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Time-efficient Reading Process for Motion-modulated Chipless RFID

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Abstract—This paper presents a multi-carrier reading process which can significantly reduce the identification time for motion-modulated chipless tags. The performance of the proposed approach is experimentally compared with the previously presented single-carrier method in terms of identification time, SNR, and achievable read range. The measurements are done for the proposed directional-Doppler modulated chipless tag consisting of rotating high resonant loop scatterers. Using the multi-carrier reading method, the identification time is reduced by a factor of 2.5 while maintaining a read range of several meters.

Index Terms—Chipless Radio Frequency Identification (RFID), Doppler effect, Motion-modulated chipless RFID

I. INTRODUCTION

The classical chipless RFID readers for frequency-coded tags [1], [2] have been mainly developed based on two architectures as Stepped-Frequency Continuous Wave (SFCW) readers [which is mostly realized with Vector Network Analyzers (VNA)] and Impulse-Radio UltraWideBand (IR-UWB) readers to measure the Radar Cross Section (RCS) of the tags [3]. The narrow IF processing bandwidth in SFCW readers provides higher SNR and frequency resolution compared to IR-UWB readers which suffer from a wide input noise bandwidth [3]. However, the IR-UWB readers designed based on sub-nanoseconds pulses are much faster than SFCW readers while ensuring compatibility with emission regulations [3]. Essentially, in classical chipless RFID, the chipless tag is supposed to be stationary in time, and consequently, the tag behaves like a Linear Time-Invariant (LTI) system in which the backscatter response contains exactly the same frequencies as the excitation. This fact has been considered as a key point when using the SFCW and IR-UWB readers which causes the read range to be limited by 1 m in most cases [4].

Motion-modulated chipless tags have been recently introduced to break the LTI property of the stationary chipless tags in order to significantly increase the read range of the chipless tags by making it possible to better isolate the response of the tag from that of the environment which is stationary [5], [6]. However, since motion-modulated chipless tags are Linear Time-Variant (LTV) transponders that produce new frequency components in the response with respect to the excitation, the mentioned classical chipless RFID readers cannot be directly used for this kind of tags. Accordingly, the reading process for motion-modulated chipless tags based

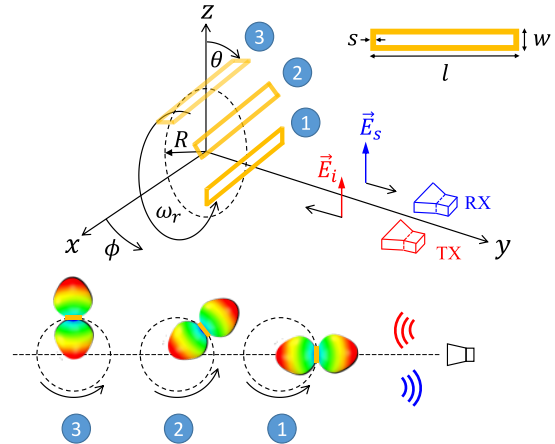


Fig. 1. Backscattering from directional-Doppler modulated chipless tag realized with rotating rectangular loop scatterer.

on differential (which is related to the modulated frequency components in the response) has been realized by sequentially single-carrier transmission and narrowband coherent reception using a signal generator and a spectrum analyzer [7]. In fact, to acquire the response of the tag in its whole coded bandwidth with N points, the single-carrier reading scenario should be repeated N times while the carrier is stepped respectively and the acquisition time at each step should respect the time-variation of the motion. Accordingly, the reading process presented in [7] is quite time-consuming especially when the identification should be done for high code capacity tags where the frequency band (several GHz) or the frequency resolution (some MHz) may be significant.

In this paper, a time-efficient reading process is proposed for motion-modulated chipless tags based on multi-carrier transmission and wideband coherent reception which significantly decreases the identification time while it maintaining the same read range as what has been previously achieved. The performance of both methods is experimentally examined to identify a directional-Doppler modulated chipless tag as an example of motion-modulated chipless tags. The presented tag is designed with resonant loop scatterers and the backscattering from the motion-modulated chipless tag is modeled analytically to be compared with the measurement results.

II. MOTION-MODULATED CHIPLESS TAG

A. Modulated backscattered field

The proposed motion-modulated chipless tag consists of rotating resonant rectangular loop scatterers is shown in Fig. 1. The rectangular loop with the length of l , the width of w , and the thickness of s is aligned along x -axis and it rotates around x -axis with the radius of R and the angular frequency of $\omega_r = 2\pi f_r$. A vertically (z) polarized plane wave at the frequency of f_0 as

$$\vec{E}_i(y) = E_0 e^{jk_y z} \quad (1)$$

impinges on the rotating tag where $k = 2\pi/\lambda$, $\lambda = c_0/f_0$, and c_0 in the free space light velocity. As shown in Fig. 1, besides the rotational micro-Doppler which modulates the phase of the backscattered wave [7], the magnitude of the backscattered wave is also modulated during the rotation since the reradiation pattern of the rectangular loop scatterer is modified as it rotates (the three respective reradiation pattern of the loop are shown in Fig. 1 at the three instants of the rotation), which is called directional amplitude modulation [8]. According to [7], [8], the time-varying complex envelope of the backscattered field from directional-Doppler modulated chipless tag can be expressed as

$$\vec{E}_s(y, t) = S_{vv}^n(f_0) E_0 \frac{e^{-jk_y y}}{y} \sin^2(\omega_r t) e^{j\beta \sin(\omega_r t) z} \quad (2)$$

where $S_{vv}^n(f_0) = S_{vv}(\phi = \pi/2, \theta = \pi/2, f_0)$ is the stationary vertical scattering coefficient of the loop scatterer at the normal direction ($\phi = \pi/2, \theta = \pi/2$) and $\beta = 4\pi R/\lambda$ is the micro-Doppler modulation index, while the term $\sin^2(\omega_r t)$ is the magnitude modulation proportional to the reradiation pattern of the resonant loop scatterer and the term $e^{j\beta \sin(\omega_r t) z}$ is the Doppler (phase) modulation. The modulated backscattered field $\vec{E}_s(y, t)$ in (2) is a periodic function of time with the same period as rotation which can be written in frequency domain as

$$\vec{E}_s(y, f) = S_{vv}^n(f_0) E_0 \frac{e^{-jk_y y}}{y} \sum_{n=-\infty}^{+\infty} C_n \delta(f - n f_r) \hat{z} \quad (3)$$

where $C_n = 0.5 J_n(\beta) - 0.25 [J_{n-2}(\beta) + J_{n+2}(\beta)]$ and $J_n(\beta)$ is the first kind Bessel function of order n . Similar to [7], [8], the frequency components generated by rotation-induced modulation are located at the harmonics of the rotation frequency ($n f_r$) based on which the differential RCS of the motion-modulated chipless tag can be defined.

B. Differential RCS

The differential RCS of the proposed motion-modulated chipless tag can be obtained using the same approach presented in [7]. Based on the equality of $\sum_{n=-\infty}^{\infty} |C_n|^2 = 0.375$ which can be obtained numerically, the differential RCS of the directional-Doppler modulated chipless tag is derived as

$$\sigma_d(f_0) = \sigma(f_0) (0.375 - 0.25[J_0(\beta) - J_2(\beta)]^2) \quad (4)$$

where $\sigma = 4\pi |S_{vv}^n(f_0)|^2$ is the stationary RCS of the loop scatterer at the normal direction. The equation (4) perfectly predicts the associated differential RCS of the motion-modulated tag in terms of its stationary RCS and the rotation characteristics which can be used to verify the measurement results based on the simulated RCS of the tag.

Algorithm 1 Measurement procedure

Require: Measurement bandwidth = BW

Require: Number of points = n

Require: Number of acquired frequency slots = m

Require: Number of carrier per slot = $p = \lfloor \frac{n}{m} \rfloor$

Center frequencies = $f_{c1}, f_{c2}, \dots, f_{cm}$

Carrier frequencies = f_1, f_2, \dots, f_n

for $k = 1 : m$ **do**

Require: Generator

Output signal = $A_0 \sum_{i=1}^p \cos(2\pi f_{[i+p(k-1)]} t + \alpha_i)$

Require: Spectrum

Center frequency = f_{ck}

Span = bw

Sample rate = SR

Acquisition time = t_a

Data transfer time = t_r

end for

Total number of measurements = m

Total measurement time $t_{total} = m \times (t_a + t_r)$

C. Reading process

According to (3), to identify the motion-modulated chipless tags using the backscattered field, the differential RCS at each carrier frequency f_0 should be obtained by the measurement of the motion-induced frequency components around each carrier. Thus, on one hand, the reading process should cover the large coding bandwidth (several 100 MHz up to several GHz) of the chipless tag [2], and on the other hand, it should provide sufficient frequency resolution (corresponding to the sufficient acquisition time) to observe the motion-induced components. Basically, the measurement scenario using a signal generator and a spectrum analyzer (which operate coherently) can be expressed by the procedure shown in Algorithm 1. Based on Algorithm 1, to measure the differential RCS at n points in a bandwidth of BW , generally there are two methods of measurement: Method (A) presented by [7] with $m = n$, $p = 1$, and $f_{ci} = f_i$; $i = 1, \dots, n$ in which the signal generator sequentially sends single-carrier waves and the spectrum analyzer acquires the backscattered signal in a narrow bandwidth ($bw < \text{several kHz}$) with a slow sample rate ($SR < \text{several kS/s}$), and Method (B) proposed by this work in which the measurement bandwidth BW is divided into m slots (up to 100 MHz) and the signal generator sends a multi-carrier ($p = \lfloor n/m \rfloor$ carriers) wave at each slot while the spectrum analyzer acquires the backscattered signal in the corresponding span (bw up to 100 MHz) with a high sample rate (SR up to several 100 MS/s). Worth mentioning that, the

acquisition time t_a in both methods should respect the time-variation of the movement (e.g covering several periods of the rotation) and also provide sufficient frequency resolution to observe modulation components. The performance of the two methods [(A) and (B)] in terms of reading time, provided SNR, and consequently the achievable read range is experimentally compared in the next section where the Method (B) will be more time-efficient with the same achievable read range as Method (A).

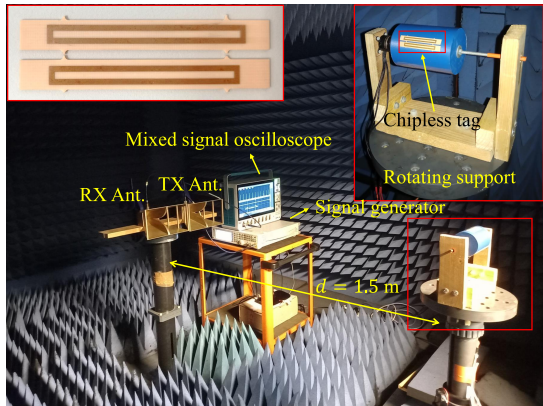


Fig. 2. The used measurement bench for time-efficient identification of motion-modulated chipless tag. The fabricated chipless tag and the rotating support are shown respectively in the left and right inset. The two resonance of the fabricated chipless tag is respectively measured at 1982 MHz and 2082 MHz.

III. RESULTS AND DISCUSSION

A. Measurement bench

The measurement bench used to realize the two reading methods [Method (A) and (B)] for the motion-modulated chipless tag is presented in Fig. 2. The bench is installed in an anechoic chamber and it is composed of a Vector Arbitrary Signal Generator (VASG) (Agilent N5182A) and a mixed signal oscilloscope (MSO) (Tektronix MSO68B) respectively connected to the transmitting (TX) and receiving (RX) antennas configured mono-statically both in vertical polarization. The VASG and the MSO are synchronized using a 10 MHz common reference signal. The VASG has a 31 MHz baseband I/Q modulation bandwidth which generates a single CW in Method (A) and multi-carrier waves in Method (B). The MSO as a real-time spectrum analyzer can acquire the coherently demodulated I/Q components of the backscattered signal in the defined span bw (up to 1.25 GHz) with a $SR = 1.25 * bw$ sample rate (up to 1.56 GS/s) and can store up to 340 M I/Q data points. Both instruments are remotely controlled by a PC using MATLAB scripts so that the measurement time can be precisely calculated using the time counting function in MATLAB. The rotational motion is realized using a motor-driven cylindrical support with the radius of $R = 35$ mm shown in the right inset of Fig. 2. A prototype of the chipless tag which consists of two microstrip rectangular loops with $l_1 = 55$ mm, $l_2 = 53$ mm, $w_1 = w_2 = 4$ mm, and $s = 1.2$ mm is fabricated using RO4003C Rogers substrate

TABLE I
MEASUREMENT PARAMETERS

	Method (A) [4]	Method (B) [This work]
BW	240 MHz	240 MHz
n	88	88
m	88	8
p	1	11
bw	1 kHz	30 MHz
SR	1.25 kS/s	37.5 MS/s
$t_a + t_r$	2.26 sec	10.7 sec
t_{total}	198.8 sec	85.6 sec

with $\epsilon_r = 3.55$ and the thickness of 0.813 mm as illustrated in the left inset of Fig. 2. The chipless tag is attached to the cylindrical rotating support while it is rotated with $f_r = 32$ Hz and positioned at the distance of 1.5 m from the antennas to fulfill the far-field radiation condition. The objective is to measure differential RCS of the realized motion-modulated chipless tag at $n = 88$ equidistant points in a $BW = 240$ MHz bandwidth ($f_i = 1915 : 2.7 : 2115$ MHz $i = 1, \dots, 88$) using the two measurement methods (A) and (B) with the parameters indicated in Table I. In method (A) the backscattered signal is sequentially acquired in $m = 88$ slots (1 kHz-wide) around the single-carriers $f_{ci} = f_i$; $i = 1, \dots, 88$ while in method (B) the backscattered signal is acquired in $m = 8$ slots (30 MHz-wide) centered at $f_{ci} = 1930 : 30 : 2140$ MHz to catch the data for 11 carriers in each slot [See Fig. 3 (a)]. The acquisition time in both methods is set such that to have 1.6 Hz frequency resolution while the measurement time for each acquired frequency slot ($t_a + t_r$) is recorded using MATLAB. The output power of the VASG in method (A) and (B) is set respectively at $P_t = -10.4$ dBm and $P_t = 0$ dBm to have the same carrier power level $P_c = -10.4$ dBm in both methods.

B. Performance evaluation

The performance of the two reading methods (A) and (B) is compared in terms of SNR, identification time, and achievable read range based on the experimental results. Using FFT calculation of the captured I/Q data in method (B) around $f_{c3} = 1990$ MHz [See Fig. 3 (a)] (which is close to the first resonance of the chipless tag) the Power Spectral Density (PSD) of the backscattered signal is shown in Fig. 3 (b) where the frequency domain data has been obtained with a resolution of 1.6 Hz for 11 carriers in 30 MHz bandwidth with one acquisition. The obtained PSD in method (B) and that measured in method (A) around one carrier [the fourth carrier in Fig. 3 (b)] are compared in Fig. 3 (c) in a 600 Hz bandwidth. As an important result, the two PSDs are identical in terms of SNR. In fact, although the input noise bandwidth in method (B) is higher than that in method (A), the measured rotation-induced modulation harmonics and the noise floor have the same levels in both methods which keeps the SNR the same. It should be mentioned that the same SNR level in both methods will provide the same achievable read range for

both methods which will be discussed in terms of differential RCS measurements.

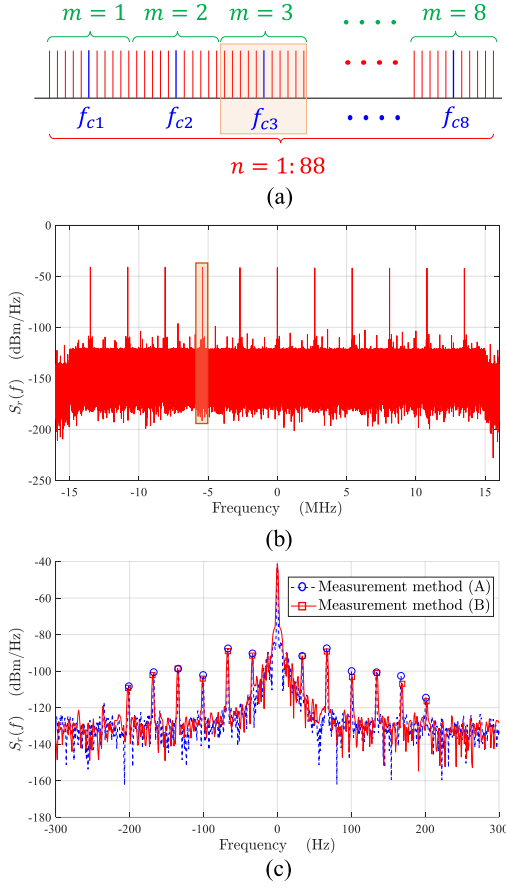


Fig. 3. (a) The carrier and slots configuration used in the method (B). (b) Calculated PSD of the backscattered signal measured in method (B) at the third frequency slot. (c) Measured PSD of the backscattered signal using method (A) and (B) in a narrow bandwidth.

The differential RCS of the motion-modulated chipless tag is calculated based on the measured PSD in both methods (A) and (B) using the approach presented in [7]. Fig. 4 shows the measured differential RCS of the rotating cylindrical support using methods (A) and (B) as a function of frequency in 240 MHz band in two states: when the chipless tag is attached ('With tag') and when the chipless tag is not present ('No tag'). The resonance frequencies of the two rectangular loops are clearly identifiable, which makes it possible to obtain the tag identifier without ambiguity. Indeed, as expected, peak apexes at the same frequencies for the RCS as for the delta RCS curves have been found. Moreover as it can be observed, the results obtained for differential RCS using method (B) is perfectly in agreement with what is obtained using method (A). Accordingly, based on the results presented in [7] using method (A), read ranges up to 10 m can be also achieved using method (B) which demonstrates the good functionality of the method (B) in terms of read range. In addition, the differential RCS of the motion modulated chipless tag is calculated using (4) based on the RCS simulation of the chipless tag and it

is shown in Fig. 4 where the both measurement results are compatible with what is predicted analytically.

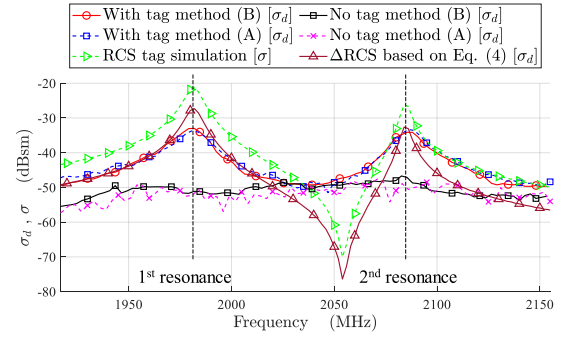


Fig. 4. Measured differential RCS of the motion-modulated chipless tag using methods (A) and (B). The measurement results are compared with results obtained by the analytical model.

Finally, as the most important result, the identification time of the motion-modulated tag using methods (A) and (B) is noted in Table I. In fact, using the method (B) the identification time can be reduced by a factor of 2.5 while the read range performance is not affected. It should be noted that this identification time reduction factor can be even up to several 10 times in case the VASG had a wider baseband modulation bandwidth.

IV. CONCLUSION

The multi-carrier reading approach was presented to identify motion-modulated chipless tags while the reading time was reduced by a factor of 2.5. In spite of using wider acquisition span, the multi-carrier method has provided the same SNR level as the single-carrier approach which results in a several meters read range for the motion-modulated chipless tag. The experimental results have been verified using the developed analytical model.

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