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Ranging of UHF RFID Tag Using Stepped Frequency Read-Out

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***Abstract*—This paper presents a phase-based method for obtaining the distance of an RFID tag with unknown properties. The tag's response is measured by the reader at several discrete frequencies at the threshold power of the tag. The dispersive properties of the modulated reflection coefficient of the tag are estimated from the measured power sensitivity and their effect is compensated in the distance estimation. The method is derived using a simple theoretical model for the tag and the performance of the method is experimentally verified at 860 MHz.**

***Index Terms*—Radio frequency identification (RFID), tracking, transponders, wireless sensors.**

I. Introduction

LOCATION sensing systems have a great deal of potential in several applications. Among the most obvious are location detection of products in a warehouse, medical personnel and patients in a hospital, equipment in a laboratory, and first responders and victims in a rescue operation. Future ubiquitous sensing, computing, and manufacturing systems will also necessitate automatic location sensing.

Most location sensing systems, such as the global positioning system (GPS) and wireless local area network (WLAN)-based systems utilize microwaves, but they can also be based on other parts of the electromagnetic spectrum, such as infrared [1], or acoustic waves [2], [3]. Location systems are reviewed for example in [4]–[6].

Radio frequency identification (RFID) can also be used for location sensing and it has several advantages over other methods in short-range applications. The RFID provides very low-cost and small tags with advanced features such as anticollision protocols and nonvolatile memory. The tags can be passive requiring no battery, which could limit the operation conditions or lifetime of the tag. Most importantly, RFID is already widely used and the existing RFID infrastructure could be used for location sensing.

RFID is typically used as a proximity location sensor. The proximity sensor simply identifies whether a certain tag is within the read-range of the reader or not, and its location resolution equals to the coverage area of the reader device. More sophisticated RFID systems utilize the received signal strength indicator (RSSI), i.e., the signal attenuation due to free-space loss for determining the tag distance [7]–[10]. The received signal strength, however, is highly sensitive to the tag and the reader alignment, tag antenna mismatch due to proximity of conductive or dielectric material, and multipath propagation. Therefore, the RSSI-based distance measurement accuracy is low when multipath propagation occurs, the tag alignment is unknown, or the tag can be mismatched due to proximity of dielectric or conductive materials. The RSSI-based distance measurement also necessitates knowledge on the modulation depth of the tag.

The time-of-flight or phase-based distance measurement principle used by the radar typically provides better distance measurement accuracy than the bare amplitude-based estimation. The radar concept for measuring the distance of modulated backscatterers, i.e., tags or transponders, is called secondary radar [11]. In this concept, the transponders reply at a frequency, which is offset from that transmitted by the reader device. Harmonic radar, where the frequency offset is a multiple of the fundamental frequency, is an example of the secondary radar and it was first proposed for traffic applications [12] and later was used for tracking insects [13]–[15] and avalanche victims [16]. The somewhat similar intermodulation radar principle is also proposed for traffic applications and for reading out wireless MEMS [17] and ferroelectric sensors [18]. Novel amplifying transponder based on switched injection-locked oscillator and an active retrodirective transponder are described in [19] and [20], respectively, to name a few applications of the secondary radar and transponders.

The phase-based distance measurement combined with the RFID could enable both the identification and the distance determination of a passive transponder that is not straightforward by the most aforementioned methods. Phase-based distance estimation of RFID is studied in a few articles. A frequency-modulated continuous wave (FMCW) RFID reader capable for distance measurement is presented in [21] and distance estimators for RFID are presented and studied by simulations in [22] and [23]. The phase-based distance determination of generic RFID tag is challenging due to two things. First, the dispersive properties of the modulated reflection coefficient of the tag affect the distance determination and should therefore be known in advance. Second, the modulated reflection coefficient is sensitive to the received power by the tag. These issues are not addressed at all in [21] and [22]. The power and frequency dependent re-

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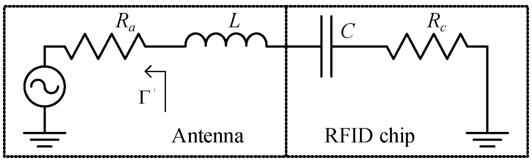

Fig. 1. Electrical equivalent circuit of the RFID antenna and chip.

flection coefficient of the tag is included in the analysis presented in [23], but no method to solve these unknown properties is proposed. In this paper, we present a phase-based method for determining the distance of an RFID tag with unknown dispersive properties and power response.

II. Ranging Principle

A. Frequency Response of the Tag

Consider an RFID tag at a distance z from the reader. The reader illuminates the tag by a CW and the tag produces modulated backscattering by switching its reflection coefficient between two states, Γ_1 and Γ_2. The corresponding signal difference between the two states at the reader device is

$$\begin{aligned}\Delta Y(\omega) &= (\Gamma_1(\omega) - \Gamma_2(\omega)) A e^{-j(2\omega/c)z} \\ &= \Delta\Gamma(\omega) A e^{-j(2\omega/c)z}\end{aligned} \tag{1}$$

where A is the unknown two-way signal attenuation, $\omega = 2\pi f$ is the angular frequency and c is the speed of light. Solving the distance z from $\Delta Y(\omega)$ necessitates that the modulated reflection coefficient $\Delta\Gamma(\omega)$ is known.

B. Modulated Reflection Coefficient of the Tag

Let us represent an RFID tag with the electrical equivalent circuit shown in Fig. 1. The capacitive RFID chip is modeled with a series resistance R_c and a capacitance C and the antenna is represented with a series resistance R_a and an inductance L.

The tag modulates its reflection coefficient by switching the capacitance between two states: C and $C \pm \Delta C$. Note that the capacitance change direction between the two states is assumed unknown and can be either positive or negative. The modulated reflection coefficient is given as

$$\Delta\Gamma(\omega) = \frac{Z_{c1} - Z_a^*}{Z_{c1} + Z_a} - \frac{Z_{c2} - Z_a^*}{Z_{c2} + Z_a} \tag{2}$$

where $Z_{c1} = R_c + 1/(j\omega C)$, $Z_{c2} = R_c + 1/(j\omega(C \pm \Delta C))$, $Z_a = R_a + j\omega L$, and * denotes complex conjugate. When $\Delta C \ll C$, (2) can be approximated as

$$\begin{aligned}\Delta\Gamma(\omega) &\approx \frac{\mp j2\omega R_a \Delta C}{(1 - \omega^2 LC + j\omega(R_a + R_c)C)^2} \\ &= \frac{\mp j2\omega R_a \Delta C}{\left(1 - \frac{\omega^2}{\omega_{\text{res}}^2} + \frac{j\omega}{(Q_L\omega_{\text{res}})}\right)^2}\end{aligned} \tag{3}$$

where the resonance frequency is $\omega_{\text{res}} = 1/\sqrt{LC}$ and the loaded quality factor $Q_L = 1/(\omega_{\text{res}} C(R_a + R_c))$. The phase of the modulated reflection coefficient is

$$\angle\Delta\Gamma(\omega) = \tan^{-1}\left\{\frac{\text{Im}\{\Delta\Gamma(\omega)\}}{\text{Re}\{\Delta\Gamma(\omega)\}}\right\}. \tag{4}$$

Approximating (4) by the first-order Taylor's expansion near the resonance gives

$$\begin{aligned}\angle\Delta\Gamma(\omega) &\approx \pm\frac{\pi}{2} + \frac{4(\omega - \omega_{\text{res}})}{\omega_{\text{res}}^2 C(R_a + R_c)} \\ &= \pm\frac{\pi}{2} + \frac{4Q_L(\omega - \omega_{\text{res}})}{\omega_{\text{res}}}.\end{aligned} \tag{5}$$

Substituting (5) into (1) gives

$$\Delta Y(\omega) = |\Delta\Gamma(\omega)| A e^{-j\omega((2/c)(z - z_{\text{offset}})) + j(\pm(\pi/2) - 4Q_L)} \tag{6}$$

where

$$z_{\text{offset}} = \frac{Q_L \lambda_{\text{res}}}{\pi} \tag{7}$$

and λ_{res} is the wavelength at the resonance frequency. For example, when the loaded quality factor of the tag is $Q_L = 10$, the distance measurement error of z at 867 MHz is 1.1 m when $\Delta\Gamma(\omega)$ is neglected (assumed constant).

C. Power Sensitivity of the Tag

The power sensitivity of the tag (the threshold power that turns the tag on) is inversely proportional to the power dissipated in the chip resistance R_c in Fig. 1, and can be written as [24]

$$\begin{aligned}P_{tag}(\omega) &\sim (R_a + R_c)^2 + \left(\omega L - \frac{1}{(\omega C)}\right)^2 \\ &\sim 1 + {Q_L}^2 \frac{\omega^2}{\omega_{\text{res}}^2}\left(\frac{\omega^2}{\omega_{\text{res}}^2} - 1\right)^2.\end{aligned} \tag{8}$$

D. Distance Estimation of the Tag

In the proposed distance estimation method, the reader device records the response of the tag at several discrete frequency points at the power sensitivity of the tag. The power sensitivity is measured at all frequencies by gradually increasing the transmit power and detecting the first reply from the tag. The tag parameters, ω_{res} and Q_L are then estimated using the following least squares fit:

$$\min_{\omega_{\text{res}}, Q_L, B} \sum_{\omega} \left\{(BP_{\text{tag,meas}}(\omega) - P_{tag}(\omega))^2\right\} \tag{9}$$

where B is the unknown signal attenuation due to the free-space and other loss, $P_{\text{tag,meas}}(\omega)$ is the measured power sensitivity of the tag, and $P_{tag}(\omega)$ is given by (8).

The tag parameters obtained from (9) are used to estimate the modulated reflection coefficient with (3). Note that R_a and ΔC

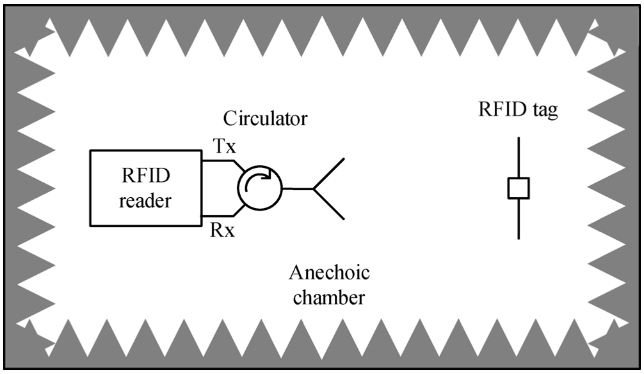

Fig. 2. Experimental measurement setup for measuring the distance of an RFID tag.

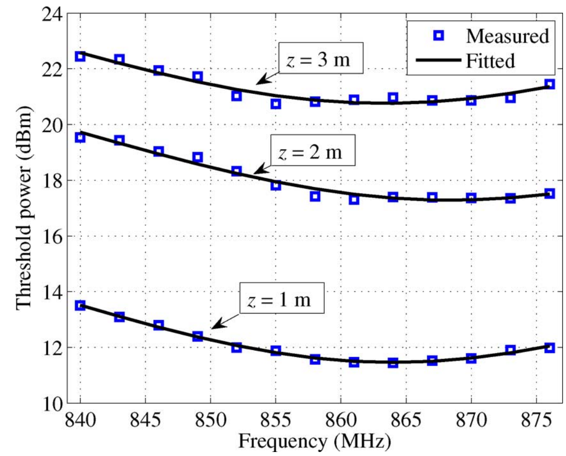

Fig. 3. The measured and fitted power sensitivity of the tag as a function of the frequency. Different lines are for different distances.

does not affect the frequency behavior of the modulated reflection coefficient and can be set to one. Hence, the fit concerns finding the resonance frequency and the quality factor of the tag.

The distance z is obtained using Fourier transform

$$\max_z \left\{ \left| \int \frac{\Delta Y_{\text{meas}}(\omega)}{\Delta \Gamma_{\text{est}}(\omega)} e^{j(2\omega/c)z} d\omega \right| \right\} \tag{10}$$

where $\Delta Y_{\text{meas}}(\omega)$ is the measured difference signal between the two reflection coefficient states of the tag and $\Delta\Gamma_{\text{est}}(\omega)$ is the modulated reflection coefficient of the tag obtained from (9) and (3). When the computing power is limited, the linear approximation of the distance correction term given in (7) can be used.

There is a constant phase ambiguity of π in the estimated modulated reflection coefficient $\Delta\Gamma_{\text{est}}(\omega)$ [the term $\pm\pi/2$ in (6)]. This phase-term does not affect the absolute value of the Fourier transform given in (10) nor the estimated distance z.

The effective impedance of the RFID chip depends on the applied power and therefore the modulated reflection coefficient of the tag is also power dependent. The response of the tag is always measured at the power sensitivity of the tag, which ensures that the properties of the tag remains unchanged and does not affect the estimated distance.

The proposed method enables ranging all the tags within the reader field simultaneously using standard inventory procedure, because the tag responses can be distinguished by their EPC codes. Also standard reader hardware can be used. The method requires only that the transmit power can be adjusted and that the phase of the difference signal ΔY can be measured.

The accuracy of the method depends on the bandwidth, the signal-to-noise ratio, and the level of multipath propagation. The effect of these parameters on the distance measurement accuracy of RFID tag is analyzed in [23]. The method is likely not applicable in Europe, where only a narrow band (865–868 MHz) is allocated to UHF RFID [25], but could be applicable especially in the USA, where the available UHF RFID band ranges from 902–928 MHz [26]. Note also that the method could provide very high accuracy in special applications where the frequency allocations can be exceeded.

III. Experiments

A. Measurement Setup

The distance estimation method is experimentally tested in an anechoic chamber using an RFID test equipment (Tagformance lite 2.0[1]) as a reader device, see Fig. 2. The transmit and receive channels of the RFID test device are coupled to a single reader antenna (SPA 8090/75/8/0/V[2]) through a circulator (V2[1]) and the tested RFID tag is placed on a movable holder. The tag antenna is comprised of two shorted patches and it measures $88 \times 30 \times 3$ mm. The tag is equipped with the Monza 2[3] RFID chip. The response of the tag is measured from 840–876 MHz with 3 MHz interval (13 frequency points) at the distances from 0.3–4.7 m.

B. Estimated Parameters of the Tag

The measured power sensitivity of the tag at 1, 2, and 3 m distances are shown in Fig. 3 with the fitted curves. The best fit is obtained at 1 m due to the best signal-to-noise ratio but the deviations are relatively low even at 3 m distance.

Fig. 4 shows the estimated quality factor and the resonance frequency of the tag at different distances. The average of the estimated resonance occurs at approximately 864 MHz with maximum deviations of $+10$ MHz and -4 MHz. The estimated quality factor ranges from 10 to 17 and its average is 14.

C. Estimated Distance of the Tag

The estimated distance of the tag as a function of the true distance is shown in Fig. 5. The red circles show the uncorrected distance estimate. In this distance, the dispersive properties of the tag are not taken into account in (9), in other words, $\Delta\Gamma_{\text{est}}(\omega)$ is assumed constant. The corrected distance obtained with the method proposed in this paper is shown with blue squares. Black lines are linear fits to both data.

[1]www.voyantic.com

[2]www.hubersuhner.com

[3]www.impinj.com

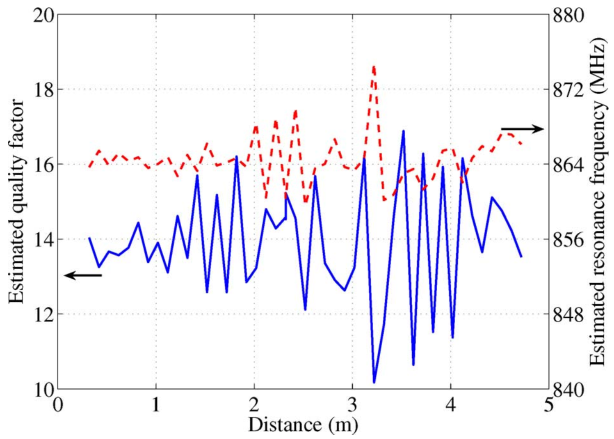

Fig. 4. The estimated quality factor and the resonance frequency of the tag at different distances.

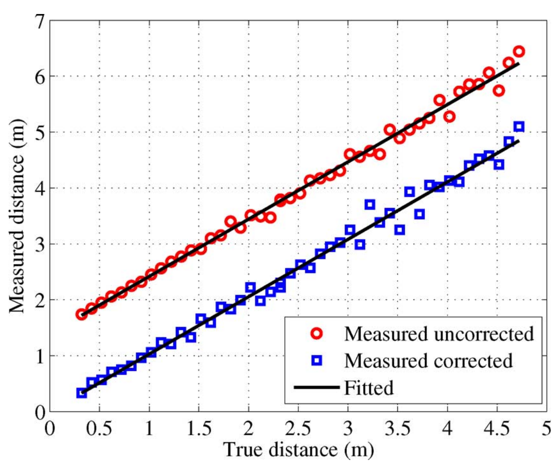

Fig. 5. The estimated uncorrected (red circles) and corrected (blue squares) distances of the tag as a function of the true distance.

The distance offset between the corrected and uncorrected results is approximately 1.4 m. This agrees well with the theoretically derived linear approximation for the offset distance, which is $z_{\text{offset}} = Q_L \lambda_{\text{res}}/\pi = 1.5\ \text{m}$ at 867 MHz with $Q_L = 14$.

The variation in the corrected distance estimate is slightly larger than that in the uncorrected distance estimate due to the uncertainty in estimating the quality factor and the resonance frequency of the tag. However, the distance measurement accuracy in this experiment is relatively good as the mean absolute error in the corrected data is 68 mm.

IV. Conclusion

We have proposed a phase-based method for determining the distance of an RFID tag with unknown properties. In this method, the reader records the response of the tag at different frequencies at the threshold power of the tag. The dispersive properties of the modulated reflection coefficient are estimated from the measured power sensitivity and are taken into account in the distance estimation. Implementing the method necessitates only that the transmit power of the RFID reader can be adjusted and that the phase of the difference signal can be measured. Thus only software modifications to the reader are required.

The method is experimentally verified at 860 MHz and it is found to provide accurate distance estimate the maximum error being 0.4 m. Better accuracy could be achieved by using larger bandwidth or longer integration time.

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