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Hand Motion-modulated Chipless RFID for Gesture Recognition

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Abstract— This paper presents real-time identification of slow motion-modulated chipless RFID which can be applied to human hand gestures to realize a full-practical long-range RFID system with gesture recognition capability. Depolarizing chipless tags configured by hand in three gestures are utilized while different motion-induced modulation effects involved in each gesture are analytically modeled. The identification based on differential RCS and gesture recognition using deterministic IQ trajectories is theoretically and experimentally demonstrated. Using the real-time reading process, the designed gesture-modulated chipless tag is identified during a few seconds at distances up to 3 m while all the hand gestures are recognized at 2 m range based on the received IQ signature.

Keywords— Differential Radar Cross Section (RCS), Hand gesture recognition, Motion-modulated chipless Radio Frequency Identification (RFID)

I. INTRODUCTION

Chipless technology has been introduced to present a new low-cost paradigm for the RFID market based on the principle of excluding electronic chips from tags structure [1]. However, since chipless tags have no source of modulation and behave as Linear Time-Invariant (LTI) systems [2], chipless RFID essentially suffers from limited read ranges of less than 1 meter.

Based on the landmark idea of backscatter communication using moving reflectors presented by [3], motion-modulated chipless RFID has been recently introduced in [4] where the time-variant feature of motion has been integrated with chipless technology to break the LTI property of chipless tags, and consequently, to significantly increase the reading distance up to several meters. Moreover, different kinds of motion-induced modulation such as load modulation [5], phase (or micro-Doppler) modulation, polarization modulation, and Directional Amplitude Modulation (DAM) have been addressed in [4] while most of the utilized motion sources are based on mechanical setups and not based on natural movements like human body motions. In addition, the presented reading approach for motion-modulated chipless RFID in [4] based on stepped-CW coherent In-phase/Quadrature (I/Q) acquisition leads to very long identification times of a few minutes for slow natural motions, which cause this reading approach to not be feasible in real RFID applications based on common natural movements.

Human hand gestures are the most common natural movements that have been applied for wireless human-machine communication based on micro-Doppler radar approaches where gestures are classified using time and memory-consuming Convolutions Neural Networks (CNN)

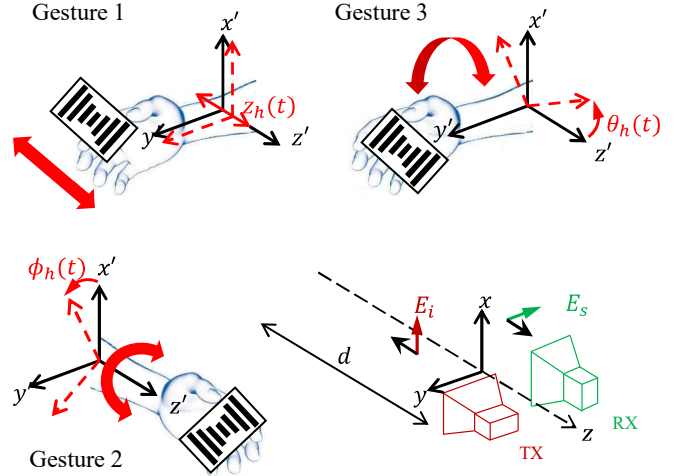


Fig. 1. Three considered human hand gestures to realize motion-modulated chipless RFID based on different modulation effects.

methods with a maximum read range of several 10 cm [6], [7]. Hand gesture recognition using classical chipless RFID has been also introduced in [8] and [9] respectively based on touch-sensing and phase multi-lateration approaches whereas the time-variant property of the hand motion has not been involved in non of these chipless gesture recognition methods that cause the limited read range of 30 cm.

This paper presents a full-practical motion-modulated chipless RFID system based on a real-time reading process that is applied for held-in-hand chipless tags modulated by different hand gestures. Besides a large reading distance and feasible tag identification time of a few seconds for hand natural motions, the analytically obtained backscattering IQ signature of the hand gesture-modulated chipless tags is utilized for gesture recognition which adds another way to communicate with the reader.

II. MODEL AND METHODOLOGY

A. Motion-modulated backscattered field

The three hand gestures considered for motion-modulated chipless RFID are shown in Fig. 1. In Gesture 1 the human hand is linearly shaken along the z axis with an amplitude of D [$z_h(t) \approx D \sin(2\pi f_h t)$]. In Gesture 2 and Gesture 3 the tag is respectively turned around z and y axis between two extreme rotation angles expressed as $\phi_1 < \phi_h(t) < \phi_2$ and $\theta_1 < \theta_h(t) < \theta_2$. For the sake of simplicity, the three gestures are assumed to be performed with the same period

Table 1. Modulation function of hand gestures

	$\psi(t)$	$\eta(\psi)$
Gesture 1	$\exp[j(\frac{4\pi D}{\lambda}) \sin(\frac{2\pi}{T_h} t)]$	0.97
Gesture 2	$\cos[2\phi_h(t)]$	0.52
Gesture 3	$\cos^2 \theta_h(t)$	0.125

of $T_h = 1/f_h$. The human hand is assumed at the distance of $d \gg D$ from the cross-polarized TX (x -polarized) and RX (y -polarized) antennas and the hand is impinged by a plane wave at the frequency of f_0 expressed as

$$\vec{E}_i(z) = E_0 e^{jkz} \hat{x} \quad (1)$$

where $k = 2\pi/\lambda$, $\lambda = f_0/c_0$, and c_0 is the free space light velocity. The considered classical chipless tag consisting of printed dipole resonators with a size comparable to a credit card is designed to be easily held in hand for different gestures as shown in Fig. 1. According to the approximated periodic motion trajectory of the chipless tag in each gesture, the main involved motion-induced modulation effect in Gesture 1, Gesture 2, and Gesture 3 can be respectively modeled as vibrational micro-Doppler modulation, polarization modulation, and directional modulation [4]. Assuming the hand keeps the depolarizing configuration (45° tilted with respect to the incident polarization) of the chipless tag during Gesture 1 and Gesture 3, the cross-polarized motion-modulated field scattered from the moving chipless tag in different hand gestures can be generally expressed as

$$\vec{E}_s^{(p)}(z, t) = \hat{y} S_{xy}(f_0) E_0 \frac{e^{-jk(z+2d)}}{z+d} \psi^{(p)}(t) \quad (2)$$

where $S_{xy}(f_0)$ is the cross-polarized scattering parameter of the chipless tag and $\psi^{(p)}(t)$ for $p = 1, 2, 3$ is the respective periodic modulation function in Gesture 1, Gesture 2, and Gesture 3 indicated in Table 1. It should be noted that the modulation function in Gesture 1 and Gesture 2 is derived analytically, while that of Gesture 3 is an approximation of the frozen-time full-wave simulation results.

B. Differential RCS and IQ backscattering signature

Based on the obtained time-domain expression of the motion-modulated backscattered field in (2) for the three gestures, differential RCS of the hand gesture-modulated chipless tag can be calculated using the general definition given by [10] which is written as

$$\sigma_d^{(p)}(f_0) = 4\pi |S_{xy}(f_0)|^2 \eta[\psi^{(p)}] \quad (3)$$

where $0 \leq \eta[\psi^{(p)}] \leq 1$ is defined as the motion-induced modulation efficiency respectively in each gesture for $p = 1, 2, 3$, which are indicated in Table 1. Worth mentioning that, the value of $\eta[\psi^{(p)}]$ is calculated based on the modulation function $\psi^{(p)}(t)$ in each gesture for the typical gesture

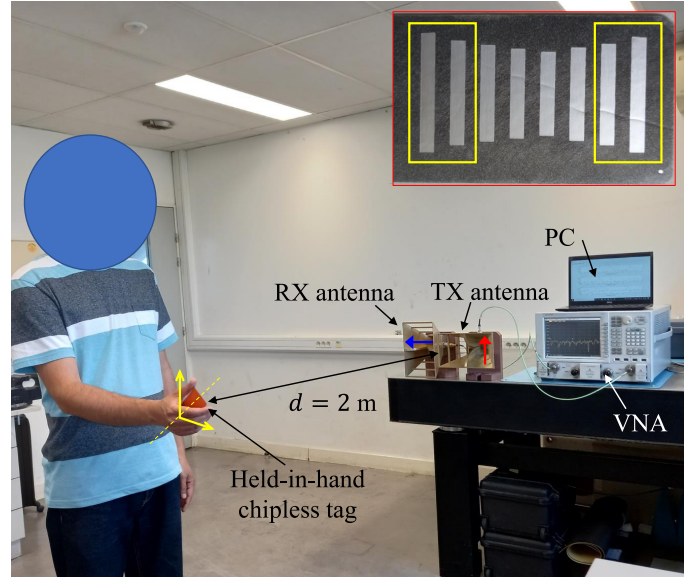


Fig. 2. Measurement setup in a real closed environment for hand gesture-modulated chipless RFID. The fabricated chipless tag and the dipole resonators associated with the first four resonance frequencies is shown in the inset.

characteristic of $D = 5$ cm for Gesture 1 at $f_0 = 4.5$ GHz, $\phi_1 = -135^\circ$ and $\phi_2 = 45^\circ$ for Gesture 2, and $\theta_1 = 0^\circ$ and $\theta_2 = 90^\circ$ for Gesture 3. Gestures with higher $\eta(\psi)$ modulate the field backscattered from the chipless tag more effectively which provides higher differential RCS that can be detected at larger distances. Note that, the function $|S_{xy}(f_0)|^2$ preserves the resonating backscattering behavior of the chipless tag from which the identification data can be retrieved based on differential RCS measurement.

Moreover, the IQ backscattering signature of the hand gesture-modulated chipless tag can be analytically obtained as $I(t) = \text{real}\{\psi(t)\}$ and $Q(t) = \text{imag}\{\psi(t)\}$ while the respective IQ trajectory in each gesture is shown in Fig. 3 (a) (red curves) during one period of gesture. The IQ trajectories shown in Fig. 3 (a) can be obviously recognized from each other which proves the gesture recognition capability based on hand gesture-modulated chipless RFID. Worth mentioning that, in contrast to the methods presented in [6], [7], the feature vectors applied for CNN-based classifier (IQ trajectories here) can be analytically determined in motion-modulated chipless RFID.

C. Real-time reading process

In contrast to the stepped-CW coherent IQ acquisition reading process presented in [4], the motion-modulated backscattered field for slow movements (like hand gestures) can be acquired by a sequence of fast frequency sweeps (sweeps that last for a duration much less than the motion period and cover the coding bandwidth of the chipless tag) which provides all the required IQ data for differential RCS measurement and tag identification during several periods of motion. This real-time reading approach leads to a significant reduction in the identification time for slow motion-modulated

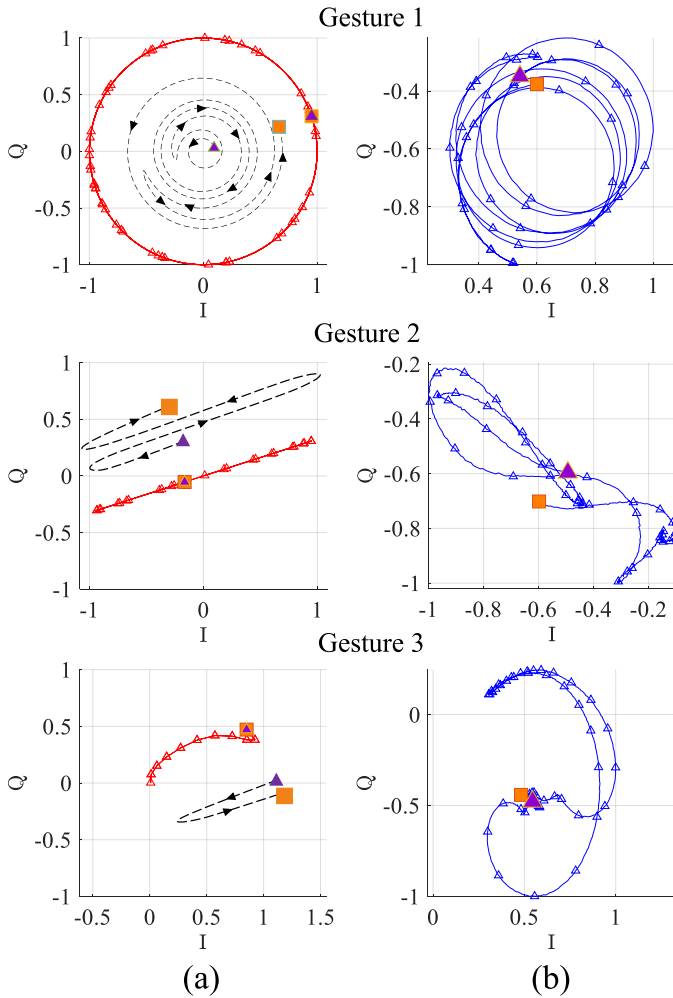


Fig. 3. (a) Analytically obtained IQ backscattering signature of the hand gesture-modulated chipless tag in three gestures during one period of motion. The start and end points on the trajectories (red curves) are respectively marked with purple triangle and orange square markers while the signal path is shown by black dashed line curves. (b) Measured IQ backscattering signature of the hand gesture-modulated chipless tag in three gestures during one period of motion with start and end points respectively marked by the purple triangle and orange square markers.

chipless RFID while the same performance as [4] can be obtained in terms of read range.

III. RESULTS AND DISCUSSION

A. Measurement scenario

The measurement setup for motion-modulated chipless RFID based on hand gesture in a real closed environment is illustrated in Fig. 2 where the Port1 and Port2 of a Vector Network Analyzer (VNA) (Keysight PNA N5222A) is respectively connected to the cross-polarized TX and RX antennas (A.H. Systems SAS-571) to implement the real-time reading process based on the frequency-sweep capability of VNA. For an output power of $P_t = 10$ dBm, the $[S_{21}]$ parameter is measured over $[4.2 : 0.01 : 5.2]$ GHz bandwidth where each frequency sweep acquisition lasts only 70 ms. A fabricated prototype of the chipless tag consisting of 8

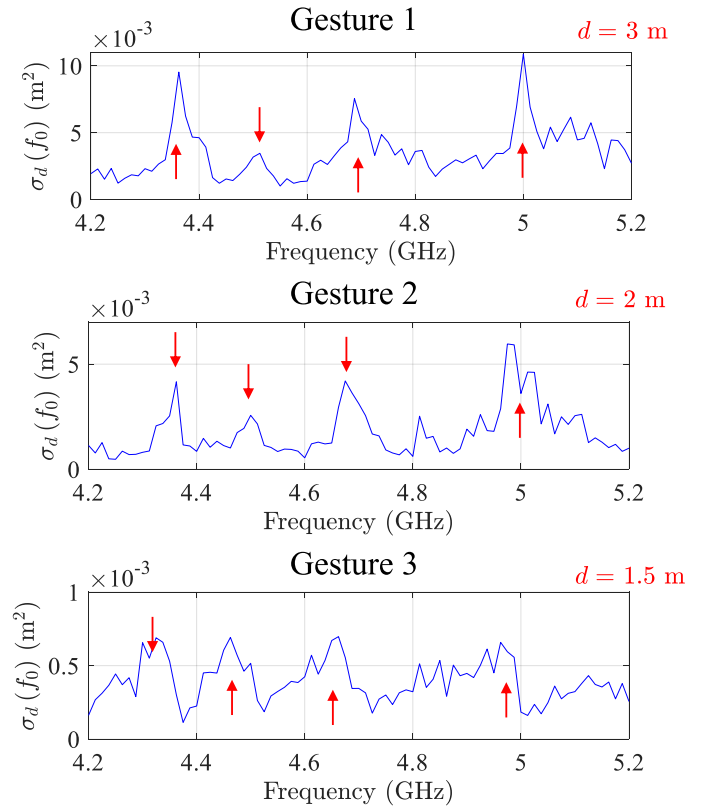


Fig. 4. Measured differential RCS of the hand gesture-modulated chipless tag at the corresponding maximum achieved read range for each of the three gestures.

printed dipole REPs is shown in the inset of Fig. 2. A human subject holds the chipless tag in his hand with a depolarizing configuration and performs the three gestures (Gesture 1, Gesture 2, and Gesture 3) in agreement with the described trajectories presented in Fig. 1 at the distance of d from the antennas. The period of all hand gestures is tried to be around $T_h = 0.8$ sec and the gesture characteristics are also tried to be compatible with the previously mentioned typical values in each gesture.

B. Tag identification and gesture recognition

The differential RCS of the hand gesture-modulated chipless tag is calculated based on the measured IQ data via the real-time reading process for the three gestures and they are shown in Fig. 4 where the first four resonances of the chipless tag are perfectly identified at the respective maximum achievable read range of $d = 3$ m, $d = 2$ m, and $d = 1.5$ m for Gesture 1, Gesture 2, and Gesture 3. In addition, the respective order of the measured differential RCS (and consequently the achieved read range) for the three gestures is in accord with what was predicted by the model in terms of $\eta(\psi)$ shown in Table 1. For all gestures, the tag is detected during the feasible identification time of 5.7 sec which completes the first full-practical example of motion-modulated chipless RFID that can be applied in real scenarios using human hand gestures.

The IQ components of the motion-modulated received signal at the first resonance frequency of the chipless tag $f_0 = 4.35$ GHz is captured at the distance of $d = 2$ m and the corresponding measured IQ trajectories are shown in Fig. 3 (b) for each hand gesture during one period of motion. The measured IQ trajectories illustrated in Fig. 3 (b) for each gesture are in agreement with what has been obtained using the model shown in Fig. 3 (a). Moreover, different deterministic IQ trajectories associated with each hand gesture (circular, linearly double round-trip, and semi-linearly single round-trip trajectory respectively for Gesture 1, Gesture 2, and Gesture 3), prove the hand gesture recognition using hand-held motion-modulated chipless tags.

IV. CONCLUSION

The hand gesture-modulated chipless RFID based on three hand gestures has been analytically modeled while different kinds of motion-induced modulation (micro-Doppler, polarization, and directional amplitude modulation) were considered in each gesture. The real-time identification and gesture recognition capability have been experimentally verified in a real environment for all the gestures with an identification time of about 6 seconds. Finally, reading distances up to 3 m have been achieved in experiments which makes this work the first full-practical example of motion-modulated chipless RFID that can be used in real long-range applications.

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