Accurate Phase-Based Ranging Measurements for Backscatter RFID Tags

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***Abstract*—Short distance, millimeter-level ranging based on backscatter RF tags remains a challenge today. We propose a composite Dual-Frequency Continuous-Wave and Continuous-Wave (DFCW/CW) radar system for localization of backscatter RF tags. The coarse DFCW range result is used to correct the cycle ambiguity of the more accurate, CW range result. A Minimum Mean Square Error (MMSE) based method is employed to combine the DFCW and CW ranging data, given spectrum constraints. The composite radar concept is demonstrated with a custom, 5.8 GHz, backscatter RF tag system, in a typical indoor laboratory environment with a strong Line-of-Sight (LOS). Results show that the MMSE technique can resolve the CW cycle ambiguity for a moving tag and results in a range error of approximately 1 mm after an acquisition period.**

***Index Terms*—RFID, localization, DFCW, phase**

I. Introduction

Backscatter RF tags have proven useful in many applications including radio frequency identification (RFID); however, there is great interest in not only identifying the tag, but obtaining its location as well [1]–[4]. Our interest lies in applications where high accuracy (on the order of millimeters) is required in channels with a strong line-of-sight (LOS), typically over short distances. Examples of such applications include entertainment (e.g., game controllers and human computer interaction) and motion capture/tracking systems, provided that the LOS is dominant.

Although many localization techniques have been investigated, most are not suitable for high-accuracy, short-range applications. For example, conventional ranging techniques based on Received Signal Strength (RSS), for either active or passive RF tags, work over relatively large areas, but suffer from poor accuracy. RFID ranging techniques based on Time of Flight (TOF) [2] or using a Frequency Modulation Continuous Wave (FMCW) radar [3] are possible, but challenging for short distance applications because it is difficult to measure the small round-trip time/frequency delay. RF phase-based ranging techniques are preferred when high accuracy is required [5] because they are fundamentally more accurate than non-coherent techniques, such as RSS-based ranging. However, a cycle ambiguity exists when the distance to be measured is longer than one wavelength, making this technique inappropriate for directly measuring distances. Alternatively, the phase difference technique can be used for RFID ranging [4], [6], [7]. Instead of exploiting phase differences in the space domain, as done in the conventional phase difference technique, a Multiple Frequency CW (MFCW) radar takes advantage of phase differences in the frequency domain and was recently introduced into the RFID community [8], [9] through simulations.

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In this paper, a composite, dual-frequency continuous-wave (DFCW) and continuous-wave (CW) radar is used to accurately localize a backscatter RF tag in a strong LOS channel. For the composite DFCW/CW radar, the CW radar provides accurate, but ambiguous distance estimates by measuring the phase difference between the transmitted and received signals at the reader. The DFCW radar gives a coarse, absolute distance measurement which is used to resolve the cycle ambiguity of the CW radar. By combining the results from both the DFCW and CW radars, an accurate, absolute distance estimate can be obtained. However, the bandwidth of the DFCW radar required to correctly resolve the CW radar cycle ambiguity is often larger than the 125 MHz allowed by the Federal Communications Commission (FCC) in the 5.8 GHz unlicensed, industrial, scientific, and medical (ISM) frequency band. This paper experimentally demonstrates a Minimum Mean Square Error (MMSE) data combining algorithm to reduce the required bandwidth of the composite DFCW/CW ranging technique.

The composite radar system is experimentally demonstrated with a custom, backscatter RF tag system operating around the 5.8 GHz ISM frequency band. The results show that absolute ranging with millimeter-level accuracy can be achieved in a strong LOS channel by combining the DFCW and CW results based on the MMSE.

The rest of the paper is organized as follows: Section II reviews the composite DFCW/CW ranging technique for localizing a backscatter RF tag; Section III describes the experimental setup; experimental results are analyzed in Section IV; and conclusions are drawn in Section V.

II. DFCW/CW Composite Ranging

This section summarizes the composite DFCW/CW ranging technique applied to a backscatter RF tag system. Since a detailed discussion of the DFCW/CW ranging technique for a conventional transmitter-to-receiver link has been provided previously [10], only a short summary pertaining to its application in a backscatter channel will be discussed.

A. Backscatter CW Ranging

In a conventional transmitter-to-receiver channel, the wrapped phase $\hat{\theta}$ measured at the receiver is equal to the

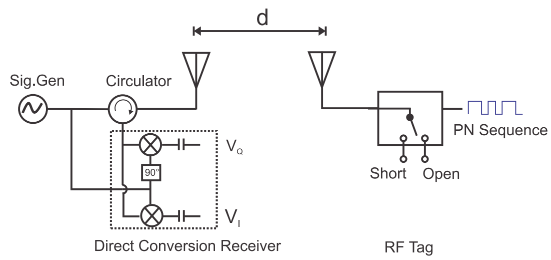

Fig. 1. A system block diagram of a backscatter RFID system which uses a pseudo-random noise (PN) code to modulate the backscatter from the tag.

unwrapped phase θ, which is proportional to the transmitter-to-receiver distance, plus an unknown integer number of 2π radian offsets (i.e., the cycle ambiguity). The same is true of the backscatter channel, except that the unwrapped phase is proportional to the total transmitter-to-tag-to-receiver distance. In a monostatic backscatter channel, the transmitter-to-tag and tag-to-receiver distances are equal; hence, the CW radar equation for a transmitter-to-receiver channel [10] can be modified for a monostatic backscatter channel by dividing the measured phase in half. The resulting monostatic, backscatter CW ranging equation is

$$\hat{d} = \frac{\hat{\theta} - \theta_0}{4\pi}\lambda = d - k\frac{\lambda}{2}, \quad (1)$$

where $\hat{d}$ is an ambiguous distance estimate, $d = [(\theta - \theta_0)/4\pi]\lambda$, θ is the unwrapped phase of the backscatter channel, θ_0 is a constant phase offset, λ is the wavelength, and k is a positive, unknown integer corresponding to the unknown wavelength offset.

B. DFCW ranging

For a DFCW radar operating at frequencies f_1 and f_2, two ambiguous phases, $\hat{\theta}_1(\vec{r})$ and $\hat{\theta}_2(\vec{r})$, are available to calculate the distance d. Each phase is related to d by (1). The unambiguous DFCW range estimate is found by subtracting $\hat{\theta}_1(\vec{r})$ from $\hat{\theta}_2(\vec{r})$ and solving for d which leads to:

$$\begin{aligned} d &= \frac{\lambda_1\lambda_2\left[(\hat{\theta}_2 - \theta_{02}) - (\hat{\theta}_1 - \theta_{01}) + 2(k_2 - k_1)\pi\right]}{4\pi(\lambda_1 - \lambda_2)} \\ &= \left[\frac{\breve{\theta}_2 - \breve{\theta}_1}{2\pi} + \breve{k}\right] \cdot \frac{\lambda_{\Delta f}}{2} \end{aligned} \quad (2)$$

where $\breve{\theta}_{1,2} = \hat{\theta}_{1,2} - \theta_{01,02}$ is the normalized measurement phase, $\breve{k} = k_2 - k_1$ represents the normalized integer k, and $\lambda_{\Delta f} = c/(f_2 - f_1)$ is the equivalent wavelength of the DFCW radar with a frequency separation of $\Delta f = f_2 - f_1$. Here, c denotes the speed of light.

As shown previously [10], the phase offsets $\theta_{01,02}$ account for the path length difference between the LO and RF ports of the mixer in the direct conversion receiver when the tag is at zero distance. Practically, $\theta_{01,02}$ can be measured and calibrated when the tag is at a known distance offset d_0. In that case, the distance d in (2) is the distance normalized to d_0. Care must be taken to remove or account for multipath in the calibration measurement.

If we limit the motion of the tag to a distance $d \le \lambda_{\Delta f}/2$, then $\breve{k} = 0$ and (2) becomes

$$d_{2f} = \frac{\breve{\theta}_2 - \breve{\theta}_1}{2\pi} \cdot \frac{\lambda_{\Delta f}}{2}. \quad (3)$$

From (3), it is clear that, with the assumption above, d_{2f} is unambiguous and can be calculated based on the measured normalized phases. However, given the limited bandwidth available for backscatter tag applications, ranging solely based on a DFCW radar is generally not attractive because of its relatively low accuracy. Intuitively, the best ranging results can be achieved by combining the information from both the DFCW and CW radars [10].

C. Data Fusion: Combining DFCW and CW ranging results

Much like ambiguity resolution in GPS systems [11], the DFCW and CW radar range estimates must be combined to determine the unknown cycle ambiguity of the CW radar.

1) Direct combining: A straight-forward way to resolve the cycle ambiguity is to determine the ambiguity integer k_1 directly by d_{2f}:

$$d = \hat{d}_1 + \left\lfloor \frac{2\ d_{2f}}{\lambda_1} \right\rfloor \cdot \frac{\lambda_1}{2} \quad (4)$$

where $\lfloor \cdot \rfloor$ represents the closest integer to the quantity inside the bracket towards zero, the subscript $(\cdot)_1$ denotes a quantity associated with f_1 where f_1 is the frequency for which the cycle ambiguity needs to be resolved.

Although simple, the direct combining method requires high accuracy (i.e., the maximum Absolute Error (AE) must be smaller than $\lambda_1/2$) for the DFCW radar which, excluding multipath effects, requires either complicated hardware for accurate phase measurements or a large frequency separation Δf. This direct combining method has been implemented previously [10] and proven useful when Δf is sufficiently large.

2) MMSE combining: Given hardware and spectrum constraints, ambiguity integer estimation can be improved with more sophisticated searching algorithms such as the MMSE-based algorithm proposed in this paper. The MMSE technique spatially averages the data history to resolve the CW cycle ambiguity instead of using a single data point. Unlike inertial ranging, where errors increase significantly (t^3, to be exact) with time, the ranging error of a DFCW radar in a strong LOS channel is usually confined to a range oscillating about the true distance (with a small bias) as the tag moves in space. Hence, spatial averaging can improve DFCW ranging accuracy.

In a practical system, the ground truth required to calculate the MSE of the DFCW ranging is generally not available. This ground truth, however, can be approximated by the CW ranging result plus an offset of a multiple (k_1) of half-wavelengths. The integer k_1 can be obtained by minimizing the mean square error (MSE) between d_{2f} and $\hat{d}_1$:

$$\underset{n}{\operatorname{argmin}}\left\{\sigma^2\right\} = \underset{n}{\operatorname{argmin}}\left\{\frac{1}{L}\int_0^L\left[d_{2f} - \hat{d}_1 - n\frac{\lambda_1}{2}\right]^2 ds\right\}, \quad (5)$$

where n is an integer number to be tested, L is the travel distance of the tag, and ds is the incremental distance over which the distance difference is integrated. In a practical system, the averaging in (5) is usually done in the time domain instead of the space domain and it is assumed that the ambiguity integer k_1 is unknown for only the first data point in $\hat{d}_1$. Ambiguities that occur on subsequent data points are corrected by incrementing/decrementing k_1 whenever a 180-degree phase change is detected.

In the following, we investigate how accurate the DFCW ranging must be to resolve the CW cycle ambiguity using the MMSE method. Note σ^2, from (5), can be written as

$$\sigma^2(\Delta k) = \frac{1}{L}\int_0^L \left[\Delta d_{2f} - \Delta d_1 + \Delta k \cdot \frac{\lambda_1}{2}\right]^2 ds, \quad (6)$$

where $\Delta d_{2f} = d_{2f} - d$ and $\Delta d_1 = d_1 - d$ denote the measurement error of the DFCW and CW radar, respectively. Here, $\Delta k = k_1 - n$ is the difference between the tested integer n and the true ambiguity integer k_1 and $\Delta\bar{d} = \Delta d_{2f} - \Delta d_1$. By breaking the integral into parts, (6) can be written:

$$\sigma^2(\Delta k) = \frac{1}{L}\int_0^L (\Delta\bar{d})^2 ds + \frac{\Delta k \lambda_1}{L}\int_0^L \Delta\bar{d}\, ds + \left(\frac{\Delta k \lambda_1}{2}\right)^2. \quad (7)$$

For the minimum of the $\sigma^2(\Delta k)$ to occur only when $\Delta k = 0$, the following condition must be satisfied:

$$\sigma^2(\Delta k)|_{\Delta k \neq 0} - \sigma^2(0) > 0,\ \Delta k = \pm 1, \pm 2, \cdots . \quad (8)$$

Substituting (7) into (8) and rearranging leads to:

$$\left|\frac{1}{L}\int_0^L \Delta\bar{d}\, ds\right| < \frac{\lambda_1}{4}\ , \quad (9)$$

where $|\cdot|$ denotes the absolute value. $\lambda_{\Delta f}$ is usually chosen to be much larger than λ_1 in order to meet frequency spectrum regulations or coherence bandwidth constraints. As a result, $\Delta d_1 << \Delta d_{2f}$ and, thus, Δd_1 can be ignored. In this case, the $\Delta\bar{d}$ in (9) can be replaced with the DFCW ranging error Δd_{2f}.

For a moving tag, the spatial integral in (5) can be easily implemented by integrating the DFCW range estimates over time. When the tag is stationary, however, the measured DFCW distance should be excluded from the MMSE combining to avoid bias errors. The stationary periods of the tag can be identified by monitoring tag's Doppler velocity, which is easily obtained from the CW ranging results.

It should be noted that cycle ambiguity estimation is only needed for system initialization or when a "cycle slip" occurs in which the system loses track of the phase cycle. After the integer k_1 is estimated, the system may switch back to the regular CW mode and no DFCW estimate is needed.

III. Experimental Setup

We carried out measurements using a spread spectrum backscatter system purchased from Southern States, LLC. A block diagram of the RFID system is shown in Fig. 1 and a photograph of the system in Fig. 2. An Agilent PSG E8257D signal generator was used to generate the required system frequencies and the RF tag was a custom, semi-passive backscatter tag that modulated the backscatter with a 6-bit, maximal-length, pseudo-random code. A patch antenna

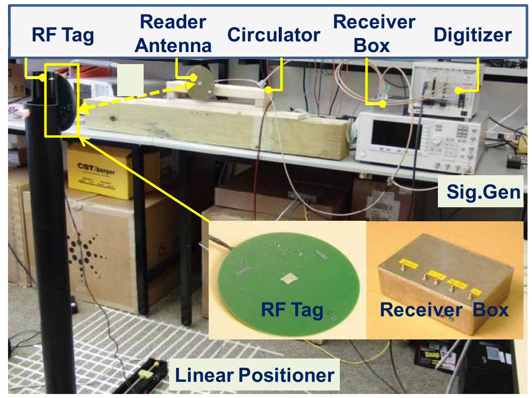

Fig. 2. The experimental setup for the DFCW/CW ranging measurements.

(approximately 10 dBi gain) was used in both the reader and tag. A linear positioner was used to accurately control the distance between the tag and the reader antenna.

The linear positioner was programmed to move 300 steps, at a step size of 2.54 mm, away from the reader antenna. At each step, the I/Q voltages output from the direct conversion box were digitized (Adlink PXI-9816H) and recorded by a computer for post processing. The same procedure was repeated for a number of system frequencies ranging from 5.6 GHz to 6 GHz at intervals of 50 MHz.

Measurements were done in a monostatic backscatter channel with a strong LOS. Scatterers included the linear positioner, tag stand, floor, and nearby workbenches, but a strong LOS was maintained.

IV. Experimental Results and Analysis

Following the procedure introduced in Section II, the processed DFCW and CW ranging results are shown in Fig. 3. The fundamental frequency f_1 for the CW ranging is 5.75 GHz, and the second frequency is 5.85 GHz. Figures 3, 4a, and 5 are plotted against the reader-to-tag distance normalized to the tag's initial position at $d_0 = 0.42$ m. It is apparent that the ranging result based on the DFCW radar is unambiguous, but coarse, while the ranging result based on the CW radar is more accurate, but biased by an unknown multiple of half-wavelengths of the CW system frequency. Even though a strong LOS existed, multipath was present and contributed, along with imperfect hardware (e.g., I/Q imbalance), to the oscillations in the DFCW range estimate.

As shown in Section II-C, the accuracy of the DFCW range estimate is crucial for resolving the CW cycle ambiguity. The DFCW ranging accuracy, however, depends on the frequency separation Δf, which is shown in Fig. 4. The fundamental frequency f_1 was set to 5.6 GHz and the other DFCW frequency to $f_2 = f_1 + \Delta f$. Fig. 4a shows the measured DFCW range error Δd_{2f} for different frequency separations. It can be seen that Δd_{2f} significantly decreases as Δf is increased from 100 MHz to 400 MHz. Fig. 4b shows that the maximum AE and Root Mean Square Error (RMSE) (σ in (6)) of Δd_{2f} decrease significantly as Δf increases from 50 MHz to 150 MHz, but only improves modestly for $\Delta f \geq 150$ MHz.

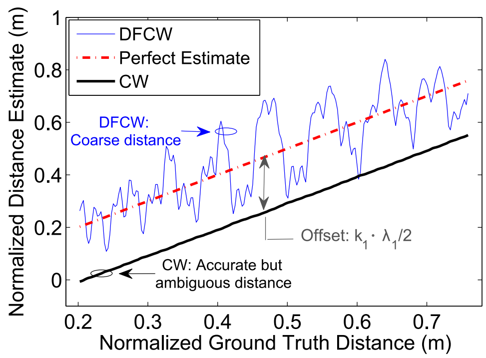

Fig. 3. Measured ranging results based on CW and DFCW radars. To illustrate the ambiguity of the CW radar, the tag's initial position was set to 0.2 m instead of the calibration point.

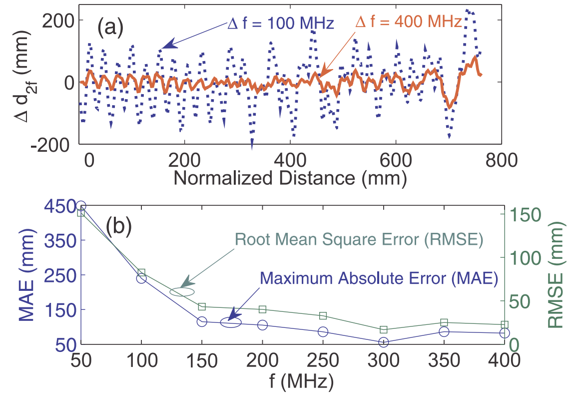

Fig. 4. The DFCW ranging error Δd_{2f} varies with (a) the normalized separation distance and (b) with the DFCW radar frequency separation Δf. Both the maximum AE and RMSE (σ in (6)) of Δd_{2f} are shown in (b).

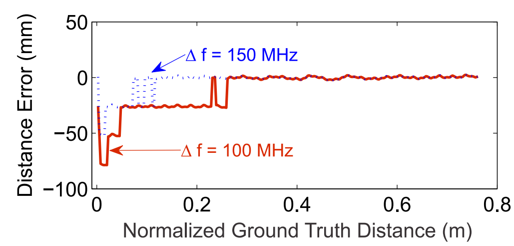

Fig. 5. The measured distance error using the composite DFCW/CW radar with MMSE combining.

In a DFCW radar, any measured phase errors caused by multipath or hardware limitations, are scaled by $\lambda_{\Delta f}$, as shown in Eq. (2); hence, for a given phase error, the DFCW distance error will decrease with increasing Δf. This fact does not mean that Δf can be arbitrarily large. Frequency spectrum regulations must be observed and, if Δf exceeds the channel's coherence bandwidth, the measured phase may not correlate with distance. Although the MMSE combining technique cannot overcome coherence bandwidth limitations, it is useful to resolve the CW cycle ambiguity when spectrum regulations limit Δf.

Using $f_1 = 5.75$ GHz as an example, we combined the measured distance results from the DFCW and CW radars based on Section II-C. Since the maximum AE is much larger than a half wavelength, MMSE combining was chosen over direct combining. The large errors at short distances correspond to the initialization window where the cycle ambiguity is not resolved, as shown in Fig. 5. For the results reported here, the length of the initialization window was 0.26 m and 0.12 m for the 100 MHz and 150 MHz bandwidths, respectively. After the cycle ambiguity was resolved, the maximum AE was 2.4 mm, and the RMS error was 0.915 mm.

The results in Fig. 5 show that the cycle ambiguity of the CW radar can be resolved using the composite DFCW/CW technique in a strong LOS channel and the MMSE-based spatial averaging reduces the required bandwidth compared direct combining. The accuracy of the composite DFCW/CW radar with MMSE combining is equal to that of a CW radar and, like other narrowband, phase-based techniques, its errors increase with multipath. If the error bound from Eq. (9) is not met, because of a large $\Delta \bar{d}$ or small averaging distance L, the cycle ambiguity will not be resolved correctly.

V. Conclusion

A phase-based ranging technique, DFCW/CW composite ranging, was used for localization of backscatter RF tags. An MMSE-spatial averaging technique was proposed and an accuracy bound derived. Experimental results show that millimeter-level accuracy can be achieved and the 5.8 GHz ISM bandwidth requirements met by combining the DFCW/CW ranging results using the MMSE spatial averaging technique when a strong LOS is present.

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