Experimental Demonstration of Transmit Diversity for Passive Backscatter RFID Systems

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***Abstract*—Passive, backscatter radio frequency identification (RFID) systems are often range limited by the power incident on the radio frequency (RF) tag. We have demonstrated an increase in the power incident on the RF tag using transmit diversity in a monostatic backscatter channel. Transmit diversity was achieved by phase conjugating the forward link of the backscatter channel associated with each reader antenna. The resulting increase in incident power will increase the range of passive backscatter systems and improve performance in fading environments.**

I. Introduction

The range of passive, backscatter radio frequency (RF) tags are often limited by the power that can be delivered to the RF tag [1], [2]. For an RF tag at a given distance from the reader, the power delivered to the RF tag's integrated circuit is limited by path loss, multipath fading, detuning, and absorption by the tagged object.

Since most RF tag readers operate near the maximum equivalent isotropic radiated power (EIRP) allowed by regulation, simply increasing the reader's transmit power or antenna gain is not a solution for range extension. Alternative methods include designing tag integrated circuits that have a lower minimum voltage threshold; using power-optimized waveforms [2], [3]; using additional continuous wave (CW) transmitters [4]; or employing higher gain antennas on the RF tag. In this paper, we demonstrate the use of another method, transmit diversity, to increase the power delivered to the RF tag in a 5.82 GHz backscatter system using a monostatic reader.

Transmit diversity [5], time-reversal [6], and beam forming are closely related concepts as each seeks to create the coherent addition of signals from multiple antennas at a particular spatial location or in a desired direction. Time reversal is based on the fact that if t is replaced with $-t$ in a solution to Maxwell's equations, the result is another valid solution that propagates in the opposite direction [7]. Time-reversal techniques can be exploited to achieve spatial focusing (even super resolution focusing in high multipath environments [7]) by transmitting a time-reversed copy of the signal such that it propagates back to the source [6]. Beamformers can steer the antenna beam by adjusting the beam-forming coefficients to achieve coherent addition of signals in a particular direction in open space. When multipath is present, however, it is often more useful to think in terms of transmit diversity, where the transmitted signal is often precoded by the complex conjugate of the channel in order to mitigate multipath fading [5, pg. 236]. In fact, conjugating the channel phase is the frequency domain equivalent of time reversal [7].

While most work on time reversal, beam forming, and transmit diversity have focused on conventional transmitter-to-receiver channels, some have applied it to backscatter systems. Ingram *et al.* used simulations to show a bit error rate improvement by choosing the optimal beam forming coefficients for a transmit and receiver array in a backscatter system operating in a fading environment [8]. Others have applied maximal ratio diversity combining at the RF tag reader receiver to mitigate multipath fading on the signal from the RF tag [9]. Several authors have proposed or demonstrated blind beamforming for RFID readers; Angerer *et al.* [9] provide several references. As an example of phase conjugation for RFID, a grounded, coplanar-waveguide, retro-reflective antenna array designed for an RF tag operating at 26 GHz was presented by Vitaz *et al.* [10]. Transmit diversity used for the purpose of increasing the power at the RF tag has received less attention, but is a potential solution that will allow RF tags to operate reliably and with greater range in multipath environments.

This paper is organized as follows: Section II presents the theory for transmit diversity in a monostatic backscatter channel, Sections III through V describe the measurement setup and results, and the paper is concluded in Section VI.

II. Backscatter Transmit Diversity

The backscatter channel can be divided into two links: the *forward link* which accounts for propagation from the reader transmitter to the tag, and the *backscatter link* which accounts for propagation from the tag to the reader receiver, as shown in Fig. 1. The static, narrowband, baseband backscatter channel between a single reader transmitter antenna, RF tag antenna, and reader receiver antenna can be written

$$\tilde{y}(\vec{r}) = \tilde{h}^b(\vec{r})\tilde{\Gamma}(t)\tilde{h}^f(\vec{r})\tilde{x}, \quad (1)$$

where $\tilde{y}(\vec{r})$ is the baseband output of the receiver; $\tilde{x}$ is the baseband representation of the continuous wave (CW) transmitted signal; $\tilde{\Gamma}(t)$ is the reflection coefficient at the tag

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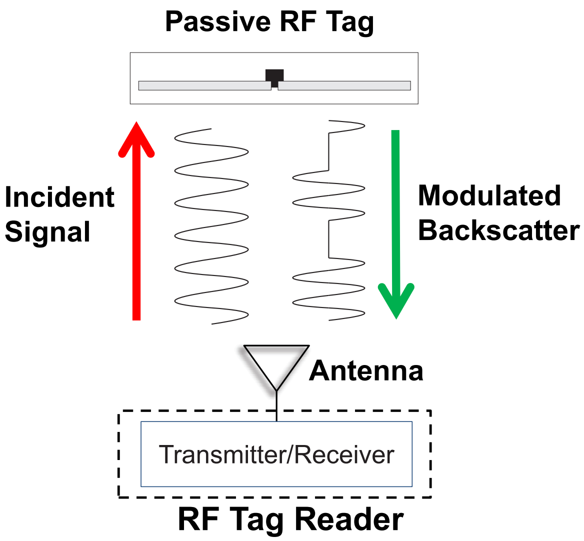

Fig. 1. A block diagram showing the forward and backscatter link between a monostatic reader and RF tag.

antenna terminals; and $\tilde{h}^f(\vec{r})$ and $\tilde{h}^b(\vec{r})$ are the baseband channel coefficients of the forward and backscatter links, respectively. Transmit diversity requires that the forward channel $\tilde{h}^f(\vec{r})$ between each reader transmitter antenna and the RF tag be known. According to (1), if the transmitted signal $\tilde{x}$ and the reflection coefficient $\tilde{\Gamma}(t)$ of the RF tag are known, then the product of the forward and backscatter links $\tilde{H}$ can be extracted from the measured signal. $\tilde{H}$ is defined as

$$\tilde{H} = H \exp(j\theta) = \tilde{h}^f(\vec{r})\tilde{h}^b(\vec{r}), \tag{2}$$

where H and θ are the magnitude and phase delay of the complete backscatter channel, respectively.

In the general case of a bistatic reader, separating the forward and backscatter links is challenging because the relationship between the two links depends on link correlation [9], [11]. For a monostatic reader, since the links are fully correlated, it can be assumed that the forward and backscatter links are the same. Therefore, in this paper, it is assumed that $|\tilde{h}^f(\vec{r})| = \sqrt{H}$ and $\angle\tilde{h}^f(\vec{r}) = \theta/2$.

III. Experimental Setup and Procedure

Transmit diversity for backscatter RFID systems was verified through experimental measurements using a backscatter system purchased from Southern States, LLC. The block diagram of the measurement setup is shown in Fig. 2 and a photograph in Fig. 3. The setup can be best explained in terms of the transmit (TX) and receive (RX) paths. In the TX path, the transmitter signal was fed through a 4-way splitter to the four IQ vector modulators (Herley Vector IQ Modulator 7122) which allow control of both the signal's attenuation and phase. Each modulator was controlled by the computer through the parallel port. The output of each modulator was connected to the TX/RX antenna through a microwave circulator (Pasternack PE8402). After propagating through the forward link of the channel, the electromagnetic wave impinged on the tag where it was modulated with a maximal-length, pseudo-random code (127 bits in length); backscattered; and received at the reader.

In the receive path, the backscattered electromagnetic wave was routed to the receiver through the circulators. The baseband I and Q signals from the receiver were fed to the digitizer (ADLINK PXI-9816H), which provided the receiver data to the computer to calculate the phase of the backscattered signal. The phase of the forward link was computed as described in Section II. To keep the receiver in the linear region of operation, appropriate attenuation was induced in the IQ modulators, and attenuators (not shown in Fig. 2) were added between each circulator and TX/RX antenna and between each circulator and receiver.

Backscatter RF tag operation was emulated using a patch antenna, a microwave switch (Minicircuits CSWA2-63DR+), and a function generator (Agilent 33521A) capable of generating the maximal-length, pseudo-random code.

To measure the phase of the backscatter channel, a signal was transmitted from one antenna of the reader array at a time by attenuating the unused TX/RX paths by approximately 50 dB compared to the radiating antenna. The phase of each TX/RX path was measured using a single, direct-conversion receiver that was individually connected to each TX/RX signal path. The IQ modulator for each measured channel was set to an equal phase shift with 16 dB attenuation. The digitized data was processed in Matlab to obtain the phase θ of the backscatter channel for each reader antenna. Once the phase of the backscatter channel for each reader antenna was measured, transmit diversity was applied by setting the phase of each IQ modulator to $-\theta/2$ while maintaining a constant attenuation of 16 dB.

After measuring the phase of each channel and applying transmit diversity, the next step was to verify its effectiveness through measurements. To measure the power increase at the tag caused by transmit diversity, we first measured the spatial power distribution without transmit diversity – i.e., each IQ modulator was set to the same attenuation (16 dB) and phase shift (zero relative phase shift between each antenna branch). The spatial power distribution was measured for 870 different locations using a spectrum analyzer connected to the RF tag antenna which was mounted on a linear positioner (from Velmex), shown in Fig. 3. After recording the spatial power distribution without transmit diversity, the next step was to apply transmit diversity for a specific target tag location using phase conjugation as described in Section II. The spatial power distribution with transmit diversity applied was measured in exactly the same way as for the spatial power distribution without transmit diversity.

IV. Results

The spatial distribution of the incident power without transmit diversity (equal attenuation and zero degree relative phase shift between the antenna branches) and with transmit diversity for each location of the measurement grid are shown in Fig. 4 and Fig. 5, respectively. After applying transmit diversity, a

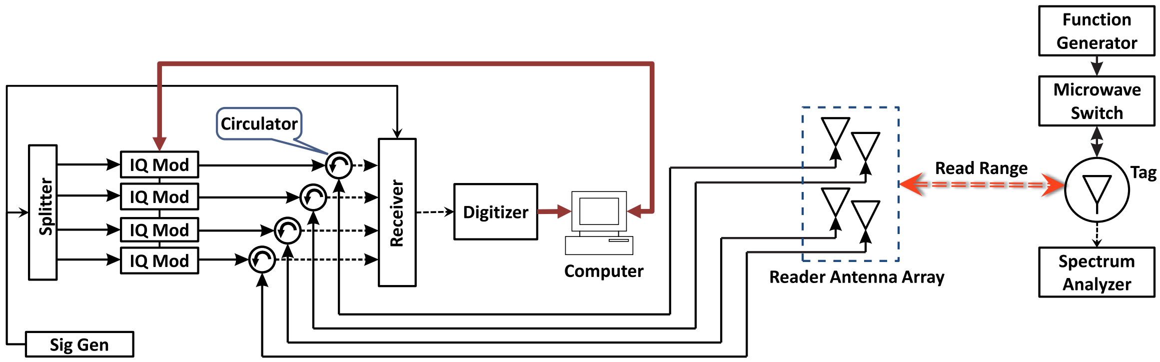

Fig. 2. A block diagram of the experimental setup used for the transmit diversity measurements.

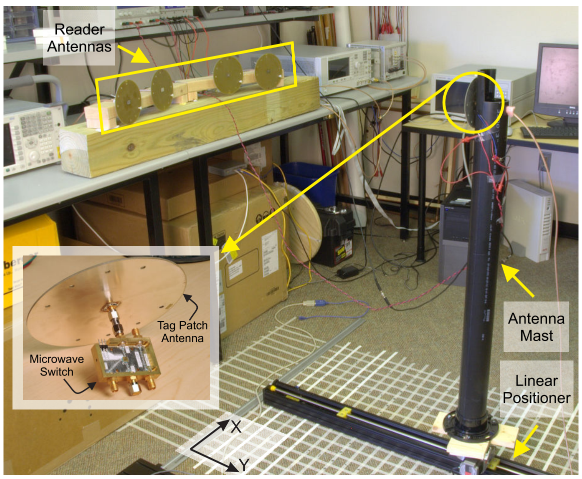

Fig. 3. The experimental setup showing the tag antenna mounted on a plastic support and linear positioner, the reader antenna array, and the measurement grid indicating the X and Y directions.

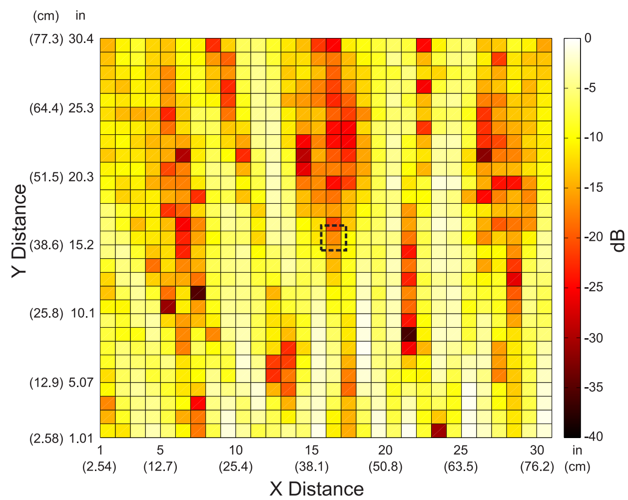

Fig. 4. This plot shows the power distribution in front of the reader antenna array *without* transmit diversity – i.e., the attenuation and phase delay of each antenna branch was the same. The coloring of each square represents the normalized power measured at the x - y location corresponding to the lower left corner of the square. The power was normalized to the maximum power measured in Figures 4 - 5 for an equal comparison. The target RF tag position used for transmit diversity in Fig. 5 is outlined by the black box.

considerable change in the fading pattern of the forward link is observed in Fig. 6. The normalized incident power measured along the X and Y directions is plotted in Fig. 7 and Fig. 8, respectively. Coherent addition of signals was achieved at the tag location using transmit diversity and a 15 dB gain was observed.

V. Discussion

Our results show that it is possible to increase the power at a target location through a backscatter channel using transmit diversity. The measured power gain of 15 dB at the target location is specific to this location and channel because the difference in power with and without transmit diversity at a particular target location will depend on the level of fading present before transmit diversity is applied. In general, using transmit diversity with M antennas will give a power gain of M compared to a single radiating antenna in open space (i.e., no multipath) or compared to the average power in the local area channel (assuming the phases of the multipath components are uncorrelated) [5], [7].

Although four antennas were used in this measurement, it is possible, in principle, to improve the tag performance with at least two antennas; however, greater spatial focusing can be achieved by adding more antennas and/or multipath. The proposed method does not require that the antennas be carefully spaced, as required by a phased array; although some arrangements may yield better performance than others.

The backscatter system used for these measurements did not provide perfect phase measurements nor could the IQ modulators provide the exact phase shift requested. We estimate the peak-to-peak phase error for each IQ modulator to be less than 4 degrees and the maximum measurement error of the complete backscatter system to be less than 16.3 degrees with a standard deviation of 7.5 degrees.

Potential applications for transmit diversity include using backscatter tags for radio frequency identification (RFID) or as backscatter sensors in the presence of people or where the tags cannot be confined to a portal. If sufficient multipath is present and an adequate number of reader antennas are used, transmit diversity will provide spatial focusing that may help

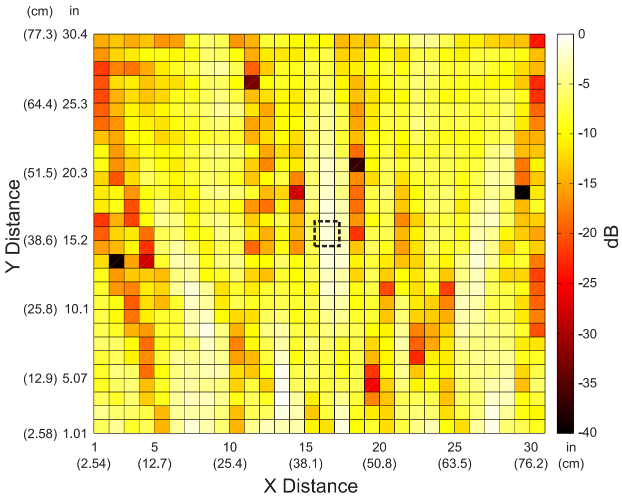

Fig. 5. This plot shows the power distribution in front of the reader antenna array *with* transmit diversity for the target location outlined by the black box. The coloring of each square represents the normalized power measured at the x - y location corresponding to the lower left corner of the square. The power was normalized to the maximum power measured in Figures 4 - 5 for an equal comparison.

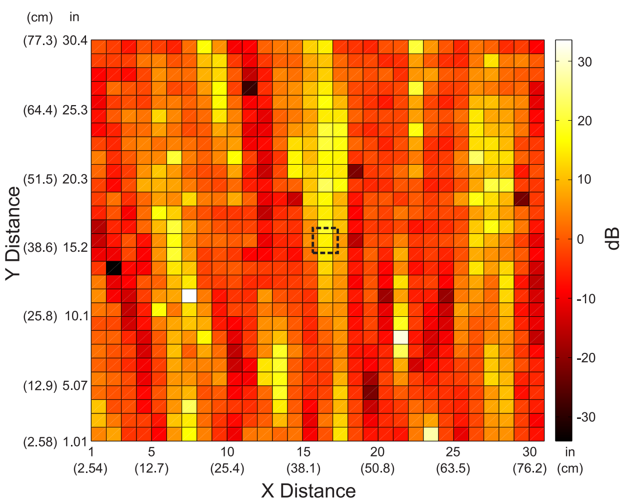

Fig. 6. The normalized power with transmit diversity (from Fig. 5) minus the normalized power without transmit diversity (from Fig. 4) in the decibel scale. The target RF tag location is outlined by the black box. The coloring of each square represents the power difference measured at the x - y location corresponding to the lower left corner of the square.

alleviate data collisions because fewer tags will be turned on [12]. Of course, the forward link of the backscatter channel must be measured for transmit diversity to be applied which requires that communication be established with the RF tag. Therefore, transmit diversity may best be used in situations where communication is established with the tag when the reader-to-tag separation distance is small and then increased or in time-varying, multipath channels where the tag may be powered on and then loose power unexpectedly. If the channel is sampled at a rate higher than that of the channel fluctuations, then coherent addition of signals at the RF tag can be maintained as the tag is moved or as the channel fluctuates.

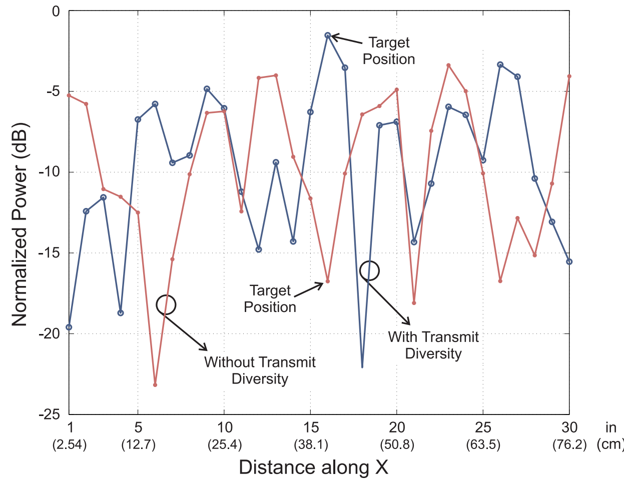

Fig. 7. The power (dB), normalized to the maximum measured in Figures 4 - 5, with and without transmit diversity along the X direction with Y equal to 40.6 cm. An improvement of approximately 15 dB with transmit diversity can be observed at the target location.

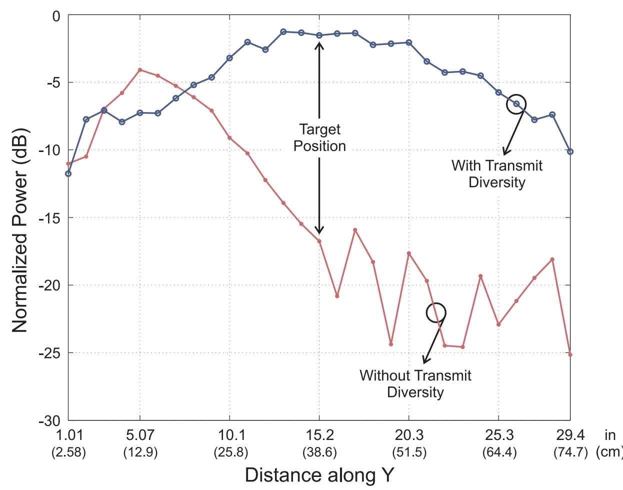

Fig. 8. The power (dB), normalized to the maximum measured in Figures 4 - 5, with and without transmit diversity along the Y direction with X equal to 38.6 cm. An improvement of approximately 15 dB with transmit diversity can be observed at the target location.

VI. Conclusion

We have presented transmit diversity measurements for a passive, monostatic backscatter RFID system at 5.82 GHz. With transmit diversity applied through phase conjugation, an approximately 15 dB improvement was observed in the incident power at the tag location. The spatial power distribution pattern was recorded with and without transmit diversity in an area of 76.2×74.7 cm around the target location. The fading pattern changed considerably with transmit diversity which suggests that the spatial power distribution can indeed be improved.

Acknowledgment

The authors would like to thank Brad Schafer (Southern States LLC) for his help with the backscatter system.

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