Performance Assessment of FMCW Radar Processing for Transponder Identification

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***Abstract*—This paper concerns the use of Frequency Modulated Continuous Wave (FMCW) radars for Radio Frequency Identification (RFID) transponders identification and range localization. In our study, we consider the transponder identification by applying a shift frequency to the RFID transmitted signal. Consequently, our investigation addresses the spectral analysis of the received signal on the FMCW radar. First, the classical FFT method is used for detection of two or more RFID transponders which could be tagged by near shift frequencies. Then, spectral estimation and high resolution methods are evaluated to enhance the detection and discrimination of transponders both in case of free space or Rayleigh fading propagation channel. Finally, the impact of non-linear frequency sweep on the performance of FMCW radar processing is examined. Modeled results are presented showing the effect of such non-linearities on detection accuracies of the transponder.**

***Index Terms*—Frequency Modulated Continuous Wave (FMCW), RFID Transponder, Spectral and High resolution methods, Non-linearity.**

I. Introduction

In recent years, radio frequency identification (RFID) has become a key technology in the field of logistics, as it allows identification and tracking of the objects to which the RFID transponders are attached. RFID systems at the HF range are used in different areas such as access control and livestock tracking. Lately RFID systems in the UHF range (860-960 MHz) and at microwave frequencies (2.45 GHz and 5.8 GHz) have also become very popular because they enable a larger operating distance [1]. While passive UHF transponders allows distances up to 10 m, active tags makes even higher range detection possible. Therefore, besides the standard data transfer function between reader and transponder, the distance information could also be evaluated [2], [3]. Recent works have demonstrated the potential for backscatter-based sensors intended for tracking persons and objects, bio-signal recording [4], logistics/asset monitoring [5] and environmental sensing [6]. The distance measurement provided by RFID localization systems is based on different principles. Conventional ranging techniques using the received signal strength indication (RSSI) works over relatively large areas, but suffer from poor accuracy. RFID ranging techniques exploiting the round-trip time of flight (RToF [2]) is possible, but challenging for short distance applications because it is difficult to measure the small round-trip time/frequency delay. The distance between reader and transponder can be also evaluated by using a Frequency-Modulated Continuous Wave (FMCW) radar. Moreover, the technique of modulated back-scattering [3], [7] provides the identity of the RFID transponder. The application of a CW radar system to UHF RFID localization is attractive because the design of RFID reader and backscatter tag required for ranging is very similar or even identical to general UHF RFID systems. In this study, we aim to assess FMCW radar processing for identification and localization. Section II describes the process of FMCW radar based on reader tag localization. Then, solutions for enhancing the detection resolution of RFID transponders based on spectral estimation methods are proposed. In Section V, the impact of RFID non-linearity on the range detection is evaluated. Finally, main conclusions are presented in section VI.

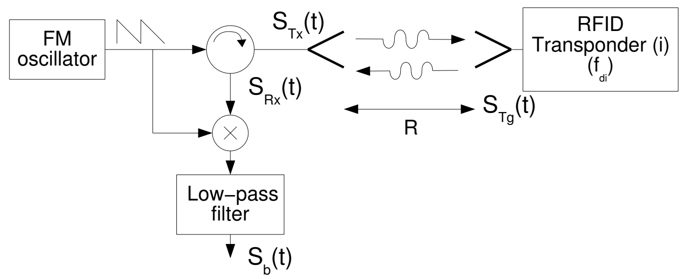


Fig. 1: Setup of FMCW radar based RFID localization system

II. RFID localization based on FMCW signal

A. Principle of modulated backscattering

We present the principle of the RFID localization system using FMCW radar in Fig. 1. The radar system transmits a signal $S_{Tx}(t)$ assumed to be a linear frequency modulated signal (LFM) in time interval [0,T]. The analytic expression of $S_{Tx}(t)$ is given by Eq. 1:

$$S_{Tx}(t) = A_{Tx} \exp\left(j2\pi\left(f_c t + \frac{B}{2T_p}t^2\right)\right) \tag{1}$$

where A_{Tx}, f_c, B, and T_p denote respectively the amplitude, the RF carrier frequency, the sweep bandwidth, and the sweep duration. Thus, the RFID transponder is considered as a secondary radar that transmits the modulated back scattered signal $S_{Tg}(t)$. This signal corresponds to the delayed received

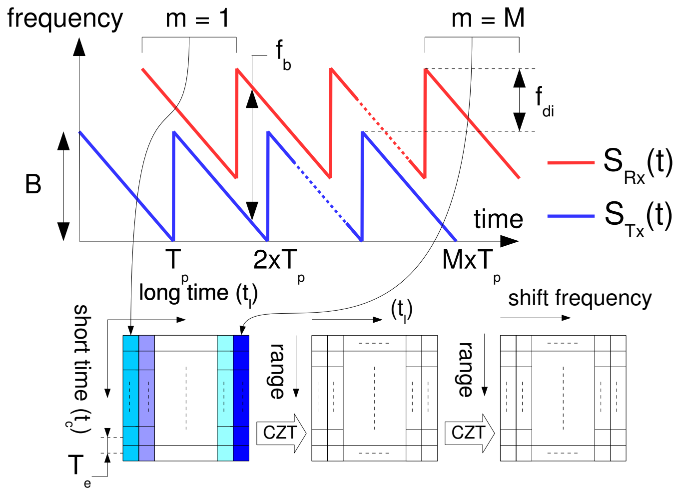


Fig. 2: Instantaneous frequency over M transmitted ramps

signal $S_{Tx}(t - R/c)$ which is also modulated by a frequency shift f_{di} applied to the carrier frequency.

$$S_{Tg}(t) = KA_{Tx} \times \exp j2\pi \left((f_c + f_{di})\, t + \frac{B}{2T_p} \left(t - \frac{R}{c} \right)^2 \right) \quad (2)$$

As the principle of FMCW radar consists in mixing the signal $S_{Tx}(t)$ with the received signal $S_{Rx}(t) = S_{Tg}(t - R/c)$ delayed after transmission by RFID transponders [8], the expression of the beat signal at the mixer output is $S_b(t) = S_{Rx}(t)^* \cdot S_{Tx}(t)$. The down converted base band spectrum $S_b(t)$ exhibits the frequency influences of a RFID transponder within the view of the FMCW radar system as depicted in Fig. 2. We define t_c as the time description during the sweep duration T_p. Moreover, the time axis t_l is defined as a time data set that collects one sample for each T_p duration: $t_l = m \cdot T_p$ with $m = 1, 2, \ldots, M$. Consequently, the beat signal $S_b(t)$ could be described both with respect to the time axis t_c and t_l:

$$S_b(t_c, t_l) = \exp j2\pi \left(f_c \frac{R}{c} - \frac{B}{2T_p} \frac{R}{c}^2 \right) \times \exp j2\pi \left(f_b t_c \right) \cdot \exp j2\pi \left(f_{di} t_l \right) \quad (3)$$

By applying a Chirp Z Transform (CZT) algorithm on $S_b(t)$, we obtain its complex spectrum. One frequency value (3) corresponds to a peak in the down converted base band spectrum that tells us the RFID transponder range position $R = f_b cT/2B$. We can recall the well-known range resolution expression δr with $\delta r = c/2B$. Moreover, one can also measure the shift frequency f_{di} induced by RFID transponder by taking into account the beat signal over M sweep durations [8]. Assuming the displacement of the RFID transponder less than the range resolution, a CZT procedure is carried out on axis time t_l to estimate the shift frequency f_{di}. Thus, the shift frequency resolution δf_d is inversely proportional to the processed signal observation time and $\delta f_d = 1/MT$.

TABLE I: Simulation Setup Parameters

Radio	Carrier frequency f_c	5.8 GHz
	Transmitter Power P_e	30 mW PIRE
	Antennas Gain G	25 dBi
	Receiver Noise factor F	5 dB
Modulation	Type	Sawtooth
	Frequency Sweep B	150 MHz
	Ramp duration T_p	80 μs
Signal Processing	Sampling Frequency F_e	20 MHz
	Nb. points (range)	1530 points
	Nb. points (frequency shift)	1600 points
	Total time	128 ms

B. Simulation results

In order to investigate the radar performances, we perform simulations with specific parameters that describe the system. These main characteristics are provided in Table I. The reflected power of the RFID transponder P_r returning to the FMCW reader is given by the radar equation [9], depending on the transmitted power P_e, the slant range R and the reflecting characteristics of the RFID transponder considered as a target (radar cross section σ). The amplification chain introduce thermal noise P_n. Moreover, we apply a Nuttall window as a weighing function on the beat signal defined with Eq.3. Consequently, the processing gain is also weighted by the normalized equivalent noise bandwidth (NENBW, [10]) which is equal to 1.9761 for the Nuttall window. In our case, the maximum visible range is determined through the requested detection performance ($P_d = 0.99$ and $P_{fa} = 0.001$). Based on Swerling 0 model, these performances induce a minimum SNR value of 13 dB with respect to the processing gain provided by number of analysis points (see Table I). The RFID response is considered as a swerling 0 target. Applying the radar equation, the SNR input minimum value in free space is equal to -45 dB below which the detection probability is insufficient. Thus, the maximum visible range is 285 m. In our study, we normalize the frequency shift of RFID transponder with respect to the center frequency of the analyzed band. Thus, Fig. 3 shows the range-shift frequency cartography of the two considered RFIDs with a Radar cross section $\sigma = 10$ dBm^2 (see Table I).

III. Resolution Improvement

The distance and frequency shift resolution of the radar are limited due to the signal processing methods. However, if the CZT is the basic tool for spectrum analysis due to its robustness and noise resistance, there are different methods which overcome the limitations of the CZT approach [11], [12]. The objective of this section is to present solutions to enhance RFID detection with respect to the frequency shift. The most commonly used spectral estimation techniques are shown in Table II. The spectral estimation methods used in this paper are selected due to their simple implementation and rapidity. A simulation is presented in Fig. 4 using the

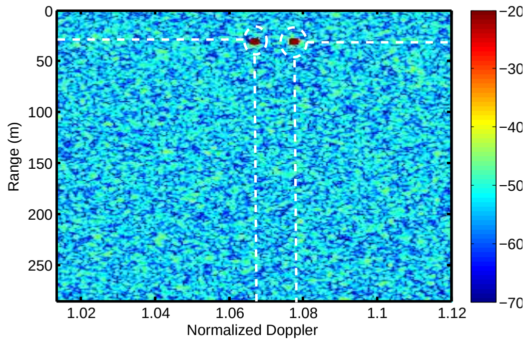
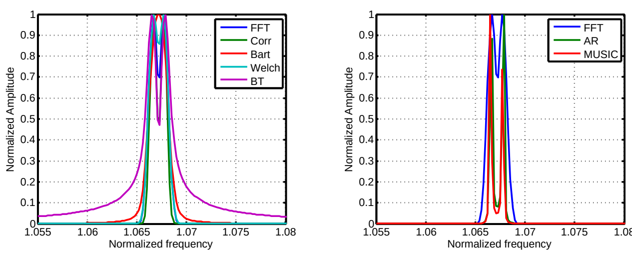


Fig. 3: 2D normalized CZT of a FMCW radar: Two transponders at R=100 m with frequency shift difference Δf=0.2 kHz

TABLE II: Spectral Analysis

Non-parametric Methods	
Periodogram	Direct approach via FFT operation
Correlogram	Correlation of the Power Spectral Density
Bartlett	Averaged Periodogram
Welch	Modified Averaged Periodogram
Blackman - Tuckey	Indirect Approach via an auto correlation
Parametric Methods	
Auto-Regressive (AR)	Linear prediction all-pole IIR filter
High Resolution Methods	
MUSIC	Linear algebraic concepts of subspaces



(a) (b)

Fig. 4: Simulation of CZT radar spectra (a) Non-Parametric methods ; (b) AR method and MUSIC algorithm.

model described in (3), when considering two transponders located at R=30 m and with two shift frequency identification spaced by Δf = 20 Hz. The most prominent limitation of parametric methods is frequency resolution. As we can see in Fig. 4(a), methods based on the auto correlation function (Correlogram, Blackman and Tukey) are able to distinguish the two transponders with greater precision. In Fig. 4(b), one can observe that the two transponders are clearly localized when using AR and MUSIC. Nevertheless, the advantage of non-parametric methods is its independence from the SNR. Moreover, MUSIC algorithm requires to know the number of sources that non-parametric methods don't. For Parametric

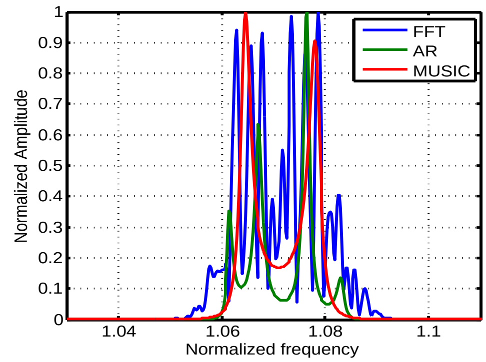


Fig. 5: Simulation of spectra with FFT, AR and MUSIC algorithm

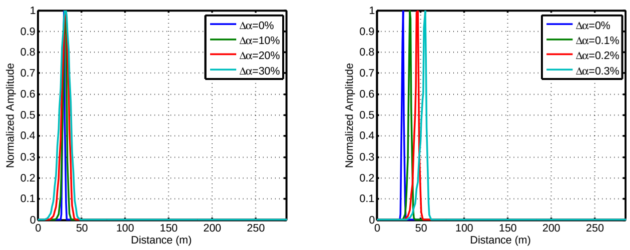
methods, we are able to distinguish two transponders even if the SNR is low by increasing the number of filter poles. Finally, we should note that the CZT is the fastest algorithm (5 times less than MUSIC algorithm). A tradeoff should be made between resolution requirement of transponder detection and real-time operation depending on the application. However, these simulations are conducted in free-space propagation conditions. Thus, the performances of these spectral estimation methods are disturbed in urban environments.

IV. Performance Analysis of FMCW system in Rayleigh Fading channel

The wireless channel is a harsh time-varying propagation environment. A signal transmitted on a propagation channel is subject to interference, propagation path loss, shadowing and fading. In order to evaluate the performance of the FMCW radar in realistic deployment scenarios, a Rayleigh channel is considered. The Rayleigh channel object is used to construct a frequency-flat Rayleigh fading channel with an input sample period T_s= 50 ns and a maximum frequency shift $f_d = 40$ Hz [13]. Two transponders located at R=30 m with two shift frequency identification spaced by $\Delta f = 0.2$ kHz are considered. The CZT result in a fading environment is compared with parametric methods (AR) and high resolution methods (MUSIC) (Fig. 5). It is shown that the CZT is enable to distinguish the two transponders because of the presence of spurious peaks. However, with the AR method and the MUSIC algorithm, the two transponders are discriminated more properly especially for MUSIC algorithm. This result highlights the potential of high resolution methods in enhancing the detection and discrimination of transponders in real environments.

V. Impact of RFID Non-linearity

A classical problem of FMCW is that the voltage controlled oscillator (VCO) adds a certain degree of non-linearity which leads to a decreasing resolution of the transponder parameter estimation. In LFM, the signal frequency is varied linearly with time across the signal bandwidth. In this section, we study the impact of non-linearity of signal model on the transponder detection [14].



(a) (b)

Fig. 6: Effect of sweep non-linearity (a) Case 1: non-linearity at FMCW reader and RFID transponder ; (b) non-linearity at RFID transponder.

A. Signal Model

In the LFM signal model, the frequency is linearly swept from 0 to B. In this section, we will consider another class of signal which instantaneous frequency $f(t)$ monotonically increases from 0 to B. The corresponding signal expression obtained is:

$$S_{Tx}(t) = A_{Tx} \exp^{j2\pi\left(f_c t + B\frac{t^{\alpha}}{\alpha T_p^{(\alpha-1)}}\right)} \quad (4)$$

The parameter α controls the frequency evolution with respect to time. Choosing α=2 corresponds to the LFM.

B. Non-linear model at FMCW reader and RFID transponder

In the first case, we consider that the signal transmitted by the FMCW reader is non-linear and the transponder respond with this same non-linearity. In the second case, we consider that the transponder respond with a signal shifted from the linear case. We introduce the term $\Delta\alpha$ which is the percentage of change between the linear case $\alpha = 2$ and the non-Linear one $\alpha = x$ where x is the non-linearity factor.

$$\Delta\alpha(\%) = \frac{(\alpha = x) - (\alpha = 2)}{\alpha = 2} \times 100 \quad (5)$$

This factor is applied at each ramp and reset to zero at the end of the frequency modulation ramp. The impact of $\Delta\alpha$ on the range resolution is evaluated for each case. Fig. 6 shows the results of sweep non-linearity on the detection performances of FMCW radar. Referring to Fig. 6(a), applying the same non-linearity at the FMCW radar and transponder results in 8 % error on distance estimation for $\Delta\alpha$=30 %. An 3dB-bandwidth increase is also observed. The degradation is quite modest when the transmitter and receiver has the same non-linearity. On the other side, Fig. 6(b) shows the corresponding results in the presence of transponder non-linearities. We can see that the FMCW radar is very sensitive to transponder imperfections. The accuracy of transponder detection gradually degrades with increasing non-linearity (error of 35 % for $\Delta\alpha$=0.2 %). The frequency shift estimation is not affected by this non-linearity factor because it is reset to zero at the end of each ramp.

VI. Conclusion

In this paper, an assessment of the performance of FMCW radar processing for RFID identification is presented. It is shown that the resolution capability of two closed transponders can be enhanced by using spectral estimation methods and high resolution methods instead of the classical CZT. The AR method and MUSIC algorithm distinguish more accurately two closed transponders but require a higher SNR and the classical CZT remains the fastest method. Nevertheless, high resolution method are more robust due to change in the propagation channel. Another problem that affect the FMCW performance is the sweep non-linearity. Non-linearity of RFID transponder result in an inaccurate estimate of its position. This first study may be a valuable input to the design process to determine the tolerable source non-linearity for a given accuracy of detection requirement. Moreover, further works will be dedicated to locating several transponders both in range and in azimuth by using two receiving antennas.

Acknowledgment

The authors would like to thank the DGA (Direction Générale de l'Armement) for funding this study.

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