Millimetre-wave Scanning Radar for the Detection and Remote Reading of Passive Electromagnetic Sensors

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***Abstract*— This communication reports the latest developments in Frequency-Modulated Continuous-Wave (FMCW) radar interrogation technique for chipless and wireless sensors. For the first time a millimetre-wave scanning radar is used for detecting and reading passive and chipless electromagnetic sensors. Measurement results show that, with a 24 cm depth resolution and a 2 degrees angular resolution, it is possible to localize and distinguish two passive sensors separated by 5 cm at a distance of 3 meters from a FMCW radar operating at 30GHz. Sensing modes visualization derived from the millimetre-wave radar scanning of a scene makes possible the separation length measurement with an accuracy of 1cm.**

***Index Terms*—millimetre-wave scanning radar, passive and chipless electromagnetic sensors.**

I. INTRODUCTION

In the last decade, environmental, industrial, and military monitoring applications have motivated an enormous amount of research activity related to wireless sensing. Some of these applications require continuous and stable measurements for an long period of time [1][2]. For such applications, it is desirable that the sensing device has a long operating lifetime. Therefore, active and semi-passive (battery-assisted) sensors are not good candidates due to their high cost and the short life time of the onboard battery. The passive sensors research activity on RFID-based or chipless sensors offers promising solutions.The RFID-based sensors incorporate an integrated circuit (IC) which enables sophisticated features such as rewritable memory and communication protocols. The power rectifier that generates the required power for activating the IC limits the maximum reading range to few meters [3][4]. To the best knowledge of the authors, the achieved reading range with RFID-based sensors is typically lower than 10 meters [5]. Surface Acoustic Wave (SAW) tags offer longer reading distance due to the absence of ICs (22 meters was recently reported [6]). However, the highest operation frequency of this sensor is typically limited to a few GHz. Recently harmonic and intermodulation radars were used for sensing applications. A reading range of 21 meters was obtained using harmonic radar [7] while 55 meters may be reached by using a harmonic radar [8]. The limiting factor of harmonic interrogation is the high frequency offset between the transmitted and received signals which makes difficult the fulfilment of the frequency regulations. The conversion loss of intermodulation tags limits the efficiency of this approach.

The technique based on the measurement of the RADAR Cross Section (RCS) variability of passive millimetre-wave sensors was proposed for the first time by the authors in 2008 [9] while the proof-of-concept was demonstrated in 2010 [10]. Compared with lower frequencies, millimetre-waves improve the sensor immunity to objects located at its vicinity by increasing the electrical length separation distance to them. Moreover they allow reducing the sensor and antenna sizes and designing directional (high gain) antennas for beamforming, multi-beam or beam-steering RADAR reader.

The wireless sensing technique based on RCS-variability measurement has been successfully applied to the remote estimation of many physical quantities (see an overview in [11]). A reading range of at least 30 meters was measured with a spatial resolution of few centimetres. Until now this technique was applied to the remote reading of passive sensors of known positions and consequently, the main lobe of the reader high-gain antenna could be pointed in the direction of the sensor. In case of the sensors occupying unknown positions, we show here that the scanning of the scene by this lobe could be performed to detect the presence of the passive and chipless sensors and to derive their locations.

In this communication and for the first time, a millimetre-wave scanning radar is proposed for detecting and reading passive and chipless electromagnetic sensors. The sensors are here passive scatterers composed of an antenna, a length of transmission line and a sensing device (variable impedance in the millimetre-wave frequency range). After a brief reminder of the beat frequency spectrum definition, a wireless technique to distinguish and get the positions of two sensors separated by a short distance is reported. This technique keeps unchanged the measurement sensitivity, measurement resolution and full-scale measurement range.

II. MILLIMETRE-WAVE FMCW RADAR INTERROGATION FOR PASSIVE ELECTROMAGNETIC SENSORS: THEORY

A. *Wireless interrogation of passive sensors using FMCW Radar*

A physical model for the calculation of RCS of a loaded antenna is reported by Harrington in [12]. It includes back-scattering of the incident electromagnetic wave by the antenna structure and the back-scattering due to the antenna loading impedance. Assuming a delay line of length l between the load and the antenna, the beat frequency spectrum of the loaded antenna can be obtained from the use of a homodyne FMCW radar. Considering a transmitted chirp with a radial frequency bandwidth $\Delta\omega$, the resulting beat frequency spectrum $b(\omega)$ measured by the radar at a given radial frequency ω is found to be:

$$b(\omega) \cong B\frac{A(\omega_0)}{2\pi R^2}\left[\frac{T_R-t_0}{T_R}\left(\frac{\sin u_0}{u_0}\right)e^{-j\left(\omega_0-\frac{\omega}{2}\right)t_0} - S_{11}(\omega_0)\frac{T_R-(t_1+t_0)}{T_R}\left(\frac{\sin u_1}{u_1}\right)e^{-j\left(\omega_0-\frac{\omega}{2}\right)(t_1+t_0)}\right] \sum_{n=-\infty}^{n=+\infty}\delta(\omega-n\omega_R) \tag{1}$$

where ω_0 is the carrier radial frequency, R the radar-to-sensor distance, T_R and ω_R denote respectively the period and radial frequency of the modulation signal, t_0 the round-trip duration from the radar to the antenna structure, t_l the delay generated by the line, δ represents the Dirac function and $S_{11}(\omega_0)$ the reflection coefficient on the sensing device at the carrier radial frequency. In Eq.(1) the constant B is derived from the radar characteristics and $A(\omega_0)$ depends on antenna geometry. Eq.(1) shows that the beat frequency spectrum combines two cardinal-sine functions. The first sine function corresponds to the contribution of the structural scattering mode with:

$$u_0 = \frac{T_R-t_0}{2}\left(\omega-\frac{\Delta\omega}{T_R}t_0\right) \tag{2}$$

while the second term is relative to the sensing mode contribution with:

$$u_1 = \frac{T_R-(t_0+t_1)}{2}\left(\omega-\frac{\Delta\omega}{T_R}(t_0+t_1)\right) \tag{3}$$

These functions are centred at the two following beat radial frequencies:

$$\omega_1 = \frac{2\Delta\omega R}{T_R c} \tag{4-a}$$

$$\omega_2 = \frac{2\Delta\omega}{T_R}\left(\frac{R}{c}+\frac{l}{v_\varphi}\right) \tag{4-b}$$

with c designate the vacuum celerity of light and v_φ the phase velocity in the delay line. According to Eqs.(1) and (4-b), if the delay line is long enough to avoid overlapping of the two modes, the contribution of the sensing mode can be given as follows:

$$b(\omega_2) \simeq -B\frac{A(\omega_0)}{2\pi R^2}S_{11}(\omega_0)e^{-j(t_0+t_1)\left(\omega_0-\frac{\omega_2}{2}\right)} \tag{5}$$

which leads to a magnitude:

$$|b(\omega_2)| \simeq b_0|S_{11}(\omega_0)| \tag{6-a}$$

where $b_0 = \left|B\frac{A(\omega_0)}{2\pi R^2}\right|$ (6-b)

According to (6-a), the contribution of the sensing mode is proportional to the reflection coefficient on the sensing device. Fig. 1 shows the measured level of the spectral component at beat radial frequency ω_2 associated to the sensing mode for various reflection coefficients. This experimental result validates the convenient linearity predicted by Eq.(6-a).

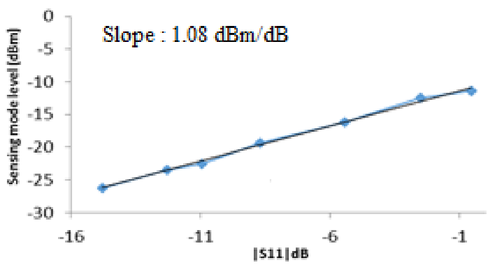


Fig 1. Measured amplitude of the spectral component at the beat frequency associated to the sensing mode for various reflection coefficients on the sensing device.

B. *Wireless identification of passive sensors using FMCW radar*

The length of the delay line is an additional parameter which is used for passive sensors identification. It controls the beat frequency of sensing modes and multiple configurations can be imagined to create specific beat frequency spectrum signatures. An example of delay lines and load configurations for passive sensors identification can be found in [13].

III. Beam Scanning for Detecting and Reading Passive Sensors: First Experimental Results

In our previous works based on the use of millimetre-wave FMCW Radar for reading and identifying passive electromagnetic sensor, the location of the sensor was known and the radar Tx-antenna pointed its main lobe in a unique direction. In this section, positions of passive sensors are considered as unknown and a wireless technique is proposed to detect, localize, read and identify passive sensors. The millimetre-wave scanning radar used in this experiment is a FMCW Radar with a bandwidth of Δf = 620 MHz and operating at 30 GHz. The depth resolution is then given by [14]:

$$d = \frac{c}{2\Delta f} \tag{7}$$

According to Eq.(7) the depth resolution is expected to be d=24 cm. A parabolic antenna having a 2 degrees beamwidth and a gain of 35 dB is used as the transmitting radar antenna (Tx-antenna). The beamwidth leads to an angular resolution φ=2 degrees. A beam scanning is performed with a rotational sweep of 0,5 degree step. The receiving antenna (Rx-antenna) of the radar is a motionless rectangular horn having a beamwidth of 60 degrees. The chirp transmitted by the Tx-antenna is back-scattered by passive sensors. In this first experiment the sensors are passive scatterers composed of an horn antenna (beamwidth: 60 degrees; gain: 18dB), a length of coaxial line and a resistance R_{device} = 0Ω (short-circuit) or R_{device} =50Ω (matched load). These two resistances correspond respectively to the minimal and the maximal values taken by of the sensing device resistance in the millimetre-wave frequency range. . The length of the coaxial line is used for separating in the beat frequency spectrum the structural scattering mode and the sensing mode. This length must be at least half of the resolution depth. During the measurement and for each rotational step of the Tx-antenna a Fast-Fourier Transform (FFT) is applied to the received signal in order to display the beat frequency spectrum b(ω). The minimum measurable separation distance between the passive sensors is then given by the radar characteristics. An oversampling is applied to the beat spectrum in order to get results with the maximal depth resolution. This is accomplished when having a sampling frequency lower than the beat frequency resolution T_R =1 kHz. A sampling frequency of $T_R/10$=100 Hz is then chosen here to perform the FFT. This sampling is followed by a smooth filtering. We consider a distance between the passive sensor and the radar of 3 meters and an electrical length of the coaxial line of 1,20 m. Fig 2 shows the measured beat frequency spectrum with and without smooth filtering when the Tx-antenna main lobe is pointed in the direction of one sensor. The first peak (-10 dBm at 3,20m) is due to the structural scattering mode. Moreover fin order to confirm that the peak between 4.5m and 4.8m is actually due to the sensing mode, we proceed to a beam scanning in the horizontal plane. This scanning makes scattering modes identification and interpretation easier. Fig 2 displays the resulting radar image. When terminated by a matched load R_{device} =50Ω (see Fig 3.a), the position of the passive sensor is deduced from the measurement of the structural scattering mode. It stands at 3 meters from the radar. An echo level of -30 dBm over a region of 40 cm depth and 11 cm width is clearly apparent in Fig. (3.a). When terminated by a short-circuit R_{device} =0Ω (see Fig 3.b), the measured echo level due to the sensing mode is of -18 dBm and is found in the direction of the structural scattering mode. The measured distance between the two peaks is 1,4m.

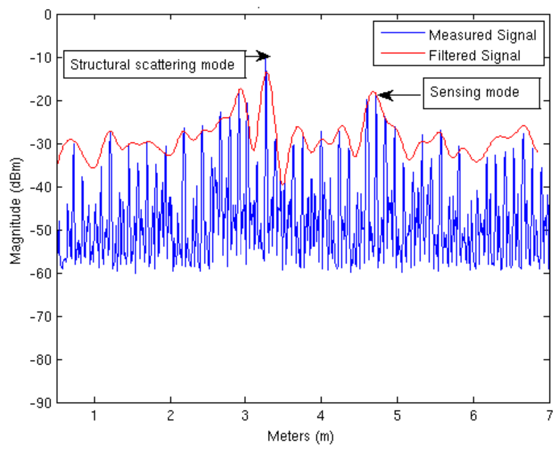
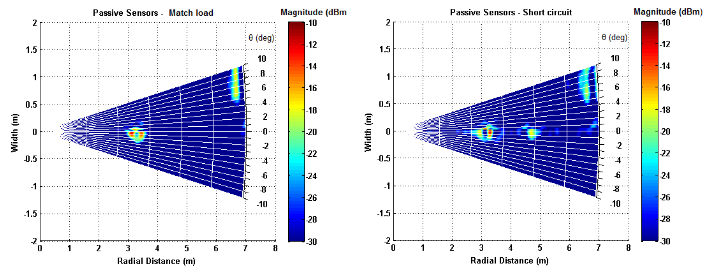


Fig 2. Measured beat frequency spectrum associated to a passive sensor when the Tx-antenna main lobe is pointed in the direction of the sensor.



(a) (b)

Fig 3. Radar image for a single passive sensor when (a) R_{device} = 50Ω and (b) when R_{device} = 0Ω.

Two passive sensors are now used in the measurement. They are located at D = 3 meters from the radar and separated from each other by a distance W (see Fig. 4). The theoretical minimum distance W_{Min} to distinguish two echoes is derived from the angular resolution $W_{Min} = 2D\sin\left(\frac{\varphi}{2}\right)$. For D=3m and φ = 2 degrees one founds W_{Min} = 5cm. The passive sensors are connected to a coaxial line of electrical lengths L_1 and L_2 respectively and, are loaded by sensing devices. In order to estimate the angular resolution, several measurements are performed with various values of the separation distance W.

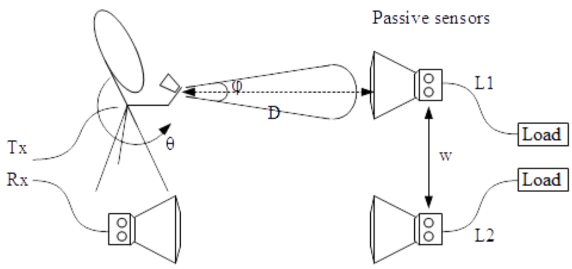
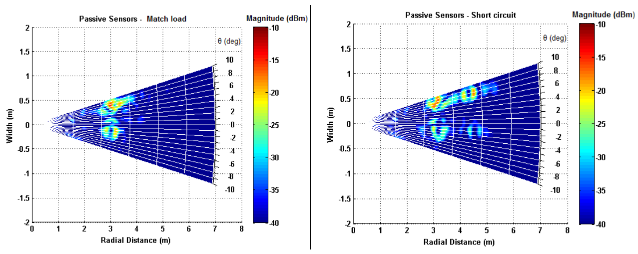


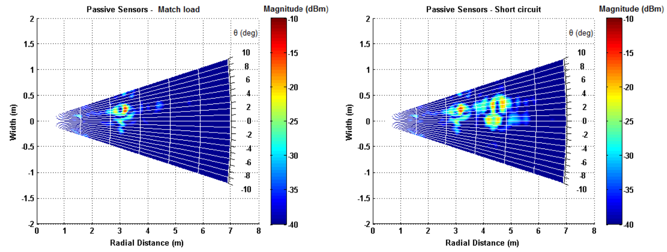
Fig 4. Experiment configuration with two passive sensors

In the first experiment W = 50cm and $L_1 = L_2$ = 1,20m. Measurement results are shown in Fig 5. As expected, when R_{device}= 50Ω only the two structural scattering modes are detected (see Fig. 5.a). The measured distance between the spots is W = 49cm. When R_{device}=0 the sensing mode of the two sensors are apparent (see Fig 5.b). The two sensing modes spots are in the same direction and at distances of 1,1m and 1,3m of their respective structural scattering modes. When W is reduced to 20 cm, the two spots associated to the structural scattering modes are more difficult to distinguish (see Fig 6.a). However, by restricting the spots to a minimum of -20dBm of back-scattered power, a distance of 24 cm may be derived between spots centres. When R_{device}=0 sensing modes of the passive sensors are located between 1,3 and 1,6 meters of their structural scattering modes (see Fig 6.b). As shown in Fig. 7, by reducing W to 5cm the two modes are still detectable but the echo level does not allow the distinction of the two sensors. A solution is to give a different echo signature to one of the two sensing modes. By increasing the transmission line length L_2 to 2m40 it is possible to separate the two sensing modes while the two structural scattering modes are still merged (see Fig 8). Assuming that scattering mode locations are at spot centres and that sensing modes are on the same direction than structural scattering modes, we can obtain an estimation of the distance between the two passive sensors by measuring the angle between the centres of the two sensing mode spots (Fig 9). We deduce from this measurement θ = 1°, D_1+L_1=5,6m and D_2+L_2=4,3m which leads to $W = \sqrt{D_1^2 + D_2^2 - 2D_1D_2\cos(\theta)} = 6cm$. Despite the depth resolution of 24 cm and strong RCS of the two passive sensors, we are able to give their positions thanks to their sensing modes and we are able to distinguish them at 5 centimetres from each other with an error of 1 centimetre.



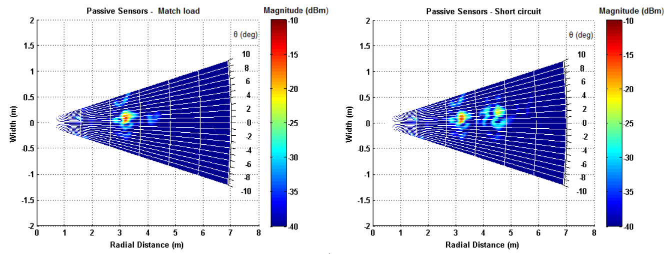
(a) (b)

Fig 5. Radar image obtained for two passive sensors and W = 50 cm and L_1=L_2=1,20m when (a) R_{device} = 50 Ω and (b) when R_{device} = 0.



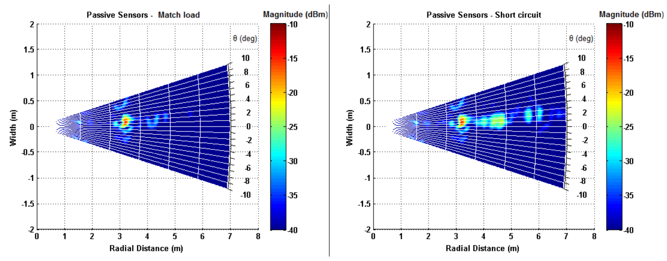
(a) (b)

Fig 6. Radar image obtained for two passive sensorsand W = 20 cm and L_1=L_2=1,20m when (a) R_{device} = 50 Ω and (b) when R_{device} = 0.



(a) (b)

Fig 7. Radar image obtained for two passive sensors and W = 5 cm and L_1=L_2=1,20m when (a) R_{device} = 50 Ω and (b) when R_{device} = 0.



(a) (b)

Fig 8. Radar image obtained for two passive sensors and W = 5 cm and L_1 =1,20m and L_2=2,40m when (a) R_{device} = 50 Ω and (b) when R_{device} = 0.

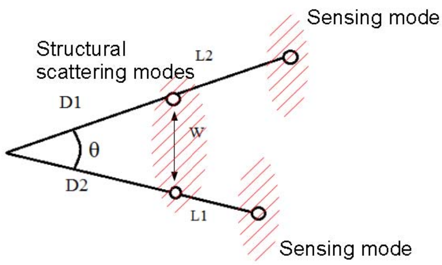


Fig 9. Geometric construction for the calculation of the separation length W from the knowledge of the radar measurement of the sensing mode locations.

IV. Beam Scanning for Detecting and Reading Passive Sensors: Multi-Sensors Approach

From the previous measurement results the maximum number of passive sensors which can be simultaneously detectable, identifiable and readable may be estimated. Hence it is possible to calculate the maximal density of detectable sensors at a given read range. Assuming that delay lines are properly chosen to avoid sensing modes overlapping, the resolution area a in which only one passive sensor can be detected is given by:

$$a = \frac{\pi\left(\left(R+\frac{d}{2}\right)^2-\left(R-\frac{d}{2}\right)^2\right)\varphi}{360} \quad (8)$$

and the maximal density S of detectable sensors is given by:

$$S = \frac{1}{a} \quad (9)$$

With an angular resolution of 2 degrees and a depth resolution of 24cm (see section III and Fig. 10), the maximal density of detectable sensors at 3 meters is then 39 sensors per meter square.

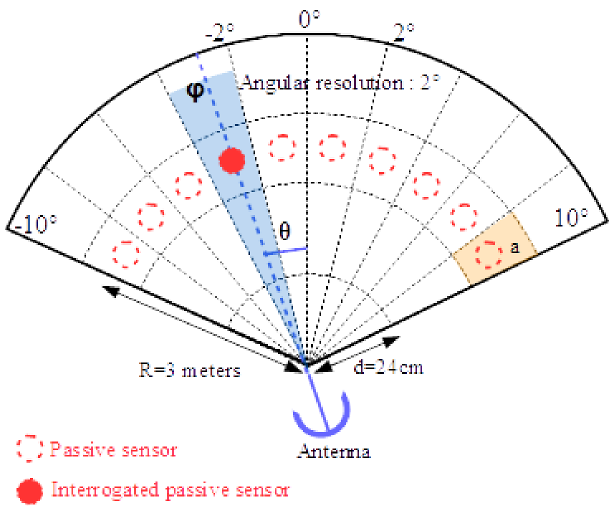


Fig 10. Illustration of the beam scanning technique for a maximum number of passive sensors at a given read range (3m). 39 sensors per meter square are detectable.

V. Conclusion

A 30GHz scanning FMCW radar is used for detecting and reading passive and chipless electromagnetic sensors. Measurement results show that it is possible to detect two sensors separated by 5cm at a 3m read range. The separation is calculated with an error of 1cm with 24 cm of depth resolution and 2 degrees of angular resolution.

References

[1] Weller, T.; Wang, J.; Nassar, I.; Dewney, J.; Davidova, R.; Frolik, J.; Sakamuri, V., "A wireless interrogator - passive sensor approach for deeply embedded sensing applications," *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*pp.1445-1448, 3-8 July 2011

[2] Qing Cao; Fesehaye, D.; Nam Pham; Sarwar, Y.; Abdelzaher, T., "Virtual Battery: An Energy Reserve Abstraction for Embedded Sensor Networks," *Real-Time Systems Symposium, 2008* ,pp.123-133, Nov. 30-Dec. 2008

[3] Feldengut, Tobias; Wang, Jue; Kolnsberg, Stephan; Kokozinski, Rainer, "A Passive Long-Range UHF Transponder with Integrated Temperature Sensor," *RFID Systems and Technologies (RFID SysTech), 2008 4th European Workshop on* , pp.1-4, 10-11, June 2008

[4] Vaz, A.; Solar, H.; Rebollo, I.; Gutierrez, I.; Berenguer, R., "Long range, low power UHF RFID analog front-end suitable for batteryless wireless sensors," *Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International* , 23-28 May 2010

[5] Donelli, M., "Design of long-range, powerless RFID sensor at 10 GHz," *Electronics Letters* , vol.49, no.20, pp.1277-1278, Sept. 2013

[6] Ping Li; Hua Xie; Wen, Yumei; Chuan Wang; Shiyuan Huang; Zhiwei Ren; Junjie He; Dang Lu, "A SAW passive wireless sensor system for monitoring temperature of an electric cord connector at long distance," *Sensors, 2011 IEEE* , pp.1831-1834, 28-31 Oct. 2011

[7] Jinsong Song; Pesonen, N.; Seppa, H.; Viikari, V., "On the use of the intermodulation communication towards zero power sensor nodes," *Microwave Conference (EuMC), 2013 European* , pp.124-127, 6-10 Oct. 2013

[8] Nassar, I.T.; Weller, T.M.; Frolik, J.L., "A Compact 3-D Harmonic Repeater for Passive Wireless Sensing," *Microwave Theory and Techniques, IEEE Transactions on* , vol.60, no.10, pp.3309-3316, Oct. 2012

[9] Jatlaoui, M., Chebila, F., Pons, P., Aubert, H., "Pressure Sensing Approach Based on Electromagnetic Transduction Principle," *Asia Pacific Microwave Conference*, Hong Kong and Macao, China, 16- 20 December 2008.

[10] Chebila, F., Jatlaoui, M., Pons, P., Aubert, H, "Pressure Measurement from the RADAR Interrogation of Passive Sensors," *IEEE International Symposium on Antennas Propagat.*, Toronto, Ontario, Canada, July 11-17, 2010.

[11] H. Aubert, F. Chebila, M. Jatlaoui, T. Thai, H. Hallil, A.Traille, S. Bouaziz, A. Rifaï, P .Pons, P. Menini, M. Tentzeris, "Wireless Sensing and Identification based on RADAR Cross Sections Variability Measurement of Passive Electromagnetic Sensors," *Annals of Telecommunications* Special Issue on Chipless RFID, Vol. 68, Issue 7, pp. 425-435, 2013.

[12] Harrington, Roger F., "Theory of loaded scatterers," *Electrical Engineers, Proceedings of the Institution of* , vol.111, no.4, pp.617-623, April 1964

[13] Jatlaoui, M.M.; Chebila, F.; Bouaziz, S.; Pons, P.; Aubert, H., "Original identification technique of passive EM sensors using loaded transmission delay lines," *Microwave Conference (EuMC), 2010 European* , pp.1106-1109, 28-30 Sept. 2010

[14] Piper, S.O., "Receiver frequency resolution for range resolution in homodyne FMCW radar," *Telesystems Conference, 1993. 'Commercial Applications and Dual-Use Technology', Conference Proceedings., National* , pp.169-173, 16-17 Jun 1993