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Ashkan Azarfar, Nicolas Barbot, Etienne Perret. Long-Range Chipless RFID for Objects in Translation using Doppler-modulated Depolarizing Tags. 2023 IEEE/MTT-S International Microwave Symposium - IMS 2023, Jun 2023, San Diego, France. pp.1073-1076, 10.1109/IMS37964.2023.10188160 . hal-04775575

HAL Id: hal-04775575

<https://hal.science/hal-04775575v1>

Submitted on 8 Dec 2024

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Long-Range Chipless RFID for Objects in Translation using Doppler-modulated Depolarizing Tags

Ashkan Azarfar, Nicolas Barbot, and Etienne Perret
 Univ. Grenoble Alpes, Grenoble INP, LCIS, 26000 Valence, France
 ashkan.azarfar@lcis.grenoble-inp.fr

Abstract— The paper describes how depolarizing chipless tags attached to objects carried by a conveyor belt can be robustly read at much larger distances compared to what classically has been reached before. The key idea is to utilize the Doppler modulation induced by the translation in order to isolate the moving tag response from that of the stationary environment, while the depolarizing property of the tag is also used to suppress the object contribution within the Doppler component. The concept is studied theoretically and verified experimentally where the moving classical chipless tag can be read at distances up to 4.5 m.

Keywords— Chipless Radio Frequency Identification (RFID), Conveyor belt, Doppler effect, Resonant Scatterer.

I. INTRODUCTION

Chipless RFID has been introduced as a technology that can be used in massive identification scenarios while it is much more cost-effective compared to classical chipped RFID. The chipless technology has been developed in terms of coding approaches and robust reading processes in recent years [1], while achieving read ranges greater than 1 meter for stationary chipless tags (chipless tags which are fixed at one location), is still a challenging problem that has been considered by limited works like [2] where the reading process is suffered from misalignment issues. However, in [3] it has been proved that this read range limitation originates from the physical fact that stationary chipless tags behave exactly as Linear Time-Invariant (LTI) systems, and consequently, this limit cannot be broken unless the LTI property is somehow removed from chipless tags.

The concept of backscatter communication based on modulated reflectors has been pioneered by Theremin [4] and Stockman [5] in the 1940s, and recently the idea has been considered in the chipless domain by [6], [7], [8]. The micro-Doppler effect produced by periodic motions like rotation has been recently utilized in [8] to violate the LTI property for chipless tags, and to reach reading distances up to 10 m. However, this idea cannot be practically applied for real identification scenarios where usually the target objects are carried by a conveyor belt and the movement is not periodic anymore. In addition, by assuming a locally fixed reader, the reading distance of the tags are varying with time which is not the case in [8]. The robust reading approach for chipless tags moving by a conveyor belt is considered in [9] based on a data processing method. To increase the detection probability of the tags in [9] using the conveyor belt, the background measurement (which should be collected in the absence of the tag) has been done before the tag passes in front of the

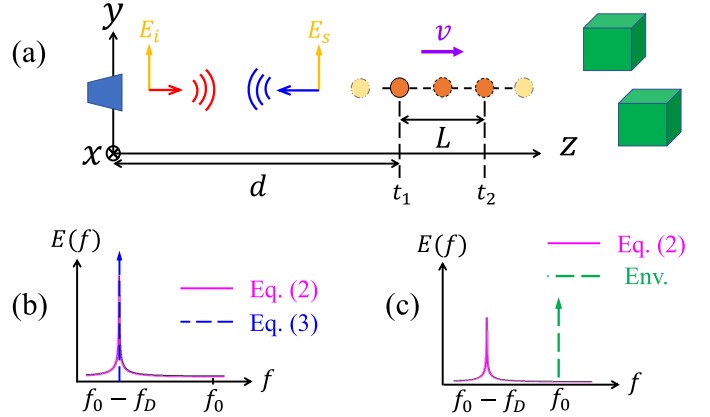


Fig. 1. (a) Backscattering from a translating scatterer with constant velocity. The spectral representation of the backscattered field from (b) the translating scatterer in free space (c) the translating scatterer with the background environment.

reader antenna. In addition, several measurements have been performed during the pass time, while in each measurement the tag has been supposed to be stationary. Indeed, although the movement of the conveyor belt is used in [9], this movement has not been utilized to overcome the chipless read range limitation by considering the moving chipless tag as a Linear Time-Variant (LTV) system modulated based on the Doppler effect. Consequently, the maximum read range in [9] could not cross beyond 1.3 m.

In this paper, the Doppler modulation due to the translational movement of the conveyor belt is utilized as an effect to break the LTI characteristic of the chipless tag so that it can be read at larger distances compared to what has been achieved until now. In addition to the Doppler effect that is considered to isolate the moving tagged object response from the stationary environment clutter, the used depolarizing chipless tag provides another degree of isolation to separate the contribution of the tag from that of the object to achieve more robust detection at large distances. We also note that all the developments presented here do not require the redesign of new chipless tags. Indeed, the measurement method applies to resonant chipless tags compatible with a reading in crossed polarization. This shows that the approach is general and only concerns the reader and the post-processing part of a chipless RFID system.

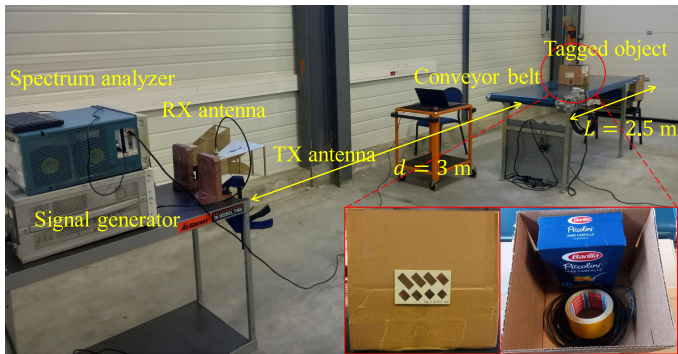


Fig. 2. Measurement bench used for tagged object identification carried by the conveyor belt. The side and inside view of the tagged object is shown in the inset.

II. ANALYTICAL MODEL

A. Backscattering from translating scatterer

Fig. 1 (a) shows a translating scatterer along the z -axis to model the mono-static scattering from depolarizing chipless tags carried by straight conveyor belts. The scatterer is assumed to have a constant velocity v in $+z$ direction during the time interval between t_1 and t_2 while the distance between the scatterer and the antenna is d at time t_1 , and $L = v(t_2 - t_1)$ is the distance passed by the scatterer during this time interval. Accordingly, the location of the scatterer can be expressed as $x(t) = 0$, $y(t) = 0$, and $z(t) = d + vt$ for $t_1 < t < t_2$. The y -polarized spherical wave radiated by the antenna at f_0 frequency that impinges on the scatterer can be written as

$$\vec{E}_i(t) = \frac{E_0}{d + vt} e^{-jk(d+vt)} \hat{y} \quad (1)$$

for $t_1 < t < t_2$ where $k = 2\pi f_0/c_0$ and c_0 is the free-space light velocity. Accordingly, the cross-polarized scattered field from the translating scatterer when $v \ll c_0$ can be obtained as

$$\vec{E}_s(t) = \frac{E_0 S_{yx}(f_0)}{(z - d - vt)(d + vt)} e^{-j2k(d+vt)} e^{jkz} \hat{x} \quad (2)$$

for $t_1 < t < t_2$ where $S_{yx}(f_0)$ is the cross-polarized scattering coefficient of the scatterer defined in the plane of the scatterer (and thus independent of the distance). Worth mentioning that, for $d \gg L$ which is the usual case in radar applications, at the location of the antenna ($z = 0$), the scattered field will be simplified as

$$\vec{E}_s(t) = [-E_0 S_{yx}(f_0)/d^2] e^{-2jk(d+vt)} \quad (3)$$

where the amplitude of the scattered field is assumed invariant in time and the $f_D = 2v/\lambda$ is the classical Doppler shift frequency associated to the linear phase modulation on the scattered field [shown by blue impulse in Fig. 1 (b)]. However, in the case of chipless RFID using conveyor belts, d is comparable with L and the amplitude modulation induced by the movement modifies the frequency spectrum of the backscattered field such that it will not be anymore a pure single component located at the Doppler frequency (f_D). It can be shown that, although the exact frequency spectrum

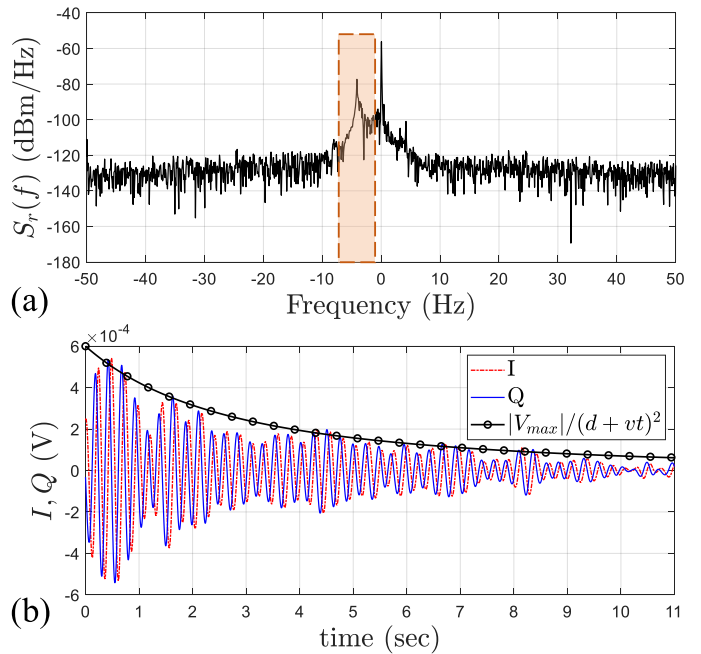


Fig. 3. (a) Measured PSD of the backscattering from translating tagged object at $f_0 = 3.59$ GHz. (b) The processed I , Q data corresponds to the translating tagged object response after removing the environment clutter.

considering both amplitude and phase modulation is also almost concentrated at f_D , it has a decaying tail around f_D which can be significant when the velocity v increases as shown in Fig. 1 (b). Moreover, considering that the translating scatterer is located in a stationary environment [shown by green boxes in Fig. 1 (a)], the backscattering from the environment will be exactly at f_0 [shown by green impulse in Fig. 1 (c)] which does not affect the reflection from the scatterer, and consequently provides the clutter suppression.

B. Differential RCS

Differential RCS σ_d has been originally defined for UHF tags based on the two states of the modulating load and it has been formulated in time-domain [10]. Recently, the definition of the differential RCS has been generalized for any modulating tag by using a frequency-domain analysis [11] which has been used to obtain the σ_d of the rotating chipless tag in [8] based on the micro-Doppler modulation. Similar to [8], the differential RCS of the translating chipless tag can be defined based on (1) and (2). However, in contrast to [8], the Doppler-modulated (translating) scatterer does not remain in a fixed range while its range is varying with time, and consequently, the backscattered field has a time-varying amplitude. Accordingly, to assign a unique distance-independent quantity to the differential RCS here, we propose to define σ_d based on the time domain fields (according to [11] which demonstrates that the time domain and frequency domain definitions are exactly equivalent) as

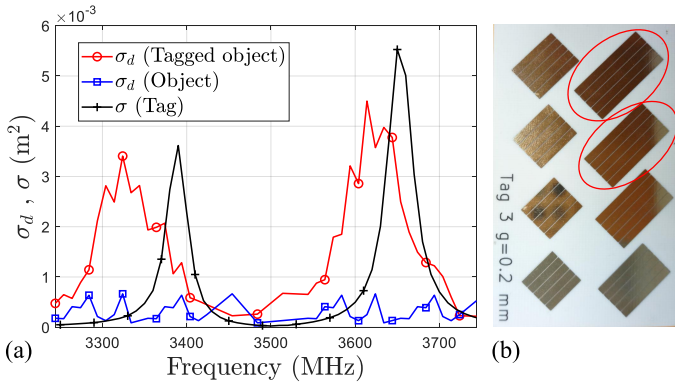


Fig. 4. (a) Measured differential RCS of the translating object with and without the tag respectively shown in red and blue, and the simulated RCS of the tag in black. (b) The fabricated prototype of the depolarizing chipless tag proposed in [12] with $g=0.2$ mm, $w=2$ mm, $l_1=21$ mm, and $l_2=19$ mm.

$$\sigma_d(f_0) = 4\pi \frac{\overline{(d+vt)^4 |E_s(t)|^2}_{t_1}^{t_2} - \overline{(d+vt)^2 |E_s(t)|^2}_{t_1}^{t_2}}{\overline{(d+vt)^2 |E_i(t)|^2}_{t_1}^{t_2}} \quad (4)$$

where $\overline{(\cdot)}_{t_1}^{t_2} = \frac{1}{\Delta t} \int_{t_1}^{t_2} (\cdot) dt$ is the time-average operator and the time-decaying magnitude of the fields are compensated with the time-varying range $(d+vt)$ such that the resultant quantity for σ_d is independent of distance. Note that, although (4) is defined in the time domain, it has the same interpretation as σ_d has in [11] and [8], since the numerator of (4) is related to differential backscattered power P_{bsd} (the first term is proportional to the total backscattered power and the second term is the static backscattered power (average value) which is subtracted to get the differential part) and the denominator of (4) is related to the incident power density. Moreover, it can be shown that in the practical situation for conveyor belts ($v > 0.1$ m/sec), the static term of the backscattered power in the UWB frequency band is negligible so that the differential RCS can be simplified as

$$\sigma_d(f_0) = 4\pi |S_{yx}(f_0)|^2 = \sigma(f_0) \quad (5)$$

which means, contrary to [8], the σ_d value does not depend on the motion properties (like the radius of rotation in [8]) and it is theoretically equal to the classical RCS (σ) of the scatterer that yields close to a 100% modulation efficiency in this case.

III. RESULTS AND DISCUSSION

A. Measurement Bench

The measurement setup in a real environment is presented in Fig. 2 which is composed of a RF signal generator (HP 8720D) and a spectrum analyzer (Tektronix RSA3408A) respectively connected to TX and RX antennas (A.H. Systems SAS-571) in cross-polarized monostatic configuration. The two instruments are made coherent using 10 MHz common reference signal. The conveyor belt with the length of $L = 2.5$ m and the speed of $v = 0.19$ m/s is located at $1 < d < 3$ m

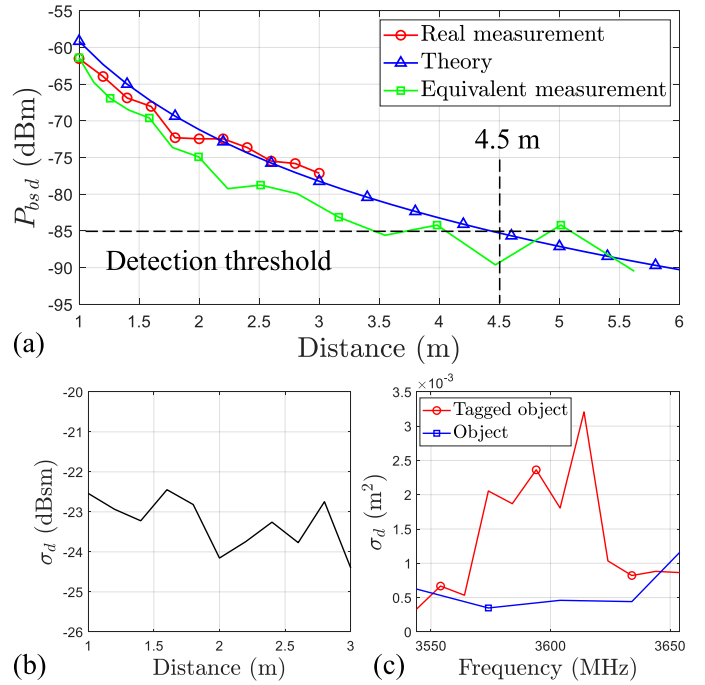


Fig. 5. (a) The measured differential backscattered power from the translating tagged object as a function of distance d between the antennas and the conveyor belt. (b) The calculated differential RCS of the translating chipless tag as a function of distance. (c) The measured differential RCS of the translating object (with and without tag) at 3 m distance.

distance from the antennas. A fabricated prototype of the depolarizing chipless tag presented in [12] has been used for measurements which is shown in Fig. 4 (b). The real tagged object shown in the inset of Fig. 2 is a typical cardboard box filled with things like a pasta pack, a tape roll, and a piece of LAN cable. The output power P_t is 5 dBm, and to measure σ_d at $3.2 < f_0 < 3.8$ GHz (to measure at each carrier frequency, the tagged object was translated one time by the conveyor belt) the object is put on the running belt while the backscattered signal is acquired for 11 seconds with 256 S/s sample rate by the spectrum analyzer.

B. Identification based on differential RCS

Based on the acquired raw inphase and quadrature I_r, Q_r voltage data at $d = 1.2$ m and $f_0 = 3.59$ GHz (the second resonance frequency of the tag), the Power Spectral Density (PSD) $S_r(f)$ of the measured backscattered signal is calculated using FFT and presented in Fig. 3 (a). As it was predicted by the model in Fig. 1 (c), the modulated power is mainly concentrated around the corresponding Doppler shift frequency $f_D = -4.5$ Hz which is highlighted in Fig. 3 (a) and the reflection from the stationary environment is located at $f = 0$ (corresponds to f_0 after down conversion). To remove the environment clutter from the raw I_r, Q_r data in time domain and just keep the tag response, a filter [shown by highlight area in Fig. 3 (a)] with the pass-band of $-5 < f < -3$ Hz is applied to $S_r(f)$, and then using IFFT, the processed I, Q data is presented in Fig. 3 (b) as a function of time. The amplitude of the measured backscattered signal is decreasing

with the time and it is illustrated in Fig. 3 (b) [black curve] that the decay rate is exactly proportional to the inverse square of the increasing range as it was expected based on the model [Equation (2)]. Moreover, the frequency of the oscillations for I , Q data is in agreement with the predicted Doppler frequency $|f_D| = 4.5$ Hz. Using the received voltage $V_r(t) = I_r(t) + jQ_r(t)$ data at $f_0 = 3.2 : 0.02 : 3.8$ GHz and based on (4), the calculated differential RCS of the tagged object and that of the object without tag are presented in Fig. 4 (a) as a function of carrier frequency. Note that (4) can be directly applied to the total backscattered field (contribution of the tagged object and environment) since the environment clutter is included by the static term in the numerator, and it is subtracted to obtain the P_{bsd} . To use (4), the backscattered and incident field is respectively obtained by $E_s(t) = [\sqrt{4\pi\eta/Z_0G\lambda^2}]V_r(t)$ and $E_0 = \sqrt{2\eta P_t G/4\pi}$ where G is the antenna gain, η is the free-space wave impedance, and $Z_0 = 50\ \Omega$ is the reference impedance of the spectrum analyzer and signal generator. The two first resonance of the chipless tag [related to the scatterers shown in Fig. 4 (b) by red lines] can be obviously detected from the calculated σ_d in Fig. 4 (a) which proves the identification capability based on differential RCS. In addition, the simulated RCS of the tag σ is compared with the measured σ_d in Fig. 4 (a) that verifies (5) and the fact that the modulation efficiency is more than 95% in this technique.

C. Read Range

Finally, the maximum read range for the tagged object carried by the conveyor belt is studied experimentally. The differential backscattered power P_{bsd} is measured at $f_0 = 3.95$ GHz with two approaches: 1) increasing the distance d as 1:0.2:3 m with a fixed $P_t = 5$ dBm (Real measurement) and 2) decreasing the P_t as 5:−1:−25 dBm at a fixed distance $d = 1$ m (Equivalent measurement) which Fig. 5 (a) presents both measurement results as a function of distance (d) in agreement with what is obtained using classical radar equation in theory. Considering a detection threshold of −85 dBm, the maximum achievable read range is obtained as 4.5 m which outperforms the ones associated with the classical chipless tag in [12] and [9] respectively by a factor of 15 and 4. Fig. 5 (b) shows the calculated σ_d at the second resonance as a function of d which verifies the validity of (4) to define a distance-independent quantity for differential RCS. At last, identification capability of the moving tag is examined at $d = 3$ m with the measured σ_d shown in Fig. 5 (c) where the second resonance of the tag is detected well.

IV. CONCLUSION

Depolarizing chipless RFID tags attached to objects carried by a conveyor belt have been read in a real environment at large distances up to 4.5 m (distance between the antennas, and the nearest end of the conveyor belt) using the benefit of Doppler modulation induced by the translation. We also showed that a very significant increase of the reading distance can be obtained by working on the reader part. Indeed a gain

on the sensitivity of the measuring bench of 5 dB would make it possible to increase by 1.5 m the reading distance. An analytical model based on the differential RCS has been proposed and the tag was successfully detected based on the measured differential RCS. Since the conveyor belt scenario is the most common case in practical applications, the idea can be promisingly attracted by logistics industry.

ACKNOWLEDGMENT

This work was supported by the European Research Council (ERC) through the European Union's Horizon 2020 Research and Innovation Program (ScattererID) under Grant N° 772539.

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