Adding RFID Capabilities to IoT Technologies: Proof-of-Concept on Microwave Doppler Sensors

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***Abstract*— The next-generation 5G network will boost the Internet of Things (IoT) by enabling ultra-fast worldwide connectivity among heterogeneous smart objects. Many current technologies will lost appeal, many others will evolve to match with the context. However, the need to identify and sense objects will be more crucial than now. In this framework, backscattering-based radiofrequency identification (RFID) technology could still play a major role through the possibility of implementing low-power identification and communication directly over other technologies belonging to the IoT ecosystem. Such an aspect is investigated in this work where RFID capabilities are introduced over X-band Microwave Motion Sensors (MMSs) typically used to detect and locate objects. The concept of Doppler-based backscattering modulation is theorized and used to design a proof 10.525 GHz RFID system leveraging on MMSs. A prototype of the novel RFID-over-MMS system has been designed, realized, and tested so to verify the aptness of the proposed concept.**

Keywords*— *Radio frequency identification (RFID), X-band antenna, Microwave motion sensor, Doppler, backscattering

I. Introduction

Nowadays, Radio frequency identification (RFID) is considered a consolidated technology adopting dedicated RF hardware as well as standardized frequency bands to provide objects identification and sensing. However, in parallel with the progress of the IoT in view of the 5G advent [1], a possible evolution of the current RFID technology can be envisioned. The idea is to implement a low-power backscattering-based communication directly over other existing technologies thus limiting dedicated hardware and, in perspective, improving pervasiveness and flexibility of the technology. In particular, novel RF or microwave transponders will enable objects identification by backscattering a slight portion of the electromagnetic field already generated by the antennas of a generic "host" technology. For instance, the implementation of RFID over a host technology, such as RFID-over-WiFi, would allow identification other than sensing while preserving all the functionalities of the host technology itself. For instance, this possibility is confirmed in [2] with an example of RFID system exploiting Bluetooth Low Energy (BLE) through an additional continuous wave generator.

In This work RFID capabilities are introduced over Microwave Motion Sensors (MMS hereafter). Generally, MMSs exploit the Doppler effect phenomenon to detect velocity and position of a target object [3],[4]. Moreover, they are used to design microwave radars for medical applications [5],[6]. These devices are extremely cost effective and have a large diffusion in home alarm systems and in ambient assisted living applications.

Doppler-based MMS works at different frequencies depending on the particular State regulation [7]. In some States, such as USA, Canada, Australia, Italy, and Belgium, the working frequency is 10.525 GHz, which will be considered in this paper, without loss of generality.

At the state of the art, examples of X-Band RFID systems in are in the literature, even if none of the them seems to be specifically designed to enable RFID functionalities over MMS or other existing technologies. Conversely, expansive and cumbersome dedicated hardware is needed to detect the transponder. In particular, a X-band RFID transponder provided with patch antennas and energy harvesting system technique is shown in [8]. Moreover, the design of a 10.75 GHz microwave backscatter tag with integrated antennas is presented in [9] as part of a complex test-bed laboratory system. Finally, an X-Band sensor-based tag implementing a backscattering modulation scheme is shown in [10].

On such a basis, a possible design strategy to develop a microwave system allowing RFID-over-MMS communication is to exploit the MMS working principle: the Doppler effect. The idea behind consists in designing a 10.525 GHz transponder capable of receiving the signal transmitted by the MMS and transmitting back a modulated bit stream that can be demodulated by the motion sensor itself. In particular, each symbol α of a bit stream to be transmitted must generate a backscattered signal perceived by the MMS as an object traveling at different speeds depending of the single bit to be transmitted. From the technical point of view, the wave backscattered by the novel transponder should look like an offset-carrier modulated signal.

According to this design approach, the proposed transponder is based on a microwave frontend provided with a microwave phase shifter and a properly designed X-band antenna array. The frontend is able to vary its Radar Cross Section (RCS) and to backscatter the desired offset-carrier modulated wave including both identification code and sensor data. This electromagnetic wave can be received by any MMS, elaborated and demodulated. Once realized, the prototype of RFID-over-MMS system has been configured to implement an offset-carrier modulation scheme and validated.

II. Theoretical Aspects

The Doppler effect is a well-known physical phenomenon consisting in a frequency shifting of an electromagnetic wave backscattered by a certain "target" object moving along a straightforward line joining the signal source and the target itself. In this section a very brief overview on theoretical aspects about the Doppler effect is reported. More in detail, by assuming that the signal transmitted by the radar antenna is:

$$s_t(t) = A_t \sin(2\pi f_o t)\,, \tag{1}$$

then, the reflected "echo" signal of a target object moving at a certain relative velocity v_r will be:

$$s_{echo}(t) = A_{echo} \sin(2\pi(f_o \pm f_d)t - \varphi), \quad f_d << f_o. \quad (2)$$

where A_t and A_{echo} are the amplitudes of transmitted and echo signals, respectively; f_o is the source frequency; φ is the echo signal phase; and f_d is the Doppler frequency shift. The relationship between Doppler frequency shift and relative velocity is:

$$f_d = \frac{2 f_o v_r}{c}, \quad (3)$$

where c is the propagation velocity.

In a real multi-target scenario, where several objects are free to move in front of the radar antenna, the received signal is a summation of signals having different amplitude, frequency, or phase:

$$s_r(t) = \sum_{i=1}^{n} A_{r,i} \sin(2\pi f_{d,i} t - \varphi_i), \quad (4)$$

where i denotes the i^{th} moving object, and n the number of detected objects. It is worth highlighting that the bandwidth of $s_r(t)$ is set by:

$$f_{\max,obj} = \max_i (f_{d,i}), \quad (5)$$

corresponding to the Doppler frequency generated by the fastest object detected.

III. X-Band RFID System working principle

As stated, the idea behind the proposed system consists in implementing a specific backscattering RFID transponder capable of communicating with the MMS. With reference to (4) the Doppler frequency f_d and the phase φ would vary proportionally to the velocity and position of a certain object. This principle can be exploited to design a particular "object" capable of backscattering a modulated wave which may be straightforwardly demodulated by a Doppler motion sensor, without any change in its standard architecture. In other words, a device capable of generating a sort of offset-carrier "artificial Doppler wave". Based on this idea, an offset-carrier backscattering modulation scheme, properly designed to match the native Doppler sensor requirements, could be implemented. A particular transponder capable of generating an offset-carrier modulation is reported in Fig. 1. It is composed of an antenna, tuned to receive the motion sensor signal at 10.525 GHz, and two other blocks: a variable attenuator, and a phase shifter. The former sets the amplitude of the backscattered signal, the latter provides a controllable and time-dependent change in the signal phase on the basis of a driver (modulating) signal. A possible representation of the Doppler sensor received signal including the off-carrier components generated by the considered transponder model is given by the following equation:

$$s_r(t) = \sum_{i=1}^{n} A_{r,i} \sin(2\pi f_{d,i} t - \varphi_i) + \\ + A_m(t) A_{r,c} \sin(2\pi f_{d,c} t + F_m(t) + \varphi_c) \quad (6)$$

where $A_m(t)$ is a generic amplitude modulating function and $F_m(t)$ is a generic angular modulating function (including the modulation index) of the backscattered carrier signal $A_{r,c} \sin(2\pi f_{d,c} t + \varphi_c)$. Moreover $f_{d,c}$ and φ_c denote the carrier frequency and phase, respectively. To avoid interference, the frequency $f_{d,c}$ should be set to be higher than the maximum frequency of the real Doppler signal generated by all the possible moving objects (7). In such a way, according to the representation in Fig. 2, all the frequency components associated to the actually moving objects, including the movement of the transponder itself, may be easily low-pass filtered and elaborated, while the higher frequency components corresponding to the modulated signal may be windowed (through Band-Pass or High-Pass filters), demodulated, and then processed separately.

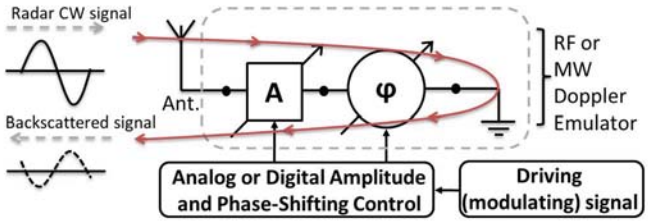

Fig. 1. Working principle and structure of a MMS-compatible Doppler transponder.

In order to make the final transponder affordable, a complex and cost-sensitive element such as the phase-shifter can be replaced with a "simpler" hi-speed microwave switch connected to different impedance loads Z_n. In spite of that, this configuration still allows the transponder to backscatter a sort of modulated "artificial Doppler wave" whose structure can be designed to fulfill a generic digital modulation scheme (i.e. FSK, PSK, ASK).

At this regard a possible architecture of a Doppler transponder implementing a "Doppler-based" 2-ASK modulation is shown in Fig. 3. If compared with a typical structure of ASK RFID tag, where the switching between two impedance loads (i.e. Z_1 and Z_2) are sufficient to backscatter a 2-ASK modulated wave, in this Doppler-based ASK modulation four impedance loads are required instead. Indeed, most of the RFID systems adopt the ASK backscattering modulation to stream data bits towards the reader by dynamically switching the two impedance loads Z_1 and Z_2 at a certain frequency f_{sw}. As known, a specific reflection coefficient Γ_1 can be associated to the transmission bit "0" and a reflection coefficient Γ_2 can be associated to the transmission bit "1". As confirmed by the theory, this conventional signal structure is not compliant with the MMS architecture since no amplitude variation is observed in the generated artificial Doppler carrier. In fact, the normalized magnitude differential radar cross-section D-RCS = $|\Gamma_1 - \Gamma_2|^2$ [12] associated to a similar transponder is not time-dependent. The result is an non-modulated sub-carrier with a frequency offset of exactly f_{sw} with respect to the main 10.525 GHz carrier.

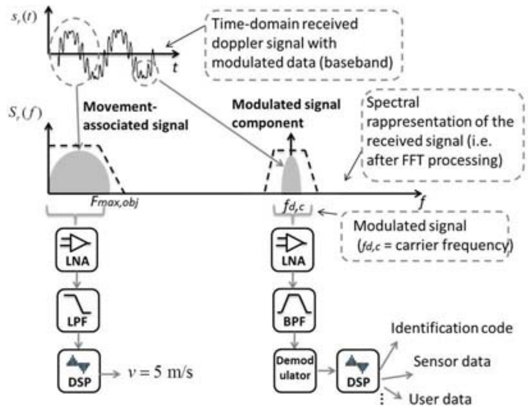

Fig. 2. Spectral composition of the received signal and elaboration steps.

On the contrary, in a MMS-compatible ASK modulation scheme as the one in Fig. 3, two conditions should be met: firstly, the transponder backscattered signal should be continuously phase-shifted to generate an offset carrier at a certain frequency (artificial Doppler wave). Secondly, the amplitude of the generated wave should be modulated according to the bit stream to be transmitted. At this regard, the transponder should switch between two additional impedances Z_3 and Z_4. The result is a backscattering modulator capable of producing an offset carrier wave at a fixed frequency whose amplitude changes on the basis of the two different D-RCS associated to the couple of selected impedances. Indeed, a first switch (SW1 in Fig. 3) selects the symbol (i.e. switching between the couple Z_1, Z_2 or between the couple Z_3, Z_4) according to the bit-stream to be transmitted and a second switch (SW2 in Fig. 3) is continuously switched at f_{sw} to produce the required off-carrier modulated two-level signal. The generated signal can be now associated a 2-ASK offset-carrier modulation recognized by the MMS as a Doppler signal. Consequently, it can be received, filtered and demodulated. It is worth noting once again that this approach does not change the structure of the microwave front-end of the motion sensor radar, so that the RFID functionalities may be straightforwardly implemented over the X-band MMS, as desired.

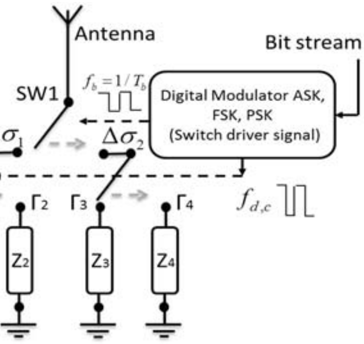

Fig. 3. Scheme of MMS-compatible Doppler-based ASK modulation

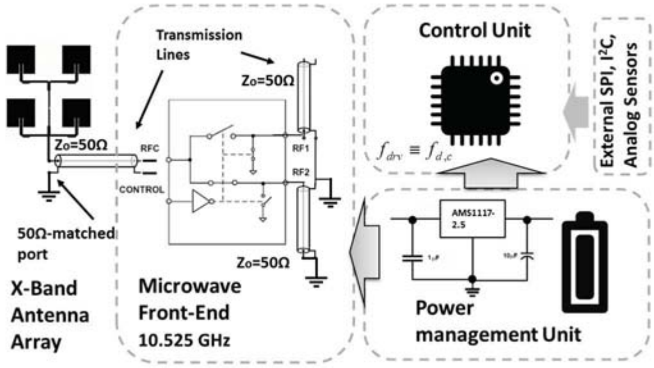

Fig. 4. Architecture of the 10.525GHz RFID transponder

IV. Design of a X-Band RFID System Over MMS

In order to demonstrate the effectiveness of the proposed approach, in this Section a first fully-programmable RFID system exploiting an indoor X-band Doppler radar working at 10.525 GHz is designed, realized, and configured to transmit both identification and sensing data through a MMS-compatible ASK modulation scheme. The system is mainly composed of two elements: the RFID transponder and the X-band radar-based receiver.

In Fig. 4 a detailed architecture of the transponder is reported. As can be observed, it is composed of a 4-element patch antenna array with input impedance 50 Ω connected to a SPDT microwave switch (model HMC1118 by Analog Devices [13]) driven by a Control Unit. This last is provided with memory and sensor interfacing capability and it is based on a ultra-low power microcontroller, as the Texas Instruments MSP430G2553 [14] in the specific case. Moreover, a Power Management Unit has been developed for battery-assisting the transponder by means of a CR2032 cell battery.

According to the above described working principle, the switch is used as microwave front-end to change the antenna reflection coefficient, and hence the D-RCS of the transponder, on the basis of the data to be backscattered. Basically, the switch common port RFC (see Fig. 4) is connected and matched to the antenna through a 50 Ω transmission line, whilst the two other ports RF1 and RF2 are in open-circuit and short-circuit state, respectively. A continuous switching between the two ports determines a backscattered phase-shifted version of the radar signal thus generating a modulated artificial Doppler wave at the desired frequency.

Once designed, the novel X-band transponder has been realized in a very preliminary prototype version having a total size of 180x70 mm2 as shown in Fig. 5. The figure clearly shows the Power Management Unit equipped with voltage regulator and voltage inverter, the Control Unit based on microcontroller and voltage selector, and the microwave switch applied on its testing board [15] realized on Rogers RO4350 substrate [16]. The former board connector (RF1 port) is left open, the latter (RF2 port) is short-circuited according to the schematic of Fig. 4. Moreover, RFC port is connected and matched to the antenna port. In particular, the tag antenna is an edge-fed 2x2 patch array designed on a 0.508mm-thick Rogers RT5880 laminate [17] with relative permittivity ε_r=2.2 and tanδ=0.0009. The four patch radiating elements are connected to a microstrip feeding network mainly composed of a central transmission line (having characteristic impedance Zo=50 Ω) and three impedance transformers whose parameters are tuned to obtain an antenna input impedance of 50 Ω. Two of the four feeding lines are meandered so to increase their electrical length of λ/2 and hence to guarantee a phase opposition with respect to the feeding signal without increasing the physical distance between the couples of radiating element. In this way, the current distributions of the four antennas are in phase despite their opposite physical orientation. Furthermore, the antenna has been also realized and characterized through a Vector Network Analyzer (VNA). A good agreement between measured and simulated $|S_{11}|$ has been found with a measured antenna resonance peak of –21.04 dB at

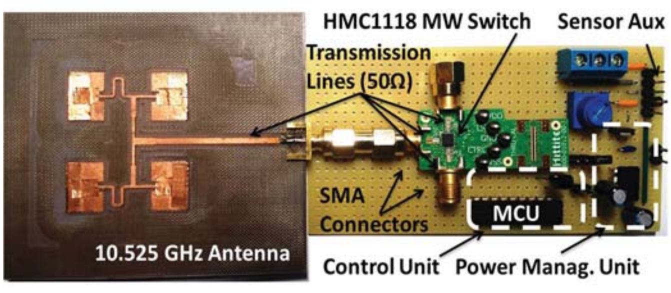

Fig. 5. Prototype of the MMS-compatible X-band RFID transponder.

10.525 GHz, as desired. Moreover, a bandwidth of 220 MHz at - 10 dB has been obtained as well. Finally, a maximum antenna gain of 13.4 dBi and a radiation efficiency of -0.61 dB have been evaluated.

Apart from the transponder, in Fig. 6 a picture of the realized X-band radar interrogator/receiver (i.e. RFID reader) is shown. As can be observed, it is mainly based on the microwave Doppler radar module “Agilsense HB100” [19], a very compact (37x45x8 mm^3) and cost-effective radar working at 10.525 GHz. This kind of radar, compliant with FCC regulation [20], is typically used as motion detector or speed detector in applications as vehicle traffic monitoring or intrusion detection systems. Its radiated power is of 13 dBm EIRP, the sensitivity is of -82 dBm, the total current consumption is of 30 mA, and the supply voltage is of 5 V. The rest of the circuit includes an LNA, a high-pass filter, and a demodulator.

Finally, in order to demonstrate the effectiveness of the proposed approach and to test the novel RFID system both transponder and receiver have been configured to implement the Doppler-based 2 ASK modulation scheme.

On the one hand, the transponder has been programmed to backscatter an ASK-modulated artificial Doppler wave having structure and data coding compliant with the ISO Standard specifications adopted for 125KHz LF RFID systems [21]. On the other hand, the X-band receiver has been equipped with a standard 125 KHz demodulator model RDM6300 [22] (see Fig. 3b) composed of an envelope detector and a UART converter to easily get and analyze raw demodulated data. More specifically, the adopted standard parameters are: ASK carrier Doppler frequency $f_{d,c}$=125 KHz, data rate 2 Kbps, identification (ID) code length 32 bits, bit-stream length 64 bits (including header, ID code, data, and parity bits) and Manchester encoding. This configuration has been adopted to test the system and obtained results will be provided in the next Section.

V. Results

In this Section the proposed X-band Doppler-based RFID system is tested and validated in particular when Doppler-basd ASK modulation is considered. The transponder is placed 1 m away from the radar receiver and programmed to backscatter a specific identification code at a Doppler frequency $f_{d,c}$=125 KHz. In this working condition the transponder has been firstly characterized in terms of |S11| at the RFC port in the frequency range 0.5 GHz - 15 GHz, and when varying the microwave switch supply voltage in the range 0.8 V - 3 V at steps of 0.2 V. The switch port RF1 is closed on a 50 Ω matched load. Finally, the microcontroller is configured to drive the microwave switch to statically connect together the ports RFC and RF1, by isolating the port RF2.

The relationship between supply voltage and reflection coefficient at the antenna port RFC has been investigated and expected degradation of the reflection coefficient magnitude when the supply voltage has been observed. Indeed, the voltage variation changes the switch working point and then its internal trans-impedance. Nevertheless, it is worth observing the presence of a threshold behavior. Indeed, it has been observed that for voltage values ranging from 1.2 V to 3 V a good functioning of the switch is obtained with a reflection coefficient lower than -10 dB.

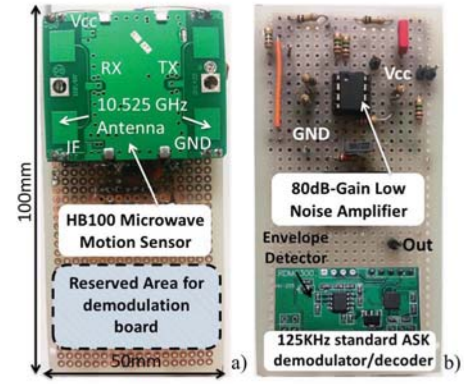

Fig. 6. Prototype of the X-band receiver. Front: HB100 MMS module a); Rear: LNA circuitry b).

Conversely, for voltage values lower than 1.2 V the reflection coefficient degradation is much more significant. In summary, this first test confirms the variation of the switch response on the basis of the selected supply voltage and reveals that a couple of two step values, as 3 V and 1 V, is, for instance, suitable to drive the switch to implement a MMS-compatible ASK modulation.

By taking advantage from this aspect, the transponder has been intensively tested in order to verify its capability to transmit the ID code exploiting the Doppler-based backscattering modulation concept. In particular, Fig. 7 shows a fragment of the measured received signal highlighting the typical ASK-modulated structure with a modulation index of 30%. Moreover, the figure also shows that bits associated to the signal envelope are clearly recognizable and correctly received, thus demonstrating the appropriateness of the proposed approach.

Finally, in order to test the device in a potentially interesting field of application, such as the telemedicine one, the 12-bit TMP112 [23] I2C temperature sensor has been interfaced with the transponder, so to verify the capability of transmitting sensing values other than the ID code and to evaluate the maximum working distance.

Specifically, both system elements have been placed in a semi-anechoic environment and the transponder has been gradually moved away from the receiver antenna at steps of 20 cm starting from 30 cm. A spectrum analyzer has been connected at the HB100 radar and the SNR has been then evaluated along with the right detection of the ID code and of the temperature value. A significant maximum detection distance of 2.10 m has been obtained with a SNR = 16dB.

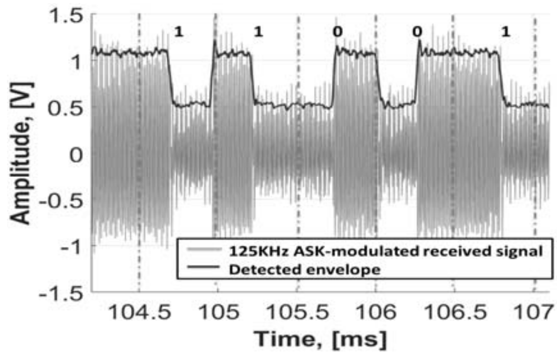

Fig. 7. Received MMS-compatible ASK signal and related envelope.

VI. CONCLUSIONS

In this work, an example of X-Band 10.525 GHz "RFID-over-MMS" system has been defined, realized and tested. It is based on the concept of offset carrier backscattering modulation which allows to transmit information like identification codes or sensor data by emulating the Doppler effect. In particular, the designed transponder is able to generate, through a properly controlled microwave front-end and antenna a particular structure of offset carrier modulated signal which is recognized and correctly demodulated by common X-band microwave motion sensors. The system has been also extensively tested when varying the working distance up to 2.1 m in a telemedicine scenario demonstrating the effectiveness of the proposed approach.

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