID emulation board is fabricated on an FR4-based rectangular PCB structure (Fig. 2). The structure is simple and convenient for emulation work. The RFID chip is equipped with two external metal pads that are electrically 180° apart. On the other hand, coaxial cables are unbalanced structures, and a balanced to unbalanced (balun) converter is needed in between, without a change in impedance (1:1 ratio). Finally, a 3.5mm SMA connector is attached to the end. Similar structures are built for Monza R4 and R6 tags (Fig. 2a). The input impedance of the emulation board is not matched to 50Ω.

The reflection coefficient (S_{11}, the ratio between the reflected power and the input power) of the emulation board is measured at different power levels using the network analyzer. The power available to the tag is given by:

$$P_{\text{av}} = P_{\text{port}} + 10\,\log_{10}(1 - |S_{11}|^2) - P_{\text{loss}} \qquad (2)$$

where, P_{port} (dB) is the power incident at the SMA port, and P_{loss} (dB) is the combined power loss in the balun and the microstrip line. The S_{11} for the emulation board using a monza-6 RFID chip is shown in Fig. 3.

Ideally, there should be a matching network connected to the structure. However, the RFID chip is a passive device that is

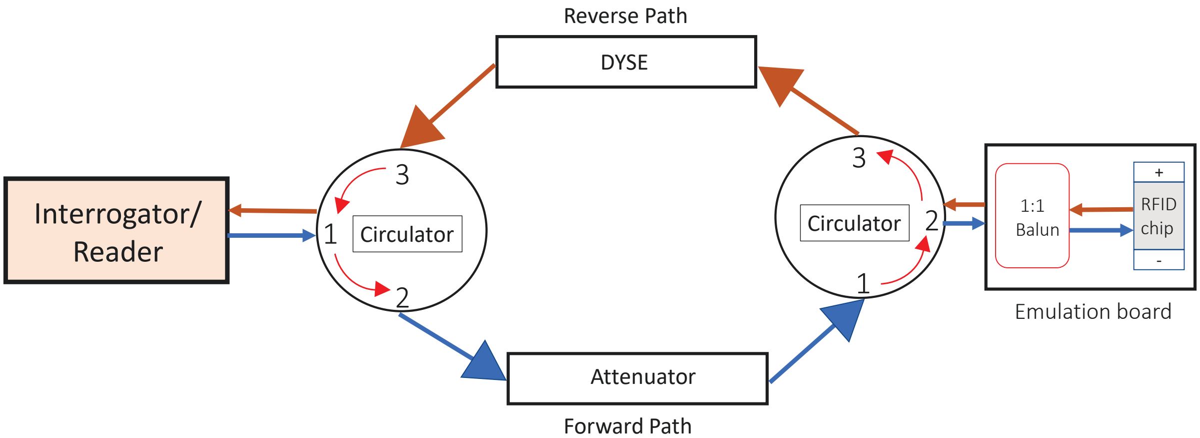

Fig. 5: Emulation of the reverse channel with DYSE.

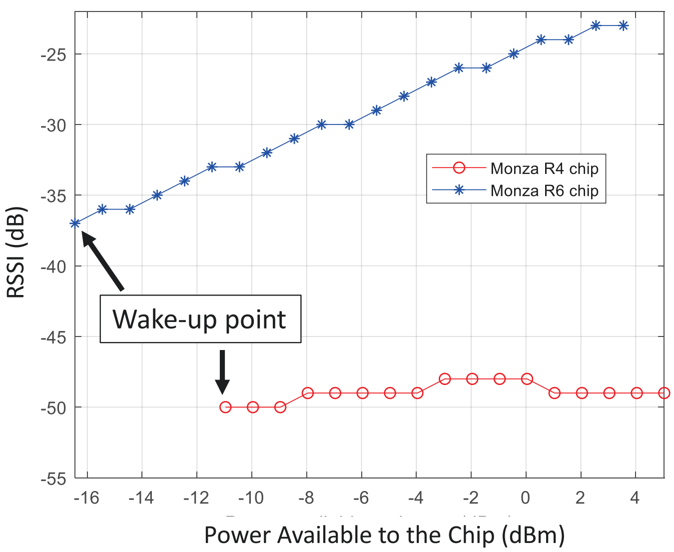

Fig. 6: RSSI vs available power for emulation boards equipped with Monza R4 and R6 chips.

dependent on power from an external reader/interrogator. The radar cross-section (RCS) of the chip changes with the power available to the chip. In other words, the chip reflects extra energy by changing its impedance. That means the impedance of the chip (or the emulation board) is a function of the available power (Fig. 3). We build a matching network for a certain level of input power (-8 dBm), and observe that the tuning is sharply deteriorated as the available power is being increased (Fig. 3). To alleviate this issue, we discard the matching network and compensate for these effects in post-processing using equation 2.

C. Experimental Setup

The experimental setup for the emulation of the reverse channel is shown in Fig. 5. A Speedway-r420 [12] interrogator is used to generate the modulated signal as well as receive the back-scattered signal. The forward and reverse channels are separated using two circulators. The three-port circulators allow RF power flow anti-clockwise from port 1 to 2, 2 to 3, and 3 to 1; not in the other direction (clockwise). As a result, they are good candidates for applications where wired RF channels need to be separated. Forward and reverse-path attenuations are controlled by a radio frequency switch matrix. There are three emulation scenarios:

1) Forward channel emulation (fixed attenuation on the reverse channel),
2) Reverse channel emulation (fixed attenuation on the forward channel), and
3) Common channel emulation (variable and equal attenuation on both channels).

We emulate all three scenarios for an attenuation range of 0 dB to 14 dB. As the intended application of the RFID tag is based upon the fluctuation of RSSI, we emphasize the RSSI trend with increasing attenuation rather than true RSSI values. Fig.4 shows that reverse and common channel emulation exhibit a similar slope, while forward channel emulation is different. From this experiment, we conclude that it is equivalent to emulate the common channels and the reverse channel. The major advantage is that the reverse channel offers an increased dynamic range compared to its forward counterpart. The forward channel is limited by the power received by the tag. The chip doesn't respond if the power reaching it is lower than its sensitivity. The absence of a robust matching network makes the situation more challenging by initializing unwanted reflection. In a realistic wireless setup, generally the forward and reverse paths are the same. The sensitivity of the Monza R6 tag is -16 dBm, and the sensitivity of the reader is around -80dBm. That means the forward path (reader to tag) is the bottleneck. Another advantage of using the reverse channel for emulation is that the DYSE has a maximum power handling capacity of around -15 dBm, which is similar to the sensitivity of Monza-6 chip. As a result, the forward channel cannot be emulated with the our channel emulator without risking damage.

D. Breathing Scenario Emulation

The bellyband antenna [6, 7] is simulated with HFSS (High-Frequency Structure Simulator). Breathing or uterine activity is sensed from the fluctuation of antenna gain, which in

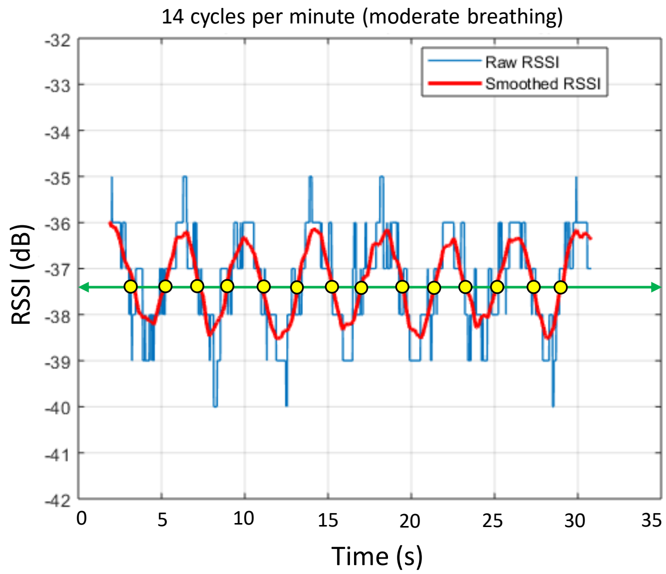

Fig. 7: Reverse-path RSSI measured during an emulation of 15 cycles per minute breathing rate. The horizontal line at center shows the final average of smoothed RSSI. The small circles on that horizontal line indicate instances of smoothed RSSI crossing the final average line.

turn makes the RSSI fluctuate. Around 3 dB fluctuation is observed between two states (inhale and exhale). Using this information, we create different radio frequency scenario files in our emulator with 3dB fluctuation in attenuation, where the temporal spacing between max/min points indicates the breathing rate.

III. Results and Discussion

A. Tag Sensitivity

Different RFID chips respond differently in terms of RSSI as a function of available power. A higher slope is better for sensing applications based upon RSSI fluctuation. Fig. 6 shows the relationship between the RSSI and the power available to the tag for Monza R4 and R6 chips on the emulation board. It is evident that Monza R6 has lower sensitivity (lower wake-up power) than the R4. Additionally, Monza R6 is highly sensitive to a change in available power. From our experiments, we find that Monza R4 and R6 series of tag chips have -11 dBm and -16 dBm sensitivity (wake-up power) respectively.

B. Breathing Rate from RSSI Fluctuation

RSSI fluctuates as the DYSE is emulating bellyband antenna gain fluctuation on the reverse channel. On average, adults have a breathing rate between 12 to 18 cycles per minute [13]. Fig. 7 demonstrates RSSI fluctuation for a moderate breathing pattern. As the raw RSSI follows the modulation trend, it must be smoothed by utilizing moving average. Fig. 8 emulates an emergency situation where the patient is breathing at 15 cycles per minute rate for 30 seconds and stops breathing for 10 seconds, and finally resumes breathing again. These kinds of situations demand immediate intervention by a physician or nurse.

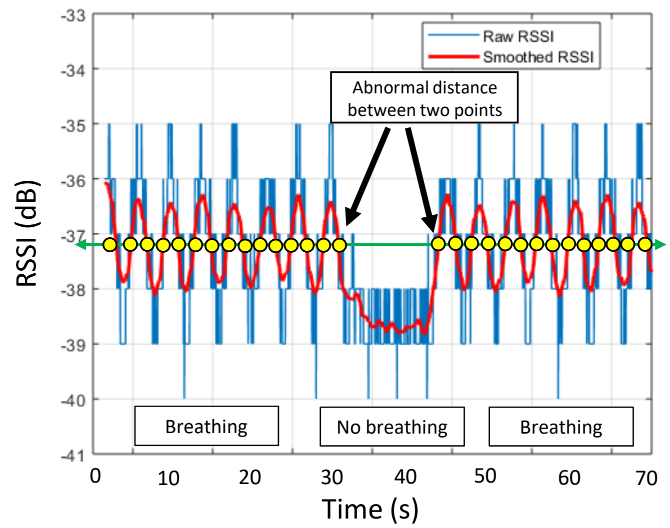

Fig. 8: 10 seconds of no breathing between 15 cycles per minute. A significantly larger delay between two zero crossings would detect the abnormality in the breathing pattern and immediately generate a warning signal.

IV. Conclusion

This work shows the development of an RFID channel emulation platform in the ISM band (902-928 MHz) with a DYnamic Spectrum Environment Emulator (DYSE). A single link comprised of an interrogator (reader) and an emulation board with Monza R6 tag is used to demonstrate the RSSI fluctuation over time which mimics the breathing of an infant or uterine activity in a pregnant woman. Post-processing of the raw RSSI is done to extract information about breathing rate or abnormality in the pattern. The elimination of a chip-specific matching network makes the emulation process faster when different types of chips are juxtaposed for performance evaluation and comparison. Future work will include: multiple reader/tag scenarios, tag localization (using phase information), tag movement tracking (by utilizing Doppler), emulation in different multipath environments, and integration with site-specific simulators.

Acknowledgement

This research is supported by the National Science Foundation under Grant CNS-1816387, the Department of Education Graduate Assistance in Areas of National Need (GAANN) program under award P200A180082, and the National Institutes of Health under Grant R01-EB029364. Any opinion, findings, and conclusion or recommendations expressed in this materials are those of the author(s) and do not necessarily reflect the reviews of the National Science Foundation, Department of Education, or the National Institutes of Health.

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