

Article

# Development of Environmental Long Range RFID Sensors Based on the Modulated Scattering Technique

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**Abstract:** This work presents the development of a wireless sensor system for environmental monitoring based on the modulated scattering technique (MST). The MST sensor probes are based on the scattering properties of small passive antennas and radiate part of the impinging electromagnetic field generated by an interrogating antenna, which also acquires the backscattered signal as information. The MST probes are able to deliver data without radio frequency front end. They use a simple circuit that alternatively terminates the antenna probe on suitable loads to generate a low modulation signal on the backscattered electromagnetic wave. In this work, the MST sensor system for environmental monitoring has been proposed to obtain the best performance in communication range, load efficiency and power harvesting. The MST sensor has been fabricated and assessed in practical scenarios. The proposed prototype, able to operate in X band at 10 GHz and able to provide a communication range of about 15 m, serves as a proof-of-concept. The acquired measurements demonstrate that the prototype is able to measure accurately and send data without radio frequency front end or bulky wired connection with the same efficiency of standard wireless sensors such as radio frequency identifier (RFID) or wireless sensor networks (WSN).

**Keywords:** wireless sensors; long range RFIDs; modulated scattering technique MST; microwave devices

## 1. Introduction

In the past few years, the demand for sensors that are low cost and have the capability to work in multi-function wireless environments has grown. The data collected from the sensors must be elaborated and transmitted related to a given environmental parameter [1]. The advantage of this sensor is evident especially in critical scenarios such as after natural disasters with restricted or dangerous areas [2].

Furthermore, they are very beneficial for practical purposes like homeland security [3], rescue operation and law enforcement services. Wireless sensor networks [4,5] (WSNs) have been successfully adopted for the advancement of long-range estimation systems, but they use dense frequency bands and require maintenance and complex communication protocols. Radio frequency identification systems (RFID) [6,7] are another type of wireless system that have been successfully used to track foods and goods. Now, they are widely used in many practical scenarios such as supermarkets and stores [8–25]. The main benefit of adopting an RFID system is the long life and low cost, but it requires a close proximity between the reader and tag. Therefore, for a long-range communication system, it would not be suitable. Another drawback of RFID is the difficulty in providing environmental probes directly on the RFID tags. To overcome this kind of issue, in [26–28], the modulated scattering technique (MST) was defined. The MST provides an alternative solution to the WSN and RFID

technologies' disadvantages. The MST probes use the scattering properties of small passive antennas as in [29,30], and because of this, they do not require a physical connection with the measurement system. MST systems do not rely on the sensitivity of the antenna tag, nor its load with respect to the relevant quantity to be sensed, like standard RFID sensors. The signal is delivered toward the MST reader, and it is insensitive to propagation effects. On the contrary, RFID sensors' performances are strongly sensitive to propagation effects, since they are impedance-based devices. In particular for RFID systems, as in [31], electromagnetic propagation problems like reflections, interferences, propagation losses and collision problems [32,33] are more important. Furthermore, the RFID is able to demodulate the signal accurately and give the answer only if examined correctly. For this reason, a local oscillator, an antenna driver, a demodulator and a data encoder are required in a standard RFID transceiver. The MST tag sends the information by modulating the impinging electromagnetic wave, without doing any operations like demodulation. Therefore, in complex scenarios, the RFID-based system would not work accurately. Moreover, RFID systems work in a very short range, while MST systems can work in free space, near-field, as well as far-field scenarios, and the operative range  $r$  can be evaluated simply by considering the radar equation, as in [34]. In particular, the MST probe antenna has different loads. These loads change by means of a suitable electronic switch. The change of antenna impedance in an MST reader introduces a low-frequency modulation signal in a backscattered electromagnetic wave, as in [27,30], and also, it reads the backscattered field. The information is retrieved from the low-frequency modulation signal provided by the tag to the backscattered wave. A radio frequency front end is not required for the MST tags. After interactions with the MST tag reader, it generates an electromagnetic wave, which carries the information. The absence of RF front end makes the tag less expensive and suitable for a small probe to reduce perturbations and noise measurements. The MST probes have been used successfully in applications like, microwave imaging [35,36], measurements in near-field electromagnetics [37–42], characterization of materials [43,44] and other applications, as given in [45–48]. In this work, an X band wireless MST monitoring system is proposed for environmental monitoring. The prototype requires only a limited amount of power and ensures a good communication range of about 15 m. It represents a good alternative to standard WSN- or RFID-based architecture. The proposed wireless sensor tag presents the following innovations: the operative frequency located in the X band at 10 GHz permits strongly reducing the tag and reader antenna dimensions. Higher frequency bands can be used to further reduce the sensor size and improve the signal bandwidth. Most of the state of the art long-range RFID tag systems work on crowded frequency bands such as WiFi at 2.45 GHz, and most of them are not passive devices, since they make use of the WiFi module [49]. The proposed system does not need RF or microwave front-ends; moreover, with respect to the other commercial or experimental devices, it is theoretically able to reach distances up to kilometers [14,27]. Thanks to these characteristics, these sensors are particularly suitable to monitoring environmental parameters during natural disasters, such as earthquakes or avalanches. A three-month measurement campaign has been carried out to evaluate the proposed MST environmental monitoring systems. In particular, meteorological quantities, namely the temperature variations and humidity, were measured during the summer season in Northern Italy.

## 2. Mathematical Formulation

The schema of a mono-static MST measurement system is shown in Figure 1. It consists of a reader aimed at communicating with a remote tag placed far away from the reader at a distance  $r$  called the communication range. The tag could be equipped with different environmental probes. The reader is composed of a sinusoidal signal generator, a microwave low noise amplifier, a homodyne detector, a circulator and a high gain antenna. The circulator is used to consider only one high gain antenna, acting both as transmitter and receiver. The reader not only generates the electromagnetic wave, which impinges on the MST tag, but it also collects the back-scattered electromagnetic wave, which carries the information reflected by the tag. The homodyne detector is mandatory to correctly retrieve the information from the backscattered electromagnetic wave [50,51]. In particular,

the high-frequency signal is converted to the baseband, and a suitable elaboration system is aimed at collecting, processing and storing the information from the low modulation signal of the backscattered wave [27]. On the left side of Figure 1 is shown the tag structure. The MST tag is composed of a small receiving antenna, an electronic switch, a set of loads, an elaboration unit, power units and a set of environmental probes. The elaboration unit reads the measured quantities from the probe. The elaboration units also act on the electronic switch; it permits connecting the antenna tag toward two different loads. The variation of impedance, connected with the antenna tag, produces a low-frequency modulation on the back-scattered electromagnetic wave. The low-frequency modulation carries the information, and it can be easily read by the reader. A good MST system design permits maximizing the communication range  $r$  [30]. This goal can be accomplished by considering the well-known radar equation reported in the following relation [34,52] (under the hypothesis of free space and far-field conditions):

$$r = \frac{1}{2} \left( \frac{P_{tx} \cdot G_{tx} \cdot \lambda^2 \cdot A_{tag} \cdot G_{tag} \cdot ME(Z_1, Z_2)}{(4\pi)^2 \cdot P_{rx}} \right)^{\frac{1}{4}} \tag{1}$$

where  $P_{tx}$  and  $G_{tx}$  are the power of the sinusoidal generator and the reader receiving antenna gain, respectively.  $P_{rx}$  is the minimum detectable power, and it depends on the receiver sensibility.  $A_{tag}$  and  $G_{tag}$  are the antenna tag aperture cross-section and gain, and  $\lambda$  is the wavelength of the sinusoidal signal generated by the reader. The quantity of ME, called the modulation efficiency, is reported in the following relation:

$$ME(Z_1, Z_2) = \frac{4Re\{Z_{tag}\} |Z_2 - Z_1|^2}{|Z_{tag} - Z_1|^2 \cdot |Z_{tag} - Z_2|^2} \tag{2}$$

where  $Z_{tag}$  is the antenna tag impedance and  $Z_1$  and  $Z_2$  are the two loads connected to the electronic switch. As can be noticed from Equation (2), the modulation efficiency ranges between  $0 \geq ME$  and  $ME \leq 4$ . Considering Equation (1), it is quite evident that the only way to improve the communication range  $r$  is to act on the values of the two loads  $Z_1$  and  $Z_2$  or to modify the antenna tag impedance  $Z_{tag}$ . The other parameters are fixed quantities. To obtain the maximization of the ME, the best values for the two loads are  $Z_1 = 0$  and  $Z_2 = Z_{tag}^*$ .  $Z_2$  is called the adsorbing load, and it is used to obtain a perfect match.

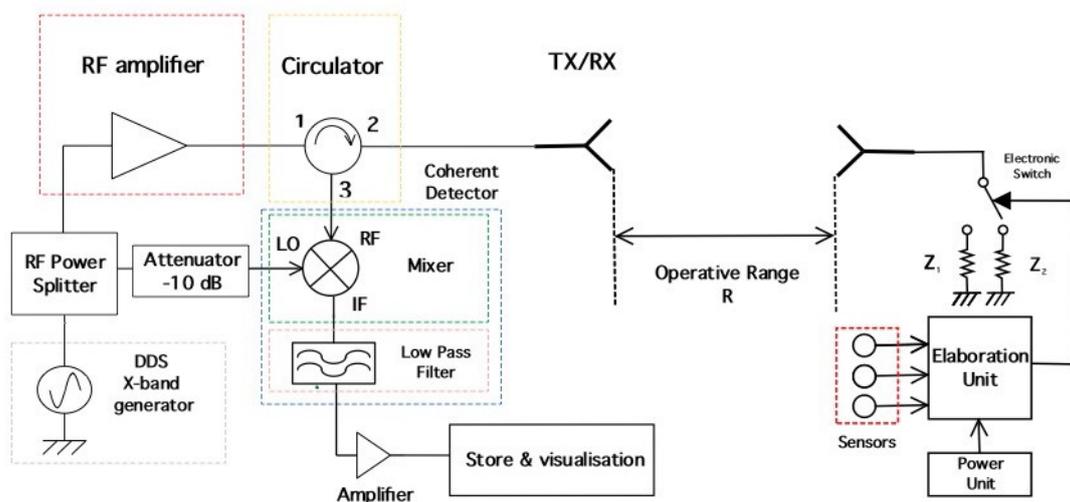


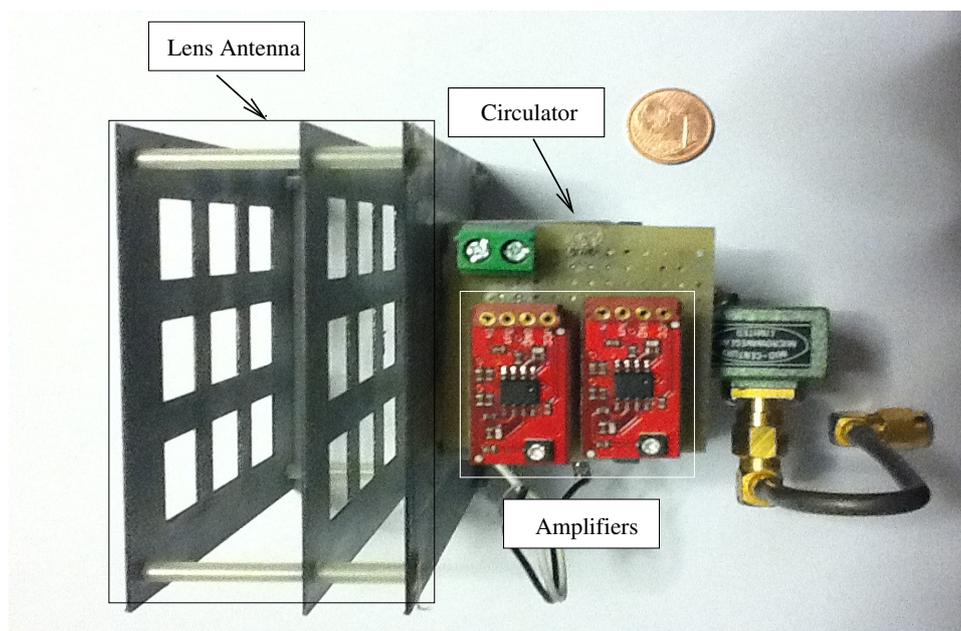
Figure 1. Schematic of a mono-static modulated scattering technique (MST)-based measurement system.

### 3. Description of the MST Environmental System

The following sub-sections are aimed at the description of the reader, MST tag structure and transmission protocol.

#### 3.1. Reader Description

In Figure 2, the picture of the MST reader's working prototype is shown. The prototype consists of a ferrite circulator, an X band microwave Gunn generator of  $P_{tx} = 50$  mW, a lens antenna characterized with a gain of  $G_{tx} = 17$  dBi and two low-frequency amplifiers with a total gain of  $G_{amp} = 20$  dB. As can be noticed from Figure 2, the reader is a classical mono-static structure (characterized by only one antenna, which acts as a receiver and transmitter at the same time). The reader is quite compact and mechanically robust. The ferrite circulator output is connected to the homodyne receiver. The receiver is composed of an unequal splitter aimed at providing the reference to the mixer, a low-cost monolithic microwave integrated circuit mixer (an anadigics AKD12000). The signal at the mixer output is then filtered by means of a low pass seven order equal ripple 0.5-dB filter. The low modulation signal is extracted from the high frequency backscattered wave using a coherent detector. Further, the two low noise amplifiers are used to amplify the obtained baseband signal, where the amplifier has a total gain of  $G_{rx} = 20$  dB. The least detectable power is about  $P_{rx} = -100$  dBm at the reader output.



**Figure 2.** Photograph of the compact MST reader.

#### 3.2. MST Tag Description

To illustrate the abilities of the MST method-based wireless sensors, the development of a wireless sensor tag is described in this section. To develop an MST sensor tag, the first step is to choose the electronic switch properly by considering the guidelines followed in [30]. MOSFET-based switches offer the best performances, which could lead to nearly the maximum theoretical upper limit for the ME. The MOSFET switch developed in Section III D of [30] was chosen for the considered MST tag prototype because it offers the best performances with respect to the communication range. The PIC18F876A microchip, a low-cost microcontroller, was chosen as the elaboration unit, to acquire, convert and send the proper modulation signal to the driven modulation circuit. This microcontroller is equipped with A/D channels to connect a different kind of sensor. Moreover, it is equipped with a low power wake-up module. To reduce the power consumption, the microprocessor is kept in stand-by mode, and it is activated by means of a suitable interrupt only to perform the

measurement. A switching step down voltage regulator, the MAX1044 (Maxim company), was used to reduce the power consumption. The elaboration and the switching sub-units were assembled into a compact two-layer structure of dimensions  $50 \times 35 \times 25 \text{ mm}^3$ . As can be seen from the photo in Figure 3, the prototype is quite compact. However, the dimensions could be further reduced since the elaboration unit was assembled with standard components and not with surface-mounted devices (SMD). To obtain a wireless temperature/humidity probe, the two A/D channels out of the four were connected to a precision temperature sensor LM35DZ and the humidity sensor HR202. The humidity and temperature sensors have been calibrated in a controlled environment. In particular, a climatic chamber (ANGELATONI DY1200 with a temperature and humidity range of  $-40 \text{ }^\circ\text{C} < T < 180 \text{ }^\circ\text{C}$  and  $10\% < H < 98\%$ ) was kindly provided by the EMC company, Genoa Italy. Figure 4a,b reports the calibration graph for the temperature and humidity sensor, respectively. As can be observed from the graph of Figure 4, the agreement is quite good. The working of the MST tag is as follows: The microcontroller collects the data for the temperature and humidity from the sensors continuously and converts them into bits using the 12-bit AD converter. Then the data are transmitted by changing the loads of the tag antenna using the MOSFET switch. To transmit the data, the modulation frequency is considered as 2 kHz. Furthermore, the modulation protocol is the same as for the RFID systems in [32,33]. In detail, as a protocol, EM4102, and for the modulation, the Manchester modulation were used. In the Manchester modulation, a low to high transition is represented by a logical one state, and a high to low transition is represented by a logical zero state. The EM4102 protocol allows immediate integration with commercial and RFID systems, databases and other RFID resources. The data organized in the EM4102 are as follows: the first nine bits of the data represent a logical one state. These first nine bits signify the start of the data string as a marker sequence. Then, the remaining string is followed by 10 groups of four data bits and one even parity bit. Finally, four bits of a column parity (even) and a stop bit (zero) are used. The MST tag performs tasks like read, convert and transmit the string data and represents the measured temperature perfectly as long as it has power. Furthermore, the length of each bit in the tag is defined in terms of clock cycles. Any bit length can be used from 64, 32 to 16 clock cycles in the EM4102 protocol. For this preliminary experiment, a 32-bit length and a reference frequency clock of 100 kHz has been used. An example of data sequence, transmitted by the tag and measured at the reader, output with a digital storage oscilloscope (DSO) is reported in Figure 5a. The tag has been placed at an operative distance  $r = 15 \text{ m}$  from the reader. Figure 5b reports the reader output when the tag is not activated. As can be seen from the waveform reported in Figure 5a, the data are clearly detected. Concerning the measurement of the MST tag prototype's power consumption, it was carried out using suitable checkpoints introduced in the driving circuit of the modulation and microcontroller section. The MST tag was tested under different realistic operative conditions. In particular, in standby, with the modulation driven circuit turned off, the microcontroller required 3 V and  $I_s = 3.5 \text{ }\mu\text{A}$ ; while during the measurement phase, the current required by the microcontroller was about  $I_o = 8 \text{ }\mu\text{A}$ , considering that the modulation circuit required about  $I_m = 2 \text{ mA}$ . The total current required by the MST tag in normal working conditions was about  $I_t = 2 \text{ }\mu\text{A}$ . The power supply was provided by two standard rechargeable (1.2 V,  $I = 1400 \text{ mA}$ ) batteries, which can ensure a measured lifetime of the MST tag of about 12 h of continuous operation.

The prototype was also equipped with a small solar panel ( $V = 3$  and  $I = 10 \text{ mA}$ ), able to guarantee not only the correct working conditions during the day, but also to recharge the two batteries, aimed at providing the necessary current during the night.

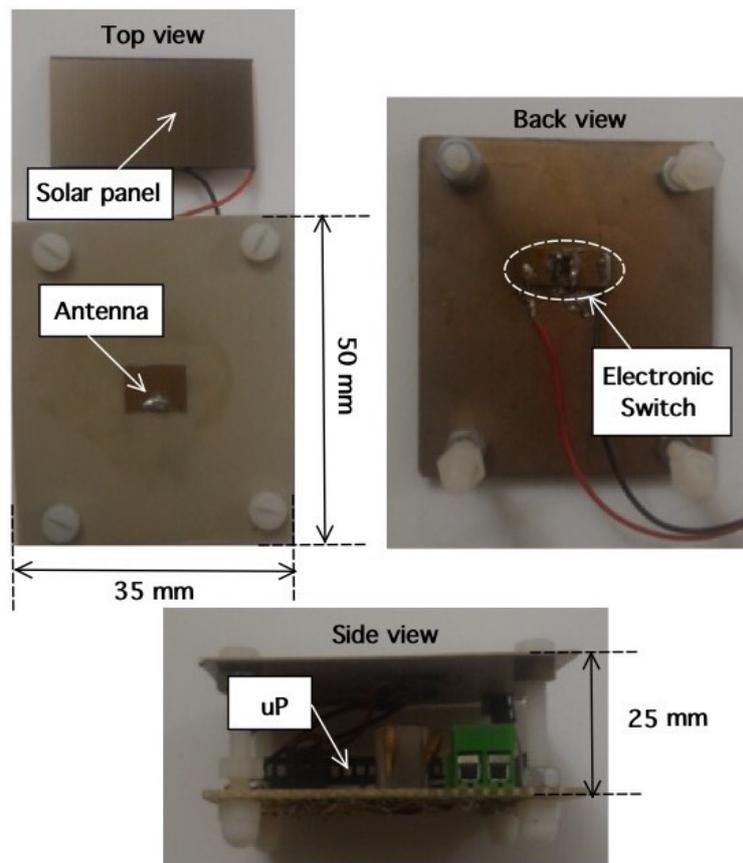


Figure 3. Photo of the MST tag equipped with temperature and humidity probes and a solar panel.

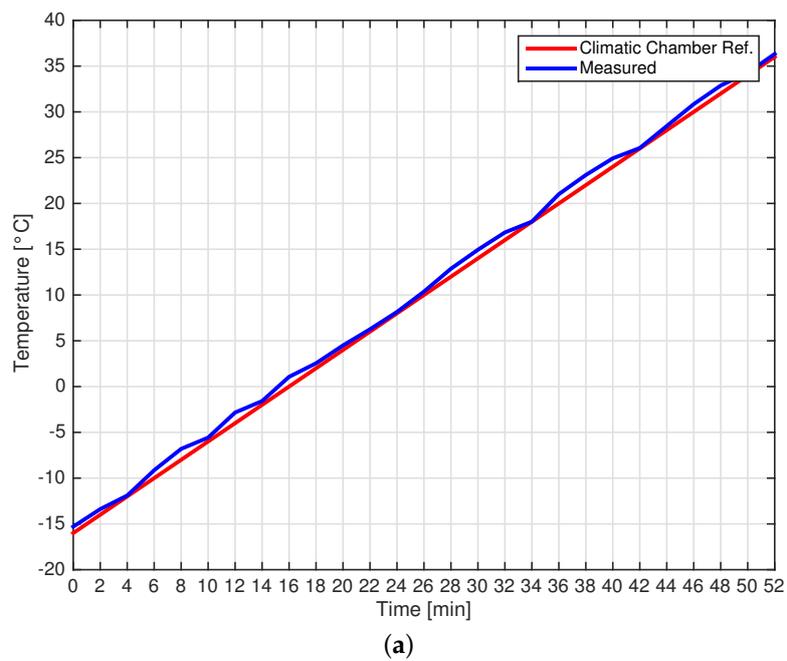


Figure 4. Cont.

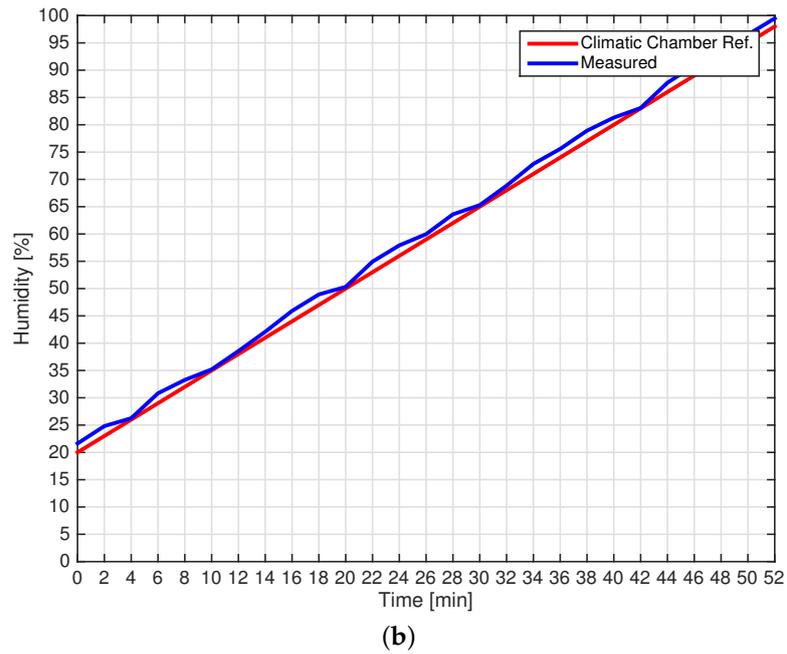


Figure 4. Temperature and humidity calibration curves obtained with a climatic chamber: (a) temperature and (b) humidity.

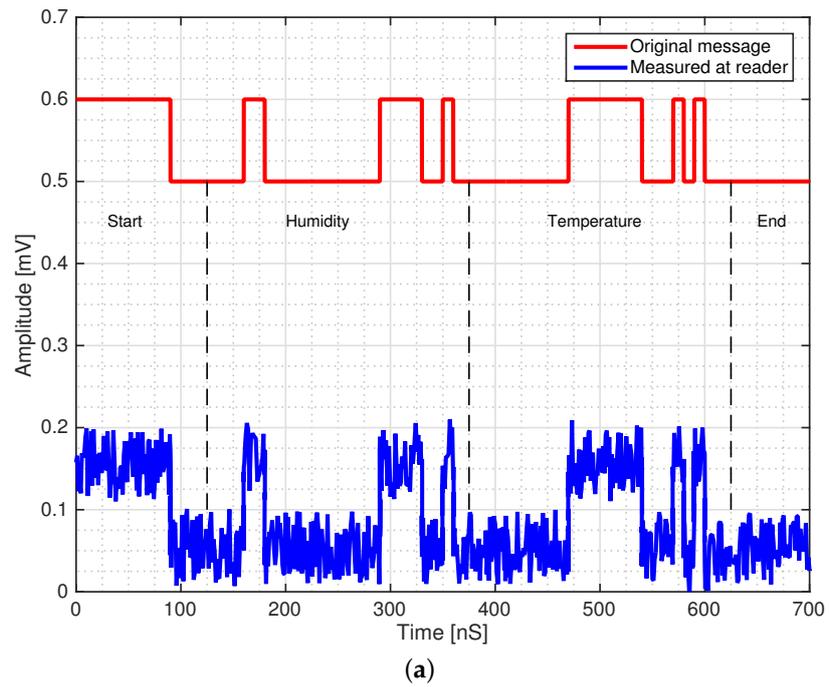
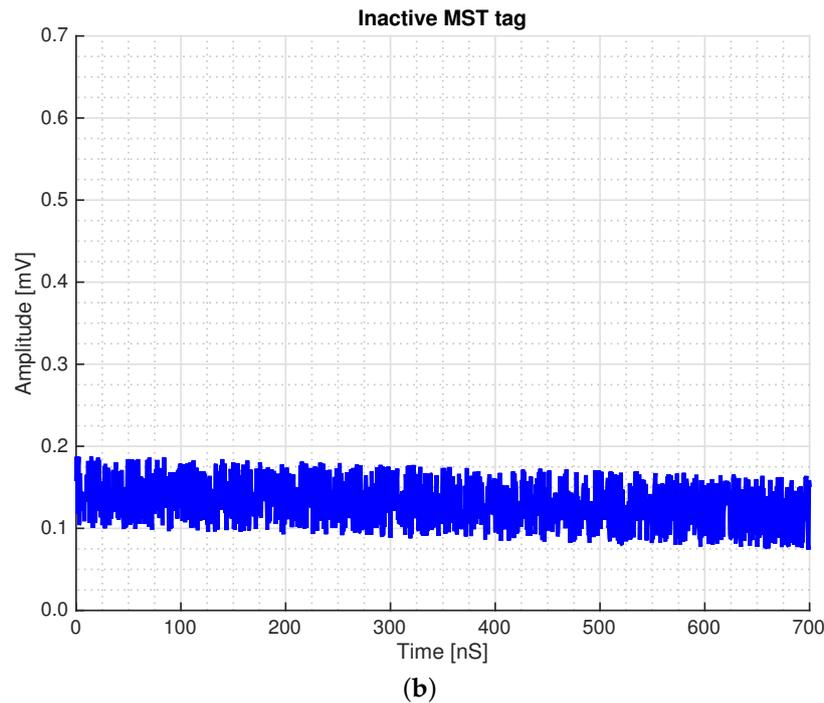


Figure 5. Cont.

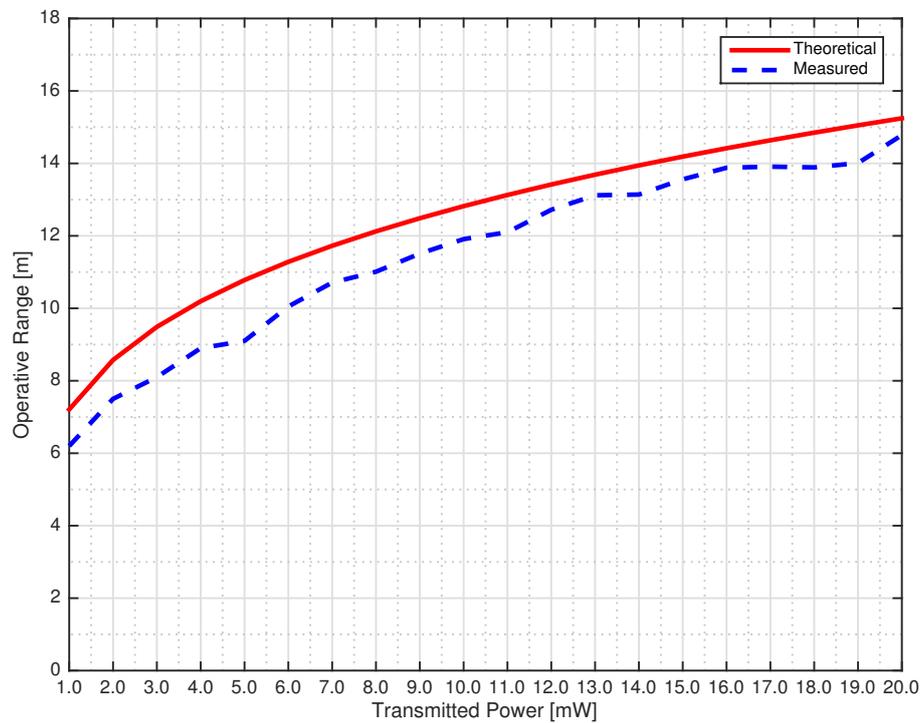


**Figure 5.** Example of the data structure received at the reader output (a). Signal detected with an inactive tag (b).

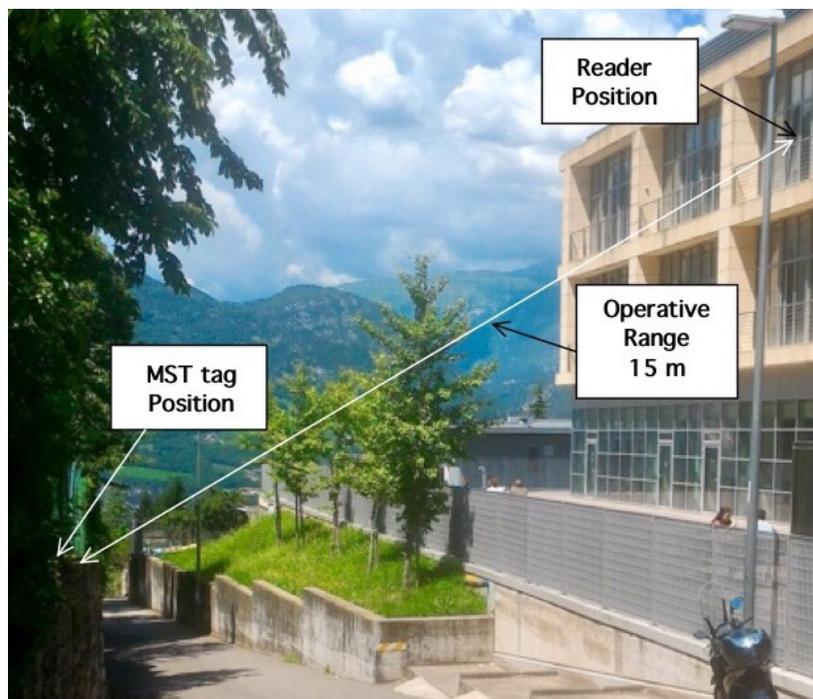
### 3.3. Experimental Setup and Measurement Campaign

Before starting the measurement campaign, the theory described in Section 2 was assessed in a controlled environment. In particular, the operative range versus the transmitted power was measured. The operative range was considered valid when the transmitted tag sequence was correctly received a hundred times. Concerning the other system parameter  $G_{tx} = 17$  dBi,  $G_{tag} = 6$  dBi are the reader and tag antenna gains, respectively, and  $P_{rx} = -110$  dBm is the minimum detectable power at the receiver,  $P_{tx} = -17$  dBm. The obtained modulation efficiency  $ME = 3.2$  was very close to the upper theoretical limit. For the transmitter a direct digital synthesis (DDS) generator is able to modify its power in the range of  $1 \text{ mW} < P_{rx} < 20 \text{ mW}$  with a step of 1 mW. The results reported in Figure 6 show a good agreement between theoretical and experimental data. To assess the capabilities of the MST sensor, it was placed in a line of sight at a distance  $r = 15$  m from the reader. The data at the reader output were elaborated by means of a laptop provided with an A/D board, and a monitoring campaign of three months was carried out. In particular, the MST sensor was placed outdoors, exposed to the weather and used to monitor the temperature and humidity during the summer season. The photo of the considered measurement scenario is reported in Figure 7. The reader has been placed beyond a window of the laboratory, and the MST tag was placed on a small wall outside the building and exposed to meteorological phenomena. The distance between the reader and the tag was measured by using a commercial laser telemeter (the Bosh PLR40C with an accuracy of  $\pm 2$  mm). The microcontroller was connected to the MST reader, and it was programmed to take a measurement every half an hour. In these operating conditions, the lifetime of the MST tag was more than 12 h. Figures 8 and 9 show the humidity and temperature values recorded during the three-month campaign. As can be noticed from the data in Figure 8, the maximum and minimum temperature values recorded were  $T_{max} = 37$  and  $T_{min} = 12$ , respectively (typical temperature values of the summer in Northern Italy). These data were compared and confirmed by the official meteorological reports. This is a further demonstration of the MST-based systems' potentialities as wireless sensors for real-time environmental monitoring applications. For the sake of comparison, the performances of other state of the art RFID systems [53–55] were compared with the proposed prototype. The data are

reported in Table 1, and as can be noticed, the proposed MST system is able to reach a higher operative range with a lower transmitting power with respect to the other considered systems.



**Figure 6.** Operative range vs. transmitted power. Continuous red line, theoretical; dotted blue line, experimental.



**Figure 7.** Photo of the experimental setup.

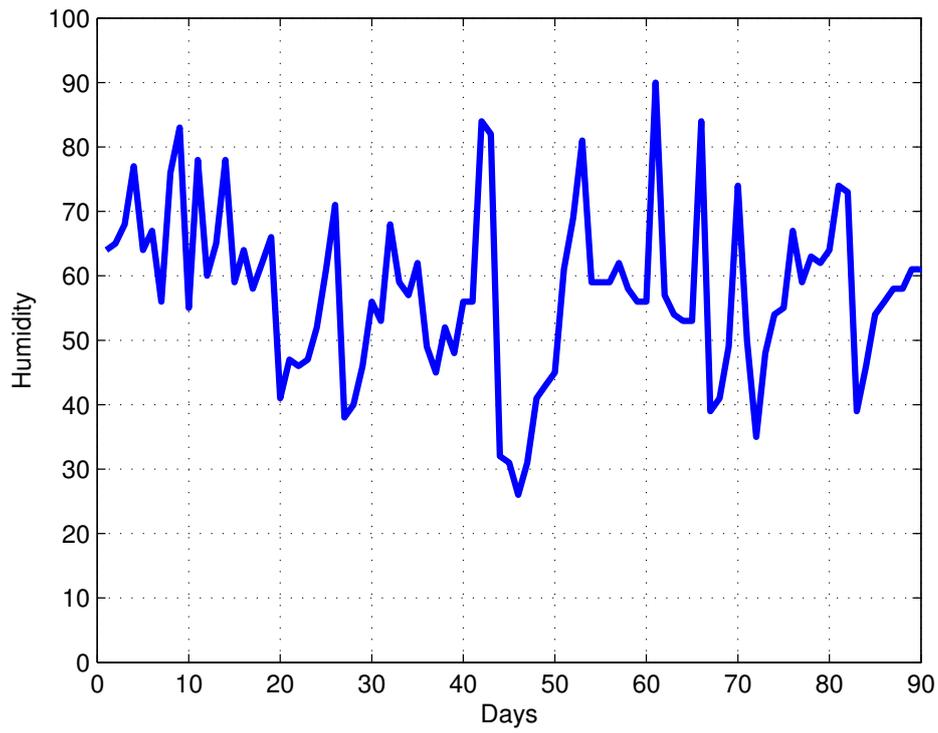


Figure 8. Three-month humidity measurement campaign data.

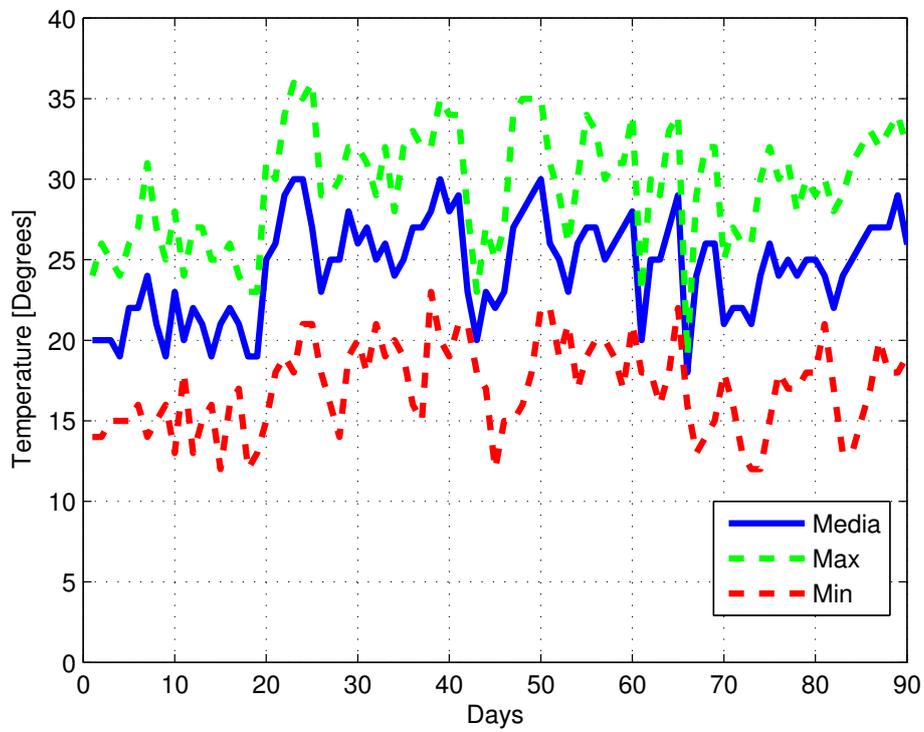


Figure 9. Three-month temperature measurement campaign data.

**Table 1.** State of the art RFID system performance comparisons.

Freq. (GHz)	TX Power (W)	Range (m)
0.915	0.5	9.25 [53]
2.450	0.007	3.30 [54]
2.450	4.0	10.00 [55]
10.0	0.002	15.00

#### 4. Conclusions

In this work, X band MST wireless sensors for an environmental system were designed, fabricated and tested. The MST system prototype was designed by a monostatic reader section, based on a high gain amplifier, a transmitting antenna, a homodyne detector and an elaboration unit based on a low-cost microcontroller. The MST probe used a rectangular patch antenna, loaded on two different loads by means of a MOSFET-based electronic switch. The system efficiency has been optimized, as well as the communication range  $r$  maximized. In particular, a distance of about  $r = 15$  m has been reached. The results of the experimental assessment demonstrated the effectiveness and potentialities of the proposed MST wireless sensor prototype and confirms that MST systems could be appealing alternatives to the standard wireless sensor. Future works will be devoted to the further miniaturization of the MST probe and the improvement of the communication range.

**Author Contributions:** M.D. proposed the idea, conceived and designed the experiments; M.M. performed the experiments and analyzed the data.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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