

Collaborative Backscatter Based on Phase Channel Estimation in Passive RF Tag Networks

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Abstract—The RF tags offer ultra-low power cost of the communication due to the passive receiver based on envelope detector. The tag-to-tag link requires presence of excitation signal, either as a dedicated continuous wave exciter or an ambient RF signal. However, the link suffers from the limited range. The capability of RF tags to passively estimate the amplitude and phase of the wireless channel between pairs of communicating tags empowers these passive tags to provide a real-time, precise, fine-grained RF fingerprint of the environment. The phase estimation also enables collaboration between neighboring tags in order to improve the range and robustness of tag-to-tag link itself. We propose strategies that through the use of optimal collaborative reflection and backscatter of a cluster of tags improve the link range. We demonstrate that a single tag on a distance of 16 cm from the transmitting tag with optimal collaborative reflection improves the link range by 40%.

I. INTRODUCTION

A wide range of IoT applications calls for ultra-low power communication between nodes in a distributed autonomous system [1]–[3]. While conventional RFID systems offer low-energy cost communication on the side of RFID tags, the presence of RFID reader limits the application of such systems beyond identification due to the high cost, low scalability and low granularity [4]. The low-power communication paradigm is enabled by backscattering-based tag-to-tag communication technique in a presence of continuous wave(CW) in the environment [5]–[8]. The tag-to-tag link is characterized by the low data rate and low communication range. The range of the tag-to-tag link is limited by the incident power at both transmitting and receiving tags. The tags are able to communicate with their neighboring tags on distances that range from a fraction of a meter up to a few meters [9]. At longer distances, a weak backscatter signal becomes difficult to resolve by the receiving tag or it can be resolved with increased energy cost, so tags rely on multihop relaying [10]. However, less hops is desired both for the latency reduction and improving the ability to label the information as contemporaneous. We propose to lessen this problem by extending the communication range by collaborative transmission from a cluster of tags by using a form of beamforming.

The beamforming technique for collaborative communication of wireless sensor nodes with active radio organized in a predefined cluster is a well known concept [11]–[13]. In RFID tags, a similar concept has been used to increase the communication range, however with multiple antennas integrated on

a single tag [14], [15]. The technique demonstrates gains in the communication range using simultaneous backscatter from multiple antennas, where the distance between the antennas corresponds to the half wavelength. This approach, however, significantly increases the form-factor of the tag, which limits the application space where it can be used. If the antennas are moved closer in an effort to reduce the form factor, the mutual coupling reduces both the received signal at the tags as well as the backscatter. For example, in a conventional RFID system, when the distance between the tags is lower than 0.3 wavelength, the tags will be, in most cases, invisible to the reader depending on their terminating impedance [16]–[18]. However, if the closely spaced tags in a predefined arrangement are modeled as an electromagnetic interconnected system [19] and their reflection coefficients optimized, the mutual coupling can actually be used to increase the communication range and incident power at the tags, as demonstrated experimentally in [20].

Recently proposed passive channel estimation [21], [22] of tag-to-tag link enables collaborative backscatter in a network of passive RF tags. We first review the estimation of the phase in tag-to-tag channel and then propose strategies for collaborative backscatter of a cluster of tags that increases the range of a tag-to-tag link.

II. TAG-TO-TAG LINK

The tag-to-tag link, comprising a transmitting(Tx) and a receiving(Rx) tag in presence of CW signal, is analyzed and characterized based on the incident RF signal at the Rx tag. For simplicity, we assume that source of CW signal is a dedicated RF exciter. The incident signal at the Rx tag comprises the direct path signal from the exciter and the signal reflected from the Tx tag. The tag integrates the envelope detector and extracts the amplitude of the received signal. Assuming that the amplitude of the signal from the exciter is much larger than the amplitude of the signal backscattered from the Tx tag, the amplitude of the RF signal at the Rx tag, v_r , is

$$v_r = V_R + V_T A_{tr} |1 - \Gamma_t| \cos(\theta_{Et} + \angle(1 - \Gamma_t) + \theta_{tr} - \theta_{Er}) \quad (1)$$

where V_R and V_T are the amplitudes of the signal received from the exciter at the Rx and Tx tag, respectively, when the other tag is not present. Γ_t is the reflection coefficient of the Tx tag. A_{tr} and θ_{tr} are the amplitude and phase of the tag-to-tag channel. θ_{Et} and θ_{Er} represent the phase of the exciter-Tx

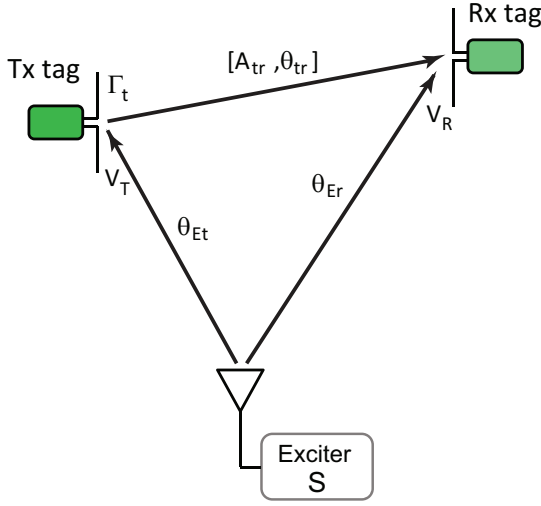


Fig. 1. Tag-to-tag channel.

tag and exciter-Rx tag channel, respectively. In this model, we neglect the reflections from the environment. From (1)

$$v_r = V_R + V_T A_{tr} \cos(\theta_{Et} + \theta_{tr} - \theta_{Er}) - V_T A_{tr} |\Gamma_t| \cos(\theta_{Et} + \theta_{tr} - \theta_{Er} + \phi_t) \quad (2)$$

where ϕ_t is the phase of the reflection coefficient Γ_t .

Communication between two tags is achieved by changing the reflection coefficient of the Tx tag between two states, $\Gamma_{t,1}$ and $\Gamma_{t,2}$. The reading range of the tag-to-tag link is defined by the minimum difference in the amplitude of the received signal at Rx tag for two states that can be resolved by passive demodulator [9]. From (3), the amplitude difference can be expressed as

$$\Delta v_r = V_T A_{tr} (|\Gamma_{t,1}| \cos(\theta_{Etr} + \phi_{t,1}) - |\Gamma_{t,2}| \cos(\theta_{Etr} + \phi_{t,2})), \quad (3)$$

where phase θ_{Etr} denotes

$$\theta_{Etr} = \theta_{Et} + \theta_{tr} - \theta_{Er}. \quad (4)$$

The voltage difference is maximized for $|\Gamma_{t,1}| = |\Gamma_{t,2}| = 1$ and

$$\begin{aligned} \phi_{t,1} &= -\theta_{Etr} \\ \phi_{t,2} &= \pi - \theta_{Etr}, \end{aligned} \quad (5)$$

with

$$\Delta v_{r,max} = V_T A_{tr}. \quad (6)$$

As $V_R \gg V_T A_{tr}$ as the distance between tags increases, the signal that the passive demodulator has to resolve in a tag-to-tag link is much smaller than the modulated signal from RFID reader that tag has to resolve in a conventional RFID system [9].

If we denote as Δv the minimum voltage that demodulator can resolve, we can define the range of the tag-to-tag link from (6) as

$$r = \frac{4\pi \Delta v}{V_T G_T \lambda}, \quad (7)$$

where G_T is a gain of Tx and Rx tag antennas.

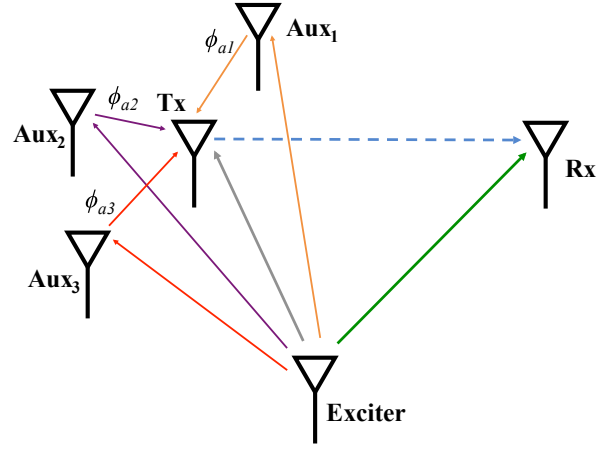


Fig. 2. Collaboration between tags for the increased range of Tx-Rx tag link.

A. Channel Phase Estimation

For the maximum range and robust tag-to-tag link, we have to measure the phase θ_{Etr} . The measurement of this phase requires a modified modulator and demodulator design of RF tag [21]. While the traditional backscatter modulator transmits data by switching between two different impedances connected to the antenna, for measuring channel phase the modulator will switch between a range of impedances. The modulator will be implemented as a multi-port switch with terminating impedances that enable the total reflection at different phase angles. For each terminating impedance, the reflection coefficient will have a unity magnitude and a reflection phase, $\phi_{t,k}$. The different phases $\phi_{t,k}$ span from $-\pi$ to π . The number of different terminating impedances is a trade-off between the resolution in estimation of the phase θ_{Etr} , power consumption and time required for the phase estimation. We have previously demonstrated that 8 different phases are sufficient for phase estimation [21]. In a static environment, the phase can be estimated once, while in a dynamic environment, the phase has to be estimated after the changes in the environment. For each reflection phase $\phi_{t,k}$, the amplitude of the incident RF signal at Rx tag, $v_{r,k}$ is recorded. This calls for analog-to-digital converter(ADC) of the baseband signal at a demodulator after the envelope detection. The energy cost of ADC conversion at the demodulator is low, as ADCs with 8-bit resolution at kSamples/s sampling rate consume 10s nW of power [23]–[25]. By interpolation, from the sampled voltage signals, we obtain the estimate of the phase θ_{Etr} .

III. COLLABORATIVE BACKSCATTER OF A CLUSTER OF TAGS

Our proposed technique relies on tag-to-tag channel estimation. Thus, the phase θ_{Etr} between any two tags within the range is assumed to be known. Figure 2 illustrates how multiple tags can collaborate to aid the transmission on a given tag-to-tag link. The neighboring auxiliary tags collaborate in order to boost the incident power at Tx tag. This consequently increases the transmitting backscattering signal received at the

Rx tag in Tx-Rx tag link. We initially assume that the distance between tags in the neighborhood of the reference tag is such that the effect of mutual coupling can be neglected.

The amplitude of the signal at the transmitting tag, V'_T , in presence of N auxiliary tags in vicinity, is a combination of direct path exciter signal and reflected signals from auxiliary tags. Using the model similar to (3), we can express V'_T as:

$$V'_T = V_T + \sum_{i=1}^N V_{Ai} A_{ait} (\cos(\theta_{Eait}) - |\Gamma_{ai}| \cos(\theta_{Eait} + \phi_{ai})), \quad (8)$$

where V_{Ai} is the amplitude of the RF signal at tag Aux_i received from the exciter. A_{ait} is the amplitude of the Aux_i -Tx channel and θ_{Eait} denotes

$$\theta_{Eait} = \theta_{Eai} + \theta_{ait} - \theta_{Et}, \quad (9)$$

where θ_{Eai} and θ_{ait} are the phase of the exciter- Aux_i and Aux_i -Tx tag channel. $|\Gamma_{ai}|$ and ϕ_{ai} are the magnitude and phase of the reflection coefficient at tag Aux_i . To increase the range of Tx-Rx tag, the reflection coefficients of the auxiliary tags are set as:

$$\begin{aligned} |\Gamma_{ai}| &= 1 \\ \phi_{ai} &= \pi - \theta_{Eait}, \end{aligned} \quad (10)$$

where phases θ_{Eait} are measured through previously described passive channel estimation. If we assume that the distance from the cluster of Tx and auxiliary tags to the exciter is much larger than the inter-distance of tags, the equation (8) simplifies:

$$V'_T = V_T (1 + \sum_{i=1}^N A_{ait} (1 + \cos(\theta_{Eait}))). \quad (11)$$

From (7), the improvement in the range of Tx-Rx link when the auxiliary tag antennas are terminated with the reflection coefficient of unity magnitude and phase ϕ_{ai} compared to the case when antennas are terminated with 50Ω resistance is

$$\frac{\Delta r}{r} = \sum_{i=1}^N A_{ait}, \quad (12)$$

We illustrate the improvement in the communication range in Figure 3, where we assume that there are 4 auxiliary tags on the same distance from Tx tag, d_{ta} . When tags are on 30 cm distance, the range improves 60%.

The proposed strategy shows that the auxiliary tags can increase the communication range only by setting an optimal reflecting phase and not participating in the communication link. Similarly to the shown constructive interference when all paths reflecting from auxiliary tags are in phase with the direct path from the exciter to the reference tag, the phases at auxiliary tags can be such that all the reflective paths subtract from the direct path, as in destructive interference. When the reference tag becomes Tx tag and starts transmitting, if auxiliary tags transmit the same data by switching between these two phase values (one for constructive, one for destructive interference), the backscatter signal seen at

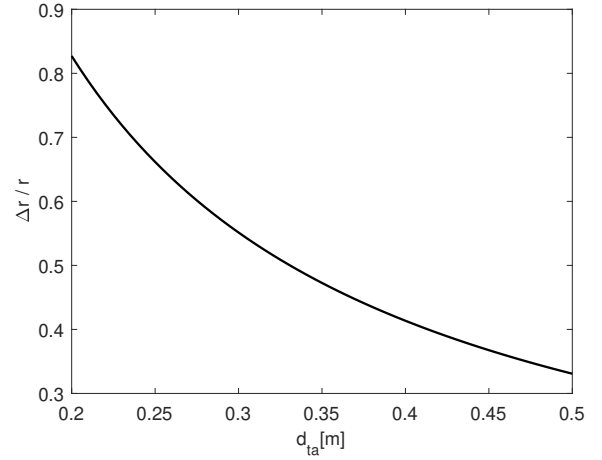


Fig. 3. The increase of the Tx-Rx tag range with collaborative backscatter with 4 auxiliary tag on distance d_{ta} from Tx tag.

Rx tag is twice increased. However, as the auxiliary tags in this case backscatter data now, the received signal at Rx tag depends on the channel phase of Aux_i -Rx tag channel as well and a different phase optimization technique is required for maximization of the link range. In addition, the backscatter at each auxiliary tag has associated energy cost, leading to the trade-off between the range and energy cost.

IV. EXPERIMENTAL RESULTS

To demonstrate the enhancement of the communication link when tags are collaborating, we performed experiments with a transmitting, an auxiliary and a receiving tag in a topology shown in Figure 2. We developed a tag prototype with discrete components shown in Figure 4. The tag includes a single dipole antenna on a separate printed circuit board (PCB). The modulator includes an RF switch which accommodates ten different reflection phases. The control logic is implemented on a low-power micro-controller (TI MSP 430). The demodulator consists of a passive envelope detector followed by a low-pass filter. The envelope detector output is connected to a separate PCB with high-resolution 16-bit 80 kbps ADC that enables data logging of this baseband signal on a PC. The exciter power is set at 15 dBm. The distance between Tx and auxiliary tag to the exciter and to the Rx tag is 1.2 m. The distance between Rx tag and exciter is also 1.2 m. We repeated experiment with two distances between Tx and auxiliary tag, 8 cm and 16 cm.

While the transmitter tag backscatters, the reflecting phase ϕ_{a1} of the auxiliary tag is changed between nine phases. Figure 5 shows the received amplitude of the backscatter signal at Rx tag as a function of the reflecting phase ϕ_{a1} . Setting the optimum phase ϕ_{a1} increases the received signal around 40% at both distances compared to the averaged received signal over all possible phases of the auxiliary tag. As expected, the mutual coupling when the separation between tags is 8 cm greatly reduces the backscatter signal.

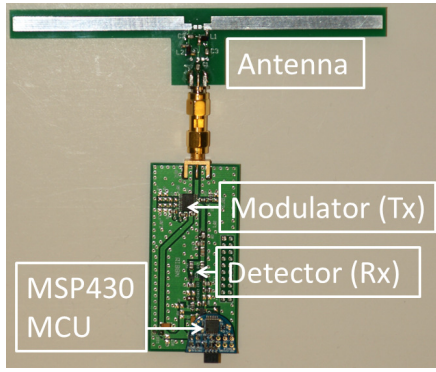


Fig. 4. The prototype tag used in the experiments.

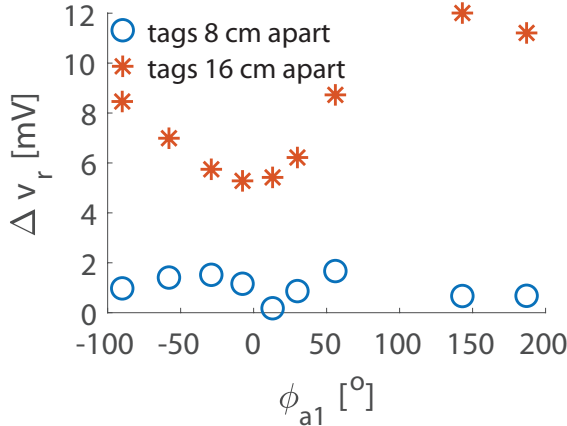


Fig. 5. Demonstrating effectiveness of collaborative backscatter.

V. CONCLUSIONS

The communication strategies proposed illustrate the gains in tag-to-tag channel when neighbouring tags collaborate if the channel phases are measured. However, as the distance between tags becomes lower than half wavelength, there is reduction in the incident power due to mutual coupling between antennas. Despite the illustrated gain obtained by the optimal reflecting, techniques like de-tuning of specific tags, have to become part of more elaborate strategies that we will explore in the future work.

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