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Wireless Remote Sensing Based on RADAR Cross Section Variability Measurement of Passive Electromagnetic Sensors

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***Abstract*— The wireless measurement of various physical quantities from the analysis of the RADAR Cross Sections variability of passive electromagnetic sensors is presented. A millimeter-wave Frequency-Modulated Continuous-Wave RADAR is used for both remote sensing and wireless identification of sensors. The remote derivation of pressure and temperature from the direct measurement of electromagnetic echo magnitude of passive and chipless sensors are reported and discussed.**

***Index Terms*— Wireless sensor network; passive and chipless sensors; millimeter-wave FMCW radar; radar cross section**

I. Introduction

The wireless measurement of a physical quantity from the analysis of the RADAR Cross Section (RCS) variability of passive sensors was proposed for the first time by the authors in 2008 [1] while the proof-of-concept was demonstrated in 2010 [2]. A Frequency-Modulated Continuous-Wave (FMCW) RADAR was used for the measurement of pressure-dependent RCS variation and for the remote derivation of the applied pressure changes. We have not found reports published before our first papers where the physical quantity is directly used for the RCS amplitude modulation of passive electromagnetic (EM) sensors and then remotely measured from FMCW RADAR interrogation.

In this paper a review of our recent results on the remote estimation of pressure and temperature from the electromagnetic echo measurement of passive and chipless sensors is presented. Moreover we show that the wireless identification of sensors can be based on FMCW RADAR measurement of the time-arrivals of multiple echoes controlled by delay lines.

II. Passive and Chipless Electromagnetic Sensors

Passive (battery-less) and wireless sensors are very good candidates for measuring physical quantities in harsh environment (e.g., high radiation or extreme temperature) and/or for applications requiring sensing devices with low-cost of fabrication, small size and long-term measurement stability. In 2007 the authors report the first passive pressure sensing device based on an electromagnetic (EM) transduction [3]. This EM sensing device converts the variation of an applied pressure into a variation of millimeter-wave resonant frequency of a resonator. It is composed of a high resistivity silicon membrane and a planar half-wavelength resonator deposited inside a circular Pyrex cavity. The membrane and the resonator are separated by a thin air slab. A pressure force applied to the membrane generates a deflection, modifies the air slab thickness, which consequently alters the electromagnetic coupling. As a result the resonant frequency of the sensing device is shifted. The resulting measured sensitivity is *370MHz/bar* between *0* to *3 bars* [4].

In general passive EM sensing devices convert the variation of a physical quantity (such as, e.g., pressure or temperature) into a known/specific variation of an electromagnetic wave descriptor. These devices are battery-free and chip-less. A review of most recent passive EM sensors developed by the authors will be presented at the conference.

III. Remote Derivation of Pressure and Temperature Based on the RCSs Variability Measurement

A. *Remote Sensing based on FMCW RADAR Reader*

In FMCW RADAR, the transmitted signal (transmitted power P_T) or *chirp* has a linear sawtooth variation of frequency with time. For such modulation the frequency is tuned linearly as a function of time by using a Voltage-Controlled Oscillator (VCO). The chirp of carrier frequency f, bandwidth (or excursion frequency) ΔF and sawtooth modulation period T_R is radiated by using a transmitting antenna (gain G_T) and is back-scattered by the target or *scatterer*. In free-space the back-scattered signal or *echo* consists of an attenuated replica of the chirp delayed by the two-way propagation delay $\Delta t=2R/c$ where R denotes the range and c denotes the vacuum celerity of light. The instantaneous frequency difference between the chirp and its delayed replica is constant and given by $2\Delta F\Delta t/T_R$. In order to measure this difference and deriving the range R the echo received by the RADAR antenna (Gain G_R) is mixed with the transmitted chirp (homodyne principle). An Analog-to-Digital conversion and Fast Fourier Transform by Hamming windowing at the mixer output signal are finally performed for obtaining the *beat frequency spectrum*. For illustration purpose a millimeter-wave FMCW RADAR operating at $f=29,45GHz$ ($\Delta F=650$ MHz, $T_R=1ms$, $P_T=13dBm=20mW$, $G_T=14dB$ and $G_R=14dB$) is used for the remote derivation of applied pressure from the measurement of the RCS of passive sensor. Such sensor was composed of an antenna (Gain $G_A=20dB$ at the carrier frequency) connected to a 50Ω coaxial cable of physical length $L=1m$ and relative permittivity $\varepsilon_r=1,7$ (or refractive index $n=1,3$), which is in turn connected to one port of the pressure EM sensing device described in Section II. The other port of the sensing device is loaded by 50Ω. The transmitted chirp interrogates the sensor, placed at a distance $R=1,4m$ from the RADAR antennas, at a frequency near the resonant frequency of the sensing device. The pressure is applied on sensing device via a nozzle placed at a distance of $40\mu m$ from the thin sensing device membrane. In the beat frequency spectrum synthesized by the millimeter-wave FMCW RADAR reader the echo level A_{ant} occurring at a beat frequency $f_{ant}=24KHz\approx2(\Delta F/T_R)[2(R+nL)/c]$ is associated with the reflection of the millimeter wave on the sensing device after reception by the sensor antenna and propagation inside the coaxial cable. As shown in Figure 1, the echo level A_{ant} depends on the applied pressure. It is called the *antenna scattering mode*. Between *0* and *2.5bars* the measured sensitivity is *0.8dBm/bar*. The full-scale echo measurement range is *5dBm* when the applied pressure ranges from *0* to *3.5bars*. When a pressure is applied on the membrane of the sensing device, the RCS of antenna-scattering-mode is varied, the back-scattered power P_R changes and as a result echo level A_{ant} is modified. The measurement of this modification allows, at least in principle, the remote estimation of the applied pressure variation. This summarizes the wireless reading principle based on the FMCW RADAR measurement of sensor-RCS variation. Remote derivation of temperature from the measurement of EM echo magnitude of new passive sensors will be presented at the conference.

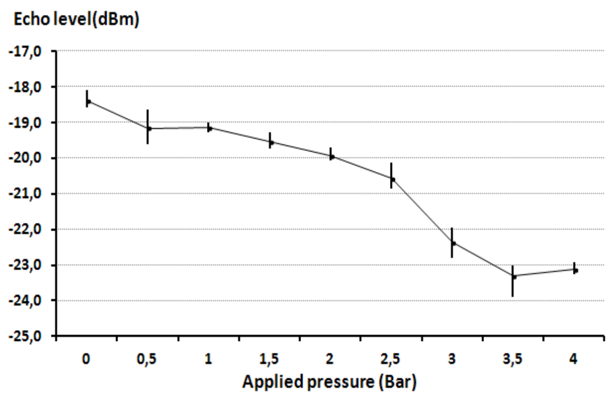

Fig. 1: Measured echo level of passive EM pressure sensor versus applied pressure at the beat frequency f_{ant} of the antenna scattering mode.

B. Remote Identification of Passive EM Sensors using FMCW RADAR Reader

The FMCW-RADAR reader used for the remote reading of passive sensors can also be utilized for identification purposes. When the passive sensor is composed of an antenna connected to a transmission line (or delay line) which loads in turn the sensing device, the measurement of the difference between the beat frequencies of the antenna-scattering-mode f_{ant} and structural-scattering-mode f_{st} allows the remote estimation of the transmission line electrical length (or propagation delay). By allocating a specific electrical length (or delay) to each sensor in a wireless network, this simple measurement may be used, at least in principle, for identification purpose. The proof-of-concept experiment will be presented at the conference.

IV. CONCLUSION

The use of a millimeter-wave FMCW Radar reader for both the wireless reading and identification of passive EM sensors is presented in this communication. It is shown that the wireless measurement of various physical quantities is possible from the analysis of the RADAR Cross Sections variability of passive electromagnetic sensors. Additionally the same FMCW RADAR can be used for identifying the passive sensors in a wireless network. Consequently the proposed wireless system uses the same reader for both remote sensing and sensors identification.

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