Screw Relaxing Detection With UHF RFID Tag

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ABSTRACT This paper presents a simple and low cost solution for the implementation of a screw relaxing sensor based on ultra-high frequency (UHF) radio frequency identification (RFID) passive tags. The proposed method opportunistically uses the natural capability of a metallic screw (or a metallic part fixed on a plastic screw) to realize an electrical continuity between two electrical lines, which is exploited to realize an open/closed switch mechanism associated to the tightened/relaxed screw status. Several switch-like possible realizations are described according to different working environments and situations, as well as tag-sensor implementation schemes. Three tag-sensors are designed and manufactured to comply with metallic or non-metallic application surfaces and to work within the UHF RFID Chinese band 920.5 – 924.5 MHz, showing a reliable discrimination capability between well-tightened and relaxed screw states. Finally, parameters such as maximum detection surface and minimum detection time are evaluated for completing the analysis of the presented detection system.

INDEX TERMS Antennas, Internet of Things, sensors, radio frequency identification (RFID), ultra-high frequency (UHF), tag-sensor, screw relaxing detection.

I. INTRODUCTION

The Internet-of-Things (IoT) scenario in which a multitude of objects or people possess the ability to communicate and transfer data over a global network is attracting the interest of many private companies as well as industries, and many projects have been already conducted in areas such as agriculture, food processing industries, environmental monitoring, security surveillance, intelligent transportation system (ITS), healthcare [1].

The integration of different technologies is a key property of IoT scenario to build up powerful industrial systems and applications. Among these technologies, radio frequency identification (RFID) is the first associated to the concept of IoT thanks to its features of being of low cost and easy to be deployed [2]. RFID allows a tag device for wirelessly transmitting its own identification information to a reader when interrogated, enabling identification and tracking of objects [3].

Wireless sensor network (WSN) is another important technology for the development of IoT because it can provide the possibility to interconnect intelligent devices for sensing and monitoring [4]. This introduces new degrees of freedom and new features for developing more complex and powerful IoT networks [5]. However, a single node of a WSN is clearly more expensive than a RFID tag, and it requires a larger amount of energy [1]. For this reason, the possibility to integrate sensing and monitoring functionalities in a RFID tag for implementing a low cost tag-sensor is recently being investigated [6], [7]. In such a case, information coming from a sensor is usually mapped into a tag antenna parameter variation, and this variation is employed to implement a data modulation mechanism for communicating with the reader device [7]. This kind of device can provide only limited...
sensing functionalities which, nonetheless, are sufficient for threshold monitoring applications [8], or for implementing classical temperature sensors [9], humidity sensors [10], etc. Tag sensors have also been proposed for other special applications, such as blood pressure measurement [11], e-skin [12], low power agricultural WSN [13], diaper wetness detection [14]. Finally, the analysis of tag signal patterns is recently investigated as an interesting methodology to gather information from a RFID tag which is not equipped with a specific sensor. This concept has been exploited for the implementation of a water filling tag sensor [15], and a more sophisticated temperature sensor with commercial UHF RFID tags [16].

In brief, tag-sensors enable the monitoring of different physical quantities, or the detection of threshold events. For what the latter is concerned, the detection of potential unsafe circumstances is surely important in vehicular as well as industrial environments, and it has already been investigated for applications in the context of structural health monitoring [17]. Cracks, corrosion, strains, bolt loosening, etc., are some possible structural circumstances where RFID tag sensors have been applied successfully [18], [19]. In this sense, screw relaxing is a situation which is rarely monitored (except for the manual inspection), even if it many times could be crucial for safety. The possibility to integrate a screw relaxing sensor into a RFID tag is surely of interest because: (a) screws are usually of large quantities, and for this reason a screw relaxing sensor has to be of low cost; moreover, a RFID tag-sensor based monitoring system is capable of interrogating a large population of devices in a limited amount of time; (b) even if an automatically monitoring system is not implemented, a RFID tag-sensor can be quickly interrogated by a handheld reader device (which is a faster procedure than the manual inspection of an operator); (c) a RFID communication system can be pre-installed for the screw relaxing detection in places not easily accessible to a human operator, or RFID tag-sensors not accessible for safety issues can be interrogated by RFID readers installed on unmanned aerial vehicles (UAVs) for autonomous inspection [20].

Motivated by the above discussion, passive RFID tag-sensors are employed in this work for the first time to detect screw relaxing events for metallic or plastic structures. The metallic body of the screw is exploited to implement a screw relaxing sensing mechanism capable of discriminating between a well-tightened state (in which the metallic body of the screw provides electrical continuity to one part of the tag device circuit), and a relaxing event (in which the electrical continuity is lacking). In fact, the specific screw status determines a different tag sensitivity, which is herein employed as the parameter to distinguish between these two screw conditions. A possible implementation of such tag-sensor has been presented by these authors in the preliminary work [21], and in this paper we will extend this topic to provide a more complete discussion. Different tag-sensor implementations will be discussed in this paper with pros and cons in accordance with the installation environment and the specific application requirements. In particular, presented tag-sensors are based on a meandered dipole structure for a non-metallic attaching surface, and on a planar inverted-F antenna (PIFA) structure that can guarantee the compatibility with metallic surfaces in a compact layout. Furthermore, prototypes of these RFID tag-sensors for the ultra-high frequency (UHF) band are manufactured on different dielectric materials, i.e., FR4, Rogers RO4003C, and F4BM350, and different substrate sizes, and tested when installed on different surfaces, showing well-distinct behaviors for discriminating well-tightened and relaxed screw conditions. It is worth noting that although the concept presented in this work has been implemented in the UHF RFID Chinese band (920.5-924.5 MHz), this can be potentially extended to any other working bandwidth.

II. UHF RFID COMMUNICATION SYSTEM AND TAG-SENSOR FOR SCREW RELAXING DETECTION

A. RFID COMMUNICATION SYSTEM

A block diagram of a typical RFID communication system which can be used for the proposed application is shown in Fig. 1.

The system is composed by a UHF RFID reader device connected to a PC which manages the whole system. The reader device RF output port is connected to a transmitting antenna employed to illuminate a specific space region in which is supposed that one or a population of tags are present. When a tag device receives a signal whose power is larger than a certain threshold $P_{th,tag}$ (called tag sensitivity), the tag device is activated and reply to the interrogation sending back an opportunely modulated signal [22].

In the case of a monostatic RFID system, i.e., a single antenna is employed for transmission and reception, and line-of-sight propagation (and under the hypothesis of perfect antennas alignment and no polarization mismatch), link budget equations (in dB) are given as [23]

$$
P_{forward} = P_{EIRP} + 20 \log_{10}\left(\frac{\lambda}{4\pi r}\right) + G_r + 10 \log_{10}\left(1 - |\rho|^2\right) \geq P_{th,chip}$$

$$P_{back} = P_{forward} + 10 \log_{10}(M) + 10 \log_{10}\left(|r|^2\right) + G_r + 20 \log_{10}\left(\frac{\lambda}{4\pi r}\right) + G_t \geq P_{th,reader}$$

FIGURE 1. Block scheme of the proposed UHF RFID system.
where $P_{\text{forward}}$ and $P_{\text{back}}$ are the forward link received power (from reader to tag) and the backward link received power (from tag to reader), respectively: $P_{\text{EIRP}} = P_t + G_t$ is the effective isotropic radiated power (whose maximum value is fixed by communication standards - $P_t$ is the transmitted power), $G_t$ and $G_r$ are the reader and tag antenna gains, respectively, $\rho$ represents the reflection coefficient at the tag chip input port, $\tau$ is the transmission coefficient between the tag chip and the antenna, $M$ is the modulation factor, $P_{\text{th,chip}}$ is the tag chip sensitivity, $P_{\text{th,reader}}$ is the sensitivity of the reader, and $\lambda$ is the wavelength. When link budget equations are respected, RFID system works normally implementing the communication according to, for example, the standard EPC Gen2 [24].

### B. RFID TAG-SENSOR AND SCREW RELAXING DETECTION CONCEPT

For the sake of a clearer comprehension, let us consider the case of a RFID reader with a sensitivity such that it is possible to always assume $P_{\text{back}} \geq P_{\text{th,reader}}$. Under this assumption, link budget equations (1) can be simplified as

$$P_{\text{EIRP}} + 20 \log_{10} \left( \frac{\lambda}{4\pi r} \right) \geq P_{\text{th,tag}}$$

$$P_{\text{th,tag}} = P_{\text{th,chip}} - G_r - 10 \log_{10} \left[ 1 - |\rho|^2 \right]$$

(2)

This means that, for a certain interrogation distance $r_0$, a minimum $P_{\text{EIRP}}$ (or, equivalently, $P_t$) is required to activate the RFID tag and receive a reply, i.e., $P_{\text{EIRP,min}} = P_{\text{th,tag}} - 20 \log_{10} \left( \frac{\lambda}{4\pi r_0} \right)$.

If a sensing element for the physical parameter $\beta$ is introduced in the RFID tag design which is capable of modifying the tag sensitivity $P_{\text{th,tag}}$, i.e., $P_{\text{th,tag}} = P_{\text{th,tag}}(\beta)$, it is sufficient to sense the tag sensitivity (by opportunely verifying the minimum $P_{\text{EIRP}}$ necessary to establish a communication link) in order to gather the information about $\beta$. In particular, the sensing element can act on $G_r$ or $|\rho|$ to cause a change on $P_{\text{th,tag}}$, as it can be deduced from (2).

According to this principle, many examples of RFID tag-sensors can be found in literature, for both “analogic” sensing (where the sensed variable $\beta$ as well as $P_{\text{th,tag}}$ can vary continuously within a certain range of values, e.g., [10]) and threshold detection (where $P_{\text{th,tag}}$ changes abruptly, e.g., [11]).

RFID tag-sensors presented in this work are used to detect the screw tightening status $\beta = \{\text{well-tightened, relaxed}\}$. This will be realized by mapping a screw-relaxing condition into a change of the tag reflection coefficient $|\rho|$ which, according to the above discussion, affects $P_{\text{th,tag}}$. In particular, only two states will be considered: $|\rho| = 0$ (matched case) which determines the minimum $P_{\text{th,tag}}$, and $|\rho| = 1$ (unmatched) which causes the tag being unreachable (because $P_{\text{th,tag}}$ is theoretically $+\infty$). Each of these two conditions, i.e., “tag works normally” and “unreachable”, will be associated to one specific status of the screw.

In the next section, the practical implementation of the screw relaxing sensor which is able to map a screw tightening variation into a change of $|\rho|$ will be described. After that, the theoretical RFID tag-sensor design will be illustrated, and two RFID tag-sensors for different environments will be designed.

### III. SWITCH-LIKE MECHANISM WITH THE OPPORTUNISTIC USE OF THE SCREW HEAD

An ideal electrical switch connected between a source and a matched load is a device that when switches from an “open” to a “closed” position or vice versa can determine an abruptly variation of the reflection coefficient at the source. This is exactly the electrical behavior necessary to implement the screw tightening sensor as described in Sec. II-B. Therefore, the objective of this section is to illustrate how to implement a switch-like mechanism by taking advantage of the screw metallic body.

Let us consider an ideal case of a screw fastened on a dielectric substrate, as represented in Fig. 2. If two electrical lines are interrupted exactly under the screw head, since the screw head has a good electrical conductivity, when the screw is well-tightened an electrical continuity is established between the two electrical lines. On the contrary, when the screw head is relaxed, the electrical continuity is interrupted. In this case, the raising movement of the screw during its relaxing has been exploited to realize a switch-like mechanism. Therefore, in this work the metallic screw head acts as an opportunistic electrical line which connects one or more parts of an electrical circuit. When the screw relaxes, its mechanical movement (rotation/raising) causes an electrical continuity interruption between the screw and the electric circuit.

This simple concept has been herein employed to implement different switch-like mechanisms adapt for different working environments, which are schematically shown in Fig. 3. Particularly, three main cases will be treated in this work: a metallic screw tightened on a metallic surface, a metallic screw with an isolated metallic contact tightened on a metallic surface, and a plastic screw with a metallic contact tightened on a non-metallic surface.

### A. SCREW HEAD RAISING-BASED SWITCH-LIKE MECHANISM

The raising movement of the screw when it relaxes is herein exploited to implement different switch-like mechanisms as illustrated in Fig. 3. As in the example of Fig. 2, the screw is not directly fastened on the application surface, but a thin substrate, e.g., a dielectric on which the electric lines can be printed on, is inserted between the fastening surface and the screw head to realize the electrical continuity between the two lines.

When metallic surfaces are considered and assuming the metallic surface as the electrical voltage reference, i.e., ground, since electrical lines on the top layer of the dielectric substrate are parallel with the metallic surface.
on the bottom layer, they can be easily implemented with microstrip transmission lines [25] that, in the case of well-tightened screw, are short-circuited to ground as shown in Fig. 3 (a). In this case, when the screw relaxes, its raising breaks the electrical continuity between ground and electrical line, yielding to an “open circuit” state.

When a metallic screw is isolated from the ground plane, e.g., by employing a metallic screw where the metallic contact is isolated from the screw body with a plastic washer, the same structure as in Fig. 2 can be used to implement a switch-like mechanism that is normally closed; as schematically depicted in Fig. 3 (b), when screw relaxes, an “open circuit” state is verified. In the same way, when plastic screws are considered, a normally closed switch-like mechanism can be easily implemented (Fig. 3 (c)).

B. SCREW HEAD ROTATION-BASED SWITCH-LIKE MECHANISM

The rotation of the screw head during the relaxing can also be used to implement alternative switch-like mechanisms, with both metallic or plastic screws. For example, the screw is placed in the proximity of an electrical line as depicted in Fig. 4. When the screw is well-tightened, conductive glue drops or special asymmetric washers are employed to short-circuit the electrical line to ground. When the screw starts rotating, the drop falls off and the electrical line is isolated from the ground.

Switch-like mechanism implementations described here are only few possible practical realizations of a screw relaxing sensor, and other opportunities can be investigated.

C. ELECTRICAL BEHAVIOR OF SCREWS

The opportunistic use of the screw head proposed in this work is based on the hypothesis that a screw can be effectively considered as a short-circuit or that it can provide the necessary electrical continuity from an electrical point of view. This hypothesis has been confirmed by measuring the electrical behavior of stainless steel screws within the universal UHF RFID bandwidth 840-960 MHz [22]. In particular, electrical impedances $Z_{screw}$ between contact points of different screws shown in Fig. 5 which can be employed to realize switch-like behaviors described above have been measured. A vector network analyzer Agilent N5230A has been employed to firstly measure the scattering parameter $S_{11}$ at the different contact points, used then to calculate $Z_{screw}$ as [26]

$$Z_{screw} = 50 \Omega \cdot \frac{1 + S_{11}}{1 - S_{11}}$$  (3)

It should be noted that a short 50 $\Omega$ coaxial cable has been firstly calibrated with the port extension method to measure $S_{11}$ at points of interest for the short-circuit cases; after that, and the $S$ matrix has been measured with a two-ports fixture, and $Z_{screw}$ calculated as [26]

$$Z_{screw} = 2 \times 50 \Omega \cdot \frac{1 - S_{11}S_{22} + S_{12}S_{21} - S_{12} - S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}$$  (4)

As expected, the screw behavior is prevalently resistive and inductive, i.e., $Z_{screw} = R_{screw} + j2\pi f L_{screw}$, and measured $R_{screw}$ and $L_{screw}$ are shown in Fig. 6. $R_{screw}$ within the universal UHF RFID bandwidth is 3-5 $\Omega$ for all cases, which confirms the required screw behavior. On the other hand, an inductive component $L_{screw}$ sensitive to the current path length is present, and it is larger for the short-circuit case with metallic steel screw. Considering the example of the short-circuit and assuming that this state has to realize a return loss $|\rho| = 1$, the presence of a residual component $R_{screw}$ and $L_{screw}$ could affect significantly $\rho$ leading to ambiguous states. In fact, at 900 MHz an inductive component of 3 nH determines a reactance of 16.96 $\Omega$ which is not a short circuit and, as said, can lead to cases in which $|\rho| < 1$ which, according to (1), makes the tag theoretically reachable. As said, $L_{screw}$ increases with the increase of the current path length, i.e., the distance between the electrical line contact point on the screw body and the ground contact point; this means that if the dielectric on which the contact is realized is thick, $L_{screw}$ will be large. For this reason, it is important to use very thin substrates.

For plastic screws with metallic washer or isolated screws, $R_{screw}$ is more sensitive to the current path length increase and, for this reason, it is suggested to implement the contact mechanism with very close contacts.

IV. UHF RFID TAG-SENSOR DESIGN

Possible implementations of the passive RFID tag-sensor with the matched/unmatched mechanism described above are schematically illustrated in Fig. 7 for both differential and single-ended tag schemes. A classical passive RFID tag is composed by a tag antenna, an impedance matching network, and a tag chip (the impedance matching network is herein included for considering all the cases in which the antenna impedance is not directly matched to the tag chip impedance, but the use of not of this network depends on the specific implementation of the antenna). Furthermore, in Fig. 7 it is possible to observe the presence of a switch device which represents the behavior of the screw as described in Sec. III. This switch is placed on different points of the equivalent circuit depending on the specific implementation of the tag-sensor. In particular, in Fig. 7 (a) the switch is placed in series with the rest of the circuit, and it is clear that when the switch
is closed, the tag device can work normally, while when the switch is open, the tag chip is isolated and cannot reply to a reader interrogation (it should be noted that, in this case, the switch can also be placed between the impedance matching network and the tag chip, or between the tag chip and the ground in the single-ended implementation). In Fig. 7 (b), the parallel switch is used to short-circuit the antenna, yielding the opposite behavior of the previous implementation (when the switch is closed, the tag is unreachable, while when the switch is open, the tag works normally). Finally, in Fig. 7 (c) the switch is enclosed into the impedance matching network part, and it is used to modify the impedance matching network circuit yielding to different $\rho$ based on the switch state.

According to specific application requirements, a tag-sensor which can communicate when the screw is well-tightened and is not reachable when the screw is relaxed or vice versa can be implemented by considering the implementation examples in Fig. 7. Finally, the tag-sensor implementation schemes can also be combined together, e.g., using two tag chip devices and implementing the scheme in Fig. 7 (a) and (b) together with one antenna and one screw.

The choice of the RFID tag-sensor and, in particular, its radiating part, is strongly related to the working environment, i.e., whether it has to be attached on a metallic surface or not. Many RFID tag antenna designs are proposed in literature for both these applications, and we can roughly classify them into dipole-based (usually employed for non-metallic surfaces) which has a differential-ended structure [27], and metallic patch-based (employed for metalized surfaces) which has a single-ended structure [28], but can also be realized with a symmetric configuration and a differential-ended structure. Although the main common screw application surface is a metallic plate, in this paper we present a general treatment for both metallic and plastic screws which can work on metallic and non-metallic environments. For this reason, two RFID tag antenna designs will be presented in the following for complying with these two possibilities.

**A. DESIGN OF THE RFID TAG ANTENNA FOR METALLIC SURFACES**

For applications on metallic surfaces, we have decided to employ a microstrip patch antenna structure because of well-known advantages of being printed on very thin dielectric substrate (which is a desirable requirement for
the application described in this manuscript, as also seen in Sec. III-C, capability to be conformal to various surfaces, simple and inexpensive manufacturing, and mechanical robustness [29]. Moreover, we have considered an interrogation from a perpendicular plane with respect to the surface, which is exactly the radiation plane of microstrip patch-based antennas. Finally, because of the single-ended nature of the microstrip transmission line, a RFID tag single-ended implementation is considered.

Since tags are usually required to be small, a planar inverted-F antenna (PIFA) configuration [28] is assumed. In this case, one side of the metallic patch is short-circuited with the ground plane, and the final size is more or less one half of the standard microstrip patch length. This kind of antenna has two important advantages for the context in which we are working on: (i) it is opened on one side and it easily allows the integration with the sensor/switch and the tag chip, and (ii) it is not extremely sensitive to the external environment (in particular in the case of thin substrate).

A design model of the selected structure is shown in Fig. 8 (a). As said, it is a PIFA based tag antenna, with a metallized bottom layer connected to the top metal patch with a row of vias which realizes the necessary short circuit between top patch and ground plane as required by the PIFA design. On the metallized top layer, a rectangular slot is opened to hold the impedance matching circuit and the tag chip. The PIFA is fed by a 50 $\Omega$ microstrip line, a capacitive coupling mechanism realized with a rectangular inset, and a series inductor $L_1$ (the capacitive coupling and the series inductor make possible the impedance matching to the 50 $\Omega$ microstrip line). An U-shaped slot is opened on the metal patch surface to increase the surface current path length, reducing the antenna size (further size reduction can also be achieved). At the two ends of the U-slot, a sawtooth is included (where copper teeth protrude into the slot by both side) for frequency tuning, as it will be described in Sec. V-A. Finally, the tag has
been designed on a 200 × 200 mm² aluminum panel which represents the metallic application surface.

A simple LC matching network composed by a parallel capacitance $C$ and a series inductor $L_2$ [30] has been employed to match the complex impedance of the tag chip and the 50 Ω antenna impedance. In this work, we have considered the passive Murata UHF MAGICSTRAP LXMS21ACMF-183 [31] tag chip. Finally, a semi-circular isle has been inserted on the bottom of the tag to hold the screw for implementing switch-like mechanisms described in Fig. 3 (with metallic or isolated screws), and tag-sensor schemes with series and parallel switch, respectively. The position of the screw is chosen to let the screw touch the 50 Ω transmission line on the bottom of the PIFA (which connects the PIFA to the tag chip), which, for the series switch implementation, is interrupted in middle to let the screw contact part realize the electrical continuity (as shown in Fig. 3). When the isle is removed, the tag can be placed in the proximity of the screw head for implementing switch mechanisms described by Fig. 4.

Two tags have been designed on different substrate materials: a 0.813 mm thick tag ($W = 29.8$ mm, $L_1 = 33$ nH, $L_2 = 18$ nH, $C = 5$ pF) on Rogers RO4003C ($\varepsilon_r = 3.55$, $\tan\delta = 0.0027$), and a 0.25 mm thick tag ($W = 22$ mm, $L_1 = 39$ nH, $L_2 = 18$ nH, $C = 2.7$ pF) on F4BM350 ($\varepsilon_r = 3.5$, $\tan\delta = 0.001$). Smaller tag size may be preferable for some commercial applications, and this can be achieved for example by increasing the total length of the U-slot.

However, it is important to mention that a trade-off between the RFID tag size and its maximum read range exists, and this parameter is also important for the practical implementation of the whole system.

Simulated $\rho$ at the tag chip input port and simulated tag sensitivity $P_{\text{th,tag}}$ calculated as in (2) (under the hypothesis $P_{\text{back}} > P_{\text{th,reader}}$, and assuming an interrogation from broadside and with perfect polarization alignment) for the parallel switch (with metallic screw) and series switch (with an isolated metallic screw) implementations are shown in Fig. 8 (b) and (c), respectively. Both well-tightened and relaxed cases (for the relaxed case, the screw has been raised up of 0.1 mm – in Fig. 8 (a) the screw raising is exaggerated for clarity) have been considered, and simulation results have been calculated with the use of the commercial software Ansys HFSS. From Fig. 8 (b) and (c), it is possible to identify two distinct behaviors for the well-tightened and relaxed screw conditions in both cases of metallic and isolated screws: in fact, considering the tag designed on Rogers RO4003C for metallic screw (which realizes the parallel switch implementation and a short-circuit when it is tightened), when the screw is relaxed the simulated return loss is 16.3 dB at 920 MHz, and $P_{\text{th,tag}} = −7.6$ dBm, while when the screw is well-tightened the tag chip is short-circuited and the sensitivity is noticeably increased. For the tag designed on F4B350, sensitivity in the case of relaxed screw is increased to 6.5 dBm because of the smaller tag size (and then smaller gain); however, when the screw is well-tightened, the sensitivity is 37 dBm making the two screw situations well distinguishable. Similar results have been found for the isolated screw case (series switch implementation) as depicted on Fig. 8 (c).

Finally, it has been investigated how the presence of the metallic screw can affect the antenna performance, in particular its radiation pattern. For this reason, we have considered different screw sizes in accordance with the standard ANSI/ASME B1.13M-2005 [32], and we have simulated radiation patterns at 920 MHz (only the main plain $\varphi = 0$), as reported in Fig. 9. The screw has a minimum effect on the antenna pattern, and in particular it can increase the antenna gain acting as a metallic reflector. The screw effect on the reflection coefficient has also been investigated, finding only minor variations.

B. DESIGN OF THE RFID TAG ANTENNA FOR NON-METALLIC SURFACES

A simple dipole-based tag is designed for applications on non-metallic surfaces. Copper dipole arms printed on a 0.4 mm thick FR4 dielectric substrate are meandered for miniaturization purpose, and a T-matching mechanism [33] is employed to match the complex impedance of the passive tag chip. As for the metal tag, we have employed the Murata UHF MAGICSTRAP LXMS21ACMF-183 passive tag.

Since the application surface is not a metal, a plastic screw with a steel washer as in Fig. 5 is considered for this case. In particular, a M4 hole has been opened on the dielectric
substrate to hold the screw within the T-match loop. In this way, when the screw is well-tightened, the matching circuit is short-circuited, implementing the conceptual scheme in Fig. 7 (c). It should be noted that this mechanism can also be implemented with metallic screws. Nonetheless, it is not common to tight metallic screws on plastic or non-metallic surfaces, and for this reason we have not considered this case.

A dipole-based tag model is depicted in Fig. 10 (a), and simulated results are depicted in Fig. 10 (b). As it can be seen, when the screw is relaxed, the simulated return loss is about 19 dB around 920 MHz, and $P_{th,tag} = -18.7$ dBm. When the screw is well-tightened, instead, the steel washer short-circuit the T-match loop and the tag chip, causing an increase in sensitivity of more than 75%. Hence, also in this case two distinct behaviors are achieved for well-tightened and relaxed screw as required. Furthermore, the dipole-based tag exhibits a wider bandwidth and lower sensitivity than the two metal tags presented in Sec. IV-A, mainly because of a different antenna configuration; in fact, the dipole-based tag does not have to deal with the presence of a metallic surface which totally reflects incident electromagnetic waves with a phase reversal, leading to a strong radiation efficiency reduction [33].

Obviously, larger screws can also be employed for this scheme by enlarging the T-match loop to hold them, or simply by moving the screw outside the T-match loop to directly short-circuit the tag chip. We have also verified that the presence of larger screws do not affect significantly the antenna radiation pattern. Finally, there exists a huge literature on dipole-based tags, and for this reason many other screw relaxing detection tags can be developed based on the concept provided in this paper, e.g., the circular tag in [34] has a central hole which seems very suitable for the application proposed in this paper.

V. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, experimental results of screw relaxing detection based on the presented opportunistic use of the screw movement and the UHF RFID tag prototypes shown in Fig. 11 are presented. For Tag 1 (metal tag on Rogers RO4003C) and Tag 2 (metal tag on F4BM350), isles have been fabricated separately and are not shown in Fig. 11. Furthermore, the transmission line which connects the antenna and the tag chip impedance matching circuit has been interrupted at the center point for enabling the implementation of the series switch scheme; for the parallel switch method, on the other hand, the two interrupted transmission line ends have been soldered together.

A. FREQUENCY TUNING FOR METAL RFID TAG

Since both Tag 1 and 2 dimensions are small and they are realized on thin dielectric substrates, they cannot provide excellent bandwidth performance as discussed in Sec. IV. In this case, small dielectric material parameters variations, which can be usually encountered during the fabrication process, can lead to large working frequency shifts. For this reason, the length of the U-shaped slot of Tag 1 and Tag 2 has been used to tune the working frequency of these two tags. In particular, teeth of the sawtoothed U-shaped slot ends are opportune short-circuited for reducing the lateral length of the U-shaped slot $l_U$ (Fig. 12 (a)), with the consequent increase of the working frequency. Measured tag antenna $S_{11}$ (measured by connecting a 50 coaxial cable at the open end of the transmission line as in Sec. III-C) for the Tag 2 with different $l_U$ is shown in Fig. 12 (b).

B. MEASUREMENT SETUP AND SCREW RELAXING TEST

The measurement setup employed for testing the screw relaxing RFID tag-sensors presented in Sec. IV is shown in Fig. 13, and it is composed by an Impinj Speedway R420-based RFID reader [35] (with a maximum $P_{t,max} = 31$ dBm and $P_{th,reader} \approx -80$ dBm within the bandwidth 920.5-924.5 MHz), a programmable attenuator Mini-Circuits RCDAT-3000-63W2 [36] (with an insertion loss of about 3 dB at the frequencies of interest, and an attenuation range 0-63 dB) a CP reader antenna with $G_t \approx 9$ dBiC [37] (or another CP antenna with $G_t \approx 4$ dBiC [38] for testing the smallest tag) connected to the reader with a RF coaxial cable, and a laptop connected to the reader and the attenuator through LAN connection cables.

An automatic script similar to [39] has been written and it is executed on the laptop for controlling transmission frequency, RF switch attenuation, transmitted power, and, simultaneously, verifying the tag reply presence/absence. As explained in [39], these parameters have been regulated to verify the minimum $P_{EIRP}$ required to correctly establish a communication link (in our case, $P_{EIRP}$ is controlled by modifying the RF switch attenuation $L$), and measure $P_{th,tag}$ at a certain distance...
For emulating metallic surfaces, Tag 1 and Tag 2 have been positioned on an aluminum panel of 200 × 200 mm², while Tag 3 is placed on a foam panel. Four cases have been considered:

- Case 1: Tag 1 with isolated metallic screw for the implementation of the series switch scheme (the tag transmission line is left interrupted); in this case, when the screw is well-tightened the tag is ON, and when is relaxed the tag is OFF;
- Case 2: Tag 1 with metallic screw for the implementation of the parallel switch scheme (the tag transmission line is soldered and short-circuited); when the screw is well-tightened the tag is OFF, and when is relaxed the tag is ON;
- Case 3: Tag 2 with metallic screw and parallel switch implementation (as above, the transmission line is short-circuited); when the screw is well-tightened the tag is OFF, and when is relaxed the tag is ON;
- Case 4: Tag 3 with plastic screw; when the screw is well-tightened the tag is OFF, and when is relaxed the tag is ON.

Measurement results for well-tightened and relaxed situations for the four above described cases are depicted in Fig. 14. As it can be observed, measured and simulated sensitivities for all cases are in good agreement (except for Case 3 and Case 4 in Fig. 14 (b) – differences are due to non-ideal screw behavior as described in Section III-C), confirming the capability of this technology to well discriminate well-tightened and relaxed screw states. This is also proved by Fig. 14 (c) where the sensitivity difference between tag
ON and OFF cases $\Delta P_{th,\text{tag}}$ is depicted, showing a difference larger than 13 dBm for all measured cases.

The sensitivity of tag-sensors which implement the switch mechanism shown in Fig. 4 (a) and (b) has not been verified experimentally. Nevertheless, in Fig. 15 two possible implementations with silver drop and asymmetric washer are given as an example.

C. DETECTION AREA AND ESTIMATED DETECTION TIME

For the sake of completeness, two system detection parameters have been analyzed: the first is the maximum detection surface extension (MDS), while the second is the required detection time (RDT).

1) MAXIMUM DETECTION SURFACE SIZE

It is defined as the maximum surface perpendicular to the interrogation direction on which a tag-sensor receives a sufficient power to be activated and can correctly reply to the interrogator, satisfying (1). This parameter is important to understand how many interrogation sessions have to be done for covering a predetermined surface size. According to radiation pattern simulation results for Case 1, and system parameters similar to those described in our measurement setup, MDS has been estimated according to (1) for a circular surface (only one direction has been considered for simplicity), and results are depicted in Fig. 16 (a) (during the evaluation of MDS, we have assumed a reader antenna radiation pattern interpolated within the $3\,\text{dB}$ beamwidth $\Delta \theta$ - calculated from the empirical equation $G_r = 10 \log_{10} \left( \frac{32400}{\Delta \theta^2} \right)$ [29] and assuming equivalent horizontal and vertical beamwidth – and limited within this range; for the case of a $9\,\text{dBi}$ antenna, $\Delta \theta \approx \pm 64\,\text{deg}$). As it can be seen from Fig. 16 (a), an optimum MDS larger than $3\,\text{m}^2$ exists for an interrogation distance of $1.3\,\text{m}$.

2) REQUIRED DETECTION TIME

It is defined as the minimum required time for a tag-sensor within the MDS to be effectively detected. This parameter depends on the communication protocol latency and the specific anti-collision mechanism implementation [40], and the number of tag-sensors $N$ present within the MDS. For example, this can be evaluated from [40] as $\text{RDT} = T_0 \times N / 0.368$ (where $T_0$ is the minimum detection time when only one tag is present; with a communication speed of $640\,\text{kbps}$, and considering the protocol sequence query-RN16-acknowledgment, $T_0 = 1.4\,\text{ms}$) where a maximum a posteriori probability estimation method and optimum frame length (with an estimate error less than 4%) has been employed for determining the uplink throughput. It is herein reported in Fig. 16 (b) (the worst case, i.e., all tags can simultaneously communicate, is considered), showing that more than 100 tags can be detected within $0.5\,\text{s}$. Although this is a mere estimation of the RDT for a specific case, this is sufficient to confirm that RDTs for the proposed screw relaxing detection system are in general acceptable for practical applications.

D. DISCUSSION

The proposed RFID tag-sensor is herein designed to detect only well-tightened and relaxed screw conditions. Therefore, assuming a good polarization alignment between interrogator and tag-sensor antennas (this can be guaranteed by employing a circularly polarized antenna for the reader), screw tightness status can be verified by only monitoring the capability of the tag-sensor to reply or not to a reader interrogation, regardless of the reader distance (obviously, the reader has to be within the tag-sensor communication range).

The proposed RFID tag-sensor, however, cannot provide information about the tightness of screws. Obviously, this is the main disadvantage of the proposed RFID tag-sensor. A possible solution to this problem could be to consider the electrical conductivity variations of the switch mechanism caused by different level of screw tightness, which can affect the tag sensitivity. In this case, a tag-sensor calibration process should be performed to evaluate the tightness levels range which can be detected by the tag sensitivity variations.

Finally, other situations such as metal corrosion can happen on the screw or on the metallic application surface, impairing the screw tightening detection. As discussed in [41], the electrical conductivity is affected by the corrosion, and it will cause a tag sensitivity variation. Hence, information on tag sensitivity can be exploited for diagnostics purpose.

VI. CONCLUSION

In this paper, the problem of automatic screw relaxing detection by employing RFID technology is considered. Metallic screw body or, in the case of plastic screws, a metallic contact fixed on the screw are opportunistically exploited to realize a mechanical switch (closed for a well-tightened screw and open for a relaxes screw) which is integrated in the tag-sensor design, and enables the identification of screw relaxing situations by verifying tag interrogation reply ability. The problem has been treated from the tag-sensor design viewpoint by proposing different implementation schemes, and from the screw switch realization mechanism viewpoint by describing several ways to implement the switch-like behavior. Three different tags have been designed and manufactured for experimentally demonstrated the proposed concept, and finding that this technology is reliable in discriminating well-tightened and relaxed screw states.

Although the presented treatment comprises electrical and mechanical contents, this work has been focused more on the RFID communication system and tag-sensor implementation aspects to provide a demonstration of the proposed concept. Many mechanical aspects such as the realization of contacts to deal with the screw roughness have not been considered in detail, but require to be examined in deep for developing a complete and fully reliable technological solution for the screw relaxing detection.

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