Experimental Performance Evaluation of Passive UHF RFID Tags in Electromagnetically Critical Supply Chains

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***Abstract*— Radio Frequency Identification is going to play a very important role as auto-identification solution for many application scenarios, where item-level tagging and high performance are crucial. In such a context, the use of passive Ultra High Frequency (UHF) tags is strongly suggested but, unfortunately, general-purpose commercial tags could not meet all the requirements in presence of critical operating conditions, including the presence of metals and liquids, the misalignment between tag and reader antennas, and the need of multiple reading of tags. In this paper, the main features that a UHF tag should own to work properly in the whole supply chain are presented. A tag, named below *Enhanced tag*, satisfying all the individuated requirements has been also realized and validated in a controlled test environment simulating the pharmaceutical supply chain. Tests have been focused on the above-mentioned critical conditions. The performance of the Enhanced tag, in terms of successful read rate, has been compared with that of some commercial Far Field and Near Field UHF tags. The experimental results are impressive and clearly demonstrate that ad hoc Far Field UHF tags are able to effectively solve many of the performance degradation problems affecting general-purpose tags. Finally, the proposed tag has been also tested in extreme conditions, applying it directly on Tetra Pak packages containing liquid, with interesting results in terms of platform-tolerant features.**

***Index Terms*— Performance evaluation, RFID tags, Supply chain management, UHF antennas.**

I. Introduction

THE use of Radio Frequency Identification (RFID) technology [1] as auto-identification solution has been more and more increasing in many different application scenarios, such as manufacturing, logistics, supply chain, localization, anti-counterfeiting, etc. Among these, the tracing and tracking at item level on whole supply chains is one of the most challenging. In many contexts, in fact, a large amount of sensitive goods, differing each other in terms of consistency, size and constitutive material, must be accurately traced from the manufacturer to the retailer. The pharmaceutical supply chain, considered as use case in this work, is one of the most interesting scenarios [2]. The growing counterfeiting problem, for instance, is leading several international institutions (e.g. Food and Drug Administration, European Medicines Agency, European Federation of Pharmaceutical Industries and Associations) to encourage the use of innovative solutions in healthcare and in the pharmaceutical supply chain, to improve patient safety and enhance the efficiency of the pharmaceutical supply chain, by means of a better worldwide drug traceability [3].

The choice between the two main RFID solutions, HF or UHF, can be aided by several recent works (see for example [4]), which highlight how passive UHF RFID systems provide better performance than passive HF systems. UHF is nowadays the most promising technology for item level tracing systems on the whole supply chain. The success of UHF can be mainly attributed to the asserting of EPCglobal [5] international standard. Furthermore, UHF has several advantages over HF and LF technologies: the capability to enable multiple simultaneous reading of tags, the capacity to offer very high read rates, and the longer working distances between reader and tag (i.e. transponder).

Unfortunately, performances of UHF systems depend on several parameters [6], each strongly related to environment, design and setup choices. For example, it is well known that a supply chain is composed of several steps that have different characteristics in terms of traceability procedures (e.g., distance between reader antenna and tag antenna, speed of object moving, quantity of tags to read, etc.). In such scenarios, the choice of a RFID tag solution, able to guarantee high performance in each step of the supply chain and in any operating condition, is certainly a hard challenge.

Some approaches proposed in literature, are based on the use of general-purpose Far Field (FF) UHF tags [7, 8] applied on the secondary package of the product. Several studies, in fact, have shown that the use of FF UHF tags guarantees better performance than Near Field (NF) ones in every step of the supply chain. Indeed, as most of FF UHF tags are provided with an inner loop that short-circuits the tag chip technology (hybrid tags), they exhibit good performance even in near field conditions. In fact, this strategy allows an efficient coupling with the magnetic field generated by NF reader antennas [8].

Unfortunately, commercial FF UHF tags still suffer of many drawbacks [9]. First of all, they suffer of performance degradation in presence of electromagnetically hostile materials, such as metals and liquids [8, 10]. Another issue

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regards the strong dependence of the system performance on the mutual position between reader antenna and tag antenna, which is supposed to vary item by item in a random way. Consequently, from the electromagnetic (EM) point of view, very strict requirements must be satisfied by the tag antenna.

In this paper, the main requirements that should be satisfied in the design of RFID tags well suited to operate in critical conditions are presented. The implementation of the previous guidelines has led to design an enhanced FF UHF tag. Then, a prototype of this, named Enhanced tag, has been realized and validated in critical conditions of the pharmaceutical supply chain, considering the presence of liquids, metals and misalignment. This new passive UHF RFID tag has been compared with others commercial UHF tags of the same category through several experimental campaigns carried out in a particular test environment realized. The successful read rate has been chosen as end-user metric to evaluate tag performance. Furthermore, the proposed Enhanced tag has been also tested in extreme conditions, applying it directly on Tetra Pak packages containing liquid (milk). In this case, a performance comparison between the Enhanced tag and one of higher performing commercial FF UHF tag has been evaluated.

The rest of the paper is organized as follows. Section II reports a short overview on the RFID technology. Related works are summarized in Section III. A description of the main features of the pharmaceutical supply chain, reference scenario in this work, is reported in Section IV. Section V summarizes the main guidelines that must be followed for the design of an RFID tag able to guarantee high performance even in the critical conditions of the pharmaceutical supply chain. Section VI describes some features of the Enhanced tag as well as its characterization in terms of Received Signal Strength Indication (RSSI). The used test environment is described in Section VII. Finally in Section VIII experimental results are reported and discussed, while conclusions are drawn in Section IX.

II. Overview on The RFID Technology

The strong appeal won by RFID technology in recent years, has led to the diffusion of a very exhaustive literature on that subject. Therefore, for a complete and comprehensive overview, the interested reader is addressed to [11]. Hence, this Section gives only some hints about general RFID technology and, on the contrary, it focuses better on a particular class of RFID, the one based on passive tags and on devices (both tags and readers) working in the UHF band. More specifically, the working principle of both NF and FF UHF tags will be emphasized, as these two tag types are the most used in item-level traceability.

As well known, the working principle of RFID technology is as simple as effective and it is based on two devices, reader and tag. The reader, provided with proper antennas, combines in a single physical apparatus both transmission capabilities (to the tags) and reception capabilities (from the tags). Vice versa, the tag basically consists of a microchip storing the ID code and the antenna, other than a powering circuitry in non-passive cases. When the tag is in the region covered by the reader, after a handshake phase, it replies back with its unique ID code.

Notwithstanding the many classifications of the RFID technology, for example in terms of frequency band and energizing method, when item-level traceability is implemented the necessity of very low cost solutions (the reusability cannot be guaranteed) is paramount. As for the frequency band, UHF should be preferred to HF and LF. Consequently, the choice is driven towards passive UHF tags.

Passive tags are tags that do not need any battery and that are energized by the signal power provided by the reader. The input circuitry of an RFID chip for passive tags is an analog rectifier that converts in DC the radiofrequency signal coming from the reader. The elementary stage of the rectifier is a diode-capacitor circuit. Usually, a cascade of such elementary stages is necessary to get the required voltage, high enough to power on the rest of the circuitry (for decoding and modulation procedures).

The presence of the capacitors is relevant also for other aspects: each passive RFID chip exhibits a significant capacitive component, usually much stronger than the resistive part. This must be taken into account when the tag antenna is designed. In fact, if on the one hand the capability of rectifying the RF signal plays a crucial role, on the other hand the tag antenna should harvest and convey to the chip as much as possible of the reader energy. Consequently, a good passive RFID tag is given by a chip well matched with its proper antenna, which, consequently, must exhibit a relatively strong inductive part of its input impedance (conjugate matching). The tag antenna, in this case, is designed in order to favorite coupling with the radiative field emitted by the reader (FF tags), making it possible to realize passive tags with relatively long working range (up to 10 m). There is a vast literature on the design of FF UHF tag antennas. Most of them are label-type, i.e. realized by deposing metal over a thin flexible PEC substrate. This guarantees good performance at low cost when operating in canonical conditions. The most typical antenna shapes derives from the half-wavelength folded dipole, usually with a loop around the chip that helps on obtaining the conjugate matching, other than the NF coupling (hybrid NF-FF tags). The need of reducing size and obtaining large bands in the whole RFID UHF band (860-960 MHz) justifies the use of consolidate techniques, such as, for instance, meander-line antennas, capacitive tip-loading, pseudo-conical shapes and many others. Nevertheless, label-type antennas do not work properly when attached to objects containing metals or liquids, so that other techniques, mostly based on more expensive microstrip antennas, can be used [12].

In addition to FF tags, also NF tags are on the market. They are based on inductive rather then radiative coupling and usually are energized by specific NF reader antennas, appositely designed to minimize the radiated field. The tag antenna is usually a simple loop, whose diameter is calculated in order to guarantee the resonance at the desired frequency —a few centimeters in the UHF band—, but also more complicated shapes do exist. The short range of NF reader antennas along with the incapability to irradiate of small loop antennas cause the limitation to a few tens of centimeters of the reading range of NF tags. Nevertheless, the smaller size of NF tags and the higher tolerance to the scenario —inductive field penetrates through liquids and dielectrics— makes them useful in some application where the size is crucial and marked items are electromagnetically complex.

III. Related Works

It is important for the scientific community to understand the capabilities and limitations of the emerging passive UHF technology, and just as importantly, understand where researchers may contribute to face problems and challenges that currently are limiting a large-scale deployment of this technology. Main barriers are: (i) hardware technology current weaknesses [8] (e.g. data reliability, read rate in critical conditions, lack of unified standard for interoperability), (ii) software weakness [2] (e.g. scalability, single-point of failure, integration with information systems), (iii) relatively high costs related to tags, software customization and systems integration, (iv) security issues [13, 14], (v) lack of scientific literature on the evaluation of potential effects of RFID exposure on molecular structure and potency of drugs [15, 16].

There is a rich literature about developing and evaluating UHF RFID solutions.

[17], for instance, evaluates performances of several commercial passive UHF tags in presence of critical operating conditions, such as presence of liquids and metals, by using an experimental approach. In order to simplify the measurements and results, an end-user metric has been chosen. In particular, the performance of a tag is measured in terms of maximum reading distance in a given environment. The tests have demonstrated that no commercial FF UHF tag is readable when applied directly to metal. Further results have shown that the water degrades the tag performance significantly. The tests have also demonstrated that larger tags yield better performance. In this work, a series of experiments has been carried out by using some NF UHF tags. The results have clearly demonstrated that NF UHF tags do not solve the metal-water problem. On the contrary, it has been shown that the presence of metal or water has much more drawbacks in NF rather than FF UHF tags.

[18] investigates experimentally the relationships between the EM field levels at the tag antenna and the overall performance of a UHF RFID system. The results have underlined the importance of preliminary measurements in the setup of the system, in the evaluation of the maximum distances between tags and reader antenna, and in the estimation of a correction factor to be used in theoretical analyses.

[19] describes a benchmark suite useful to give good indications as to how well UHF solutions will work in real world scenarios. These benchmarks are able to compare the read performance of different tags in terms of distance, quality, and real rates in various situations.

[20] is another work that aims to investigate main benefits and performance of NF UHF tags in item level tagging systems. This study exploits an electromagnetic analysis based on both theoretical evaluations and measurements carried out on real UHF RFID devices. Four different commercial tags (i.e. Alien Squiggle, Texas Instruments, Impinj Button, and Impinj Satellite) have been tested mainly in terms of the system Path Gain, defined as the ratio between the power absorbed by the tag and the available power at the reader. The results have demonstrated no particular electromagnetic benefits in performance in favour to NF UHF tags.

[21] is a very interesting work focused on the need to improve the performance when an UHF tag is applied on a metallic object.

[6] highlights the importance to evaluate the performance of UHF RFID systems in real-world conditions by using suitable testbed to perform the experiments. In particular, the system efficiency is considered. This work asserts that there are many parameters that should be known and tuned to maximize the efficiency even in critical conditions. Some measurements have demonstrated that the deployment of multiple antennas might be totally useless. On the contrary, better results can be obtained using reflecting surfaces, or deploying reading-paths, avoiding reading-gates.

[10] is focused on the use of passive UHF tags, in order to analyze a performance comparison between near field and far field UHF RFID systems in every steps of the pharmaceutical supply chain. Some different commercial passive UHF tags (i.e. Impinj Thin Propeller, Impinj Paper Clip, and RSI Cube2) have been tested in an item-level system, simulating each step of the pharmaceutical supply chain in a controlled test environment. Results allow to analyze the advantages and disadvantages of using NF and FF UHF tags for item-level tracing in each step of the pharmaceutical supply chain. Experimental results show that the use of passive FF UHF tags represent a well suitable solution to guarantee both high performance and item level tagging in the whole supply chain. This work highlights also that the pharmaceutical supply chain is characterized by very critical operating conditions where tag improvements are strongly needed in order to guarantee acceptable performance.

IV. Pharmaceutical Supply Chain

In the reference scenario, shown in Fig. 1, the item-level traceability of drugs starts just after the packages are filled during the manufacturing process. In this step, each tagged product is individually scanned on the conveyor belt and then cased to be sent to the wholesalers. The wholesalers separate the products according to their identifiers and place them onto the shelves. Wholesalers receive orders from retailers. These orders often consist of small quantities of different products; they may contain a large number of items. The products in the orders of the retailers are picked and put into some large envelope bags that are scanned and confirmed before their

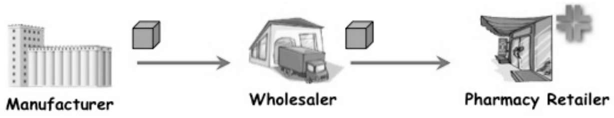


Figure 1. Pharmaceutical Supply Chain.

distribution. Upon receipt, the pharmacy retailer scans the contents of each bag without opening it.

In order to select the most adequate RFID hardware solution, though, several aspects must be compulsory taken into account, including the working frequency, the near or far field empowering methods, but also the differences among the various RFID-based checkpoints of a generic supply chain.

In fact, depending on the considered step of the supply chain, at least three different RFID checkpoints are commonly used. They differ one another in terms of interrogation distance, number of items to be read, reader antenna typology and scanning speed. It is worth pointing out that the tag marking an item must work properly in all checkpoints.

More specifically, one of the possible checkpoints is given by the so-called items line, where the tagged product must be singularly scanned by using NF reader antennas. Whatever tag is used for the item-level traceability, it should guarantee good performance even in near field conditions.

A second kind of checkpoint is given by the so-called cases line, where a case containing a number of homogeneous items packed together, passes through a NF tunnel in order to read all the items in one shot. Consequently, the RFID tags used to assure reliable item-level tracing systems should work correctly even at medium distance from the interrogator antennas. Moreover, the problem of the multiple readings of tags and of the tag overlapping should be considered.

A third kind of checkpoint is given by the so-called border gate. When a pharmacy retailer is restocked it becomes necessary to simultaneously read all the different tagged items contained in a box or in a plastic bag. The border gate, equipped with FF reader antennas, is designed for such a purpose.

Besides the RFID checkpoints peculiarities, another important aspect is the effect on the tag performance of the platform where the tag is attached. UHF tags, more than HF ones, are influenced by the presence of electromagnetically hostile materials, such as liquids and metals; this aspect is crucial because in several scenarios, as the considered pharmaceutical one, metals and liquids are massively present.

V. REQUIREMENTS AND GUIDELINES IN TAGS DESIGN

This section focuses on the properties that a tag should own in order to guarantee high performance in every supply chain steps, even when used to trace items containing electromagnetically critical materials, such as liquids and metals [8].

One of the sources of performance degradation in the items line is given by the potential misalignment between the NF reader antenna and the tag attached to the secondary package of an item. In fact, by means of a conveyor belt, the tagged item passes through two NF RFID antennas.

Nevertheless, it is possible that the item surface on which the tag lies and the plane on which the reader antennas lie are mutually orthogonal. Now, as depicted in Fig. 2, despite the almost omnidirectional tag radiation pattern in free space condition, the presence of metal or liquid inside the item strongly modifies the radiating properties, even inhibiting, in some cases, the communication with the reader.

It can be deduced, hence, that a well performing tag should guarantee at least two main lobes on the radiation pattern in every working condition, above all when it is used to trace items containing hostile materials. For instance, by considering the presence of metal or liquid close to the tag while designing the antenna, parameters such as copper thickness, shape, chip location, antenna technology and so on, should be adjusted and optimized so to obtain a dual lobe radiation pattern. Many techniques should be used. Those based on patch antennas are the most suitable, as the copper background itself reduces coupling with the item. Nevertheless, label-type tags must be preferred, so to minimize the cost.

Another reason of reading-failure in the items line is due to the use of a FF tag antenna with a NF reader antenna. Although NF reader antennas are used in the items line, NF UHF tags cannot be used because they would not work properly in the subsequent supply chain steps, where FF reader antennas are adopted. Therefore, a well performing tag should exhibit good performance both in the NF and the FF.

The most common way to reach such a goal consists of designing a FF antenna, for instance a meandered dipole or a folded dipole, with a small loop around the RFID chip. The loop impacts upon the antenna impedance, so that the antenna should be parameterized and dimensions optimized. In this way, the dipole guarantees a good behavior in FF condition, as desired. The loop, instead, favorites the coupling with the magnetic field around the reader antenna, thus allowing, de facto, the tag working even in NF conditions.

On the items line step, the packages are read one by one and no multiple-reading related problems arise; on the contrary, they will occur in the cases line and in the border gate. In such cases, shielding effects due to the presence of plenty of items

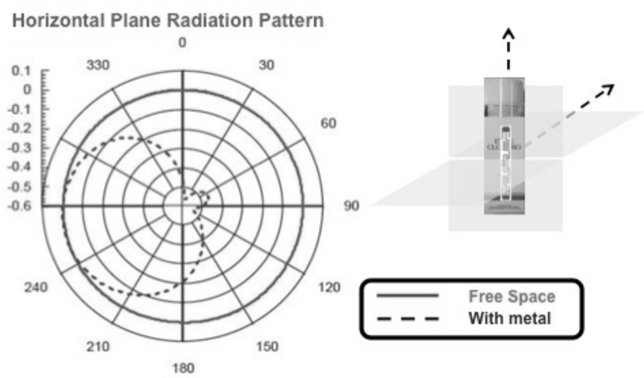


Figure 2. Horizontal radiation pattern in free space condition (solid line) and in presence of metal (dotted line) of the Alien Squiggle Tag.

as well as the potential overlapping of tags, could lead to a strong performance collapse. Furthermore, also in these cases, problems due to a potential misalignment of tag and reader antennas can arise. Consequently, a well performing tag should take into account such issues. Therefore, the tag should be designed in order to avoid the complete tag overlapping and, moreover, it should guarantee (also in this case) multiple radiation pattern lobes.

In the next section, a preliminary experimental characterization, in terms of RSSI, of the designed Enhanced tag, satisfying all of the individuated requirements, will be given.

VI. AN ENHANCED PASSIVE RFID UHF TAG

The designed and realized Enhanced tag (patent pending number TO2010A000493) is substantially based on a dual-lobe (collapsing in a particularly oriented one-lobe) conformal label-type antenna, adaptable to the different shapes of the various item packages and easy to be integrated in them. The shape of the antenna has been modeled in order to make the complete tag overlapping highly improbable. Moreover, the common design solution, based on the use of an inner loop around the microchip, has been adopted in order to guarantee good performance also in NF condition. The antenna has been realized in copper tape. Cost and size are comparable with canonical general-purpose UHF tags. Unfortunately, because of the patent-pending status, no details can be given on the shape and on the electromagnetic solutions adopted in order to reach the prefixed goal. Nevertheless, this is not even fundamental because the primary purpose of this work is, on the contrary, to demonstrate that an ad-hoc design of tags is able to effectively solve many of the performance degradation problems affecting general-purpose UHF tags.

In Fig. 3 is reported the comparison, in terms simulated horizontal plane radiation pattern, between the Enhanced tag (Fig 3a) and the commercial Thin Propeller tag (Fig. 3b), when the tags are attached to a cardboard-made secondary package containing a metallic cylinder.

It can be observed that the radiative behavior of the two devices is radically different.

In the Thin Propeller tag case, the radiation pattern is not omnidirectional anymore and the link with the reader is possible only if the reader antenna is faced with the tag itself.

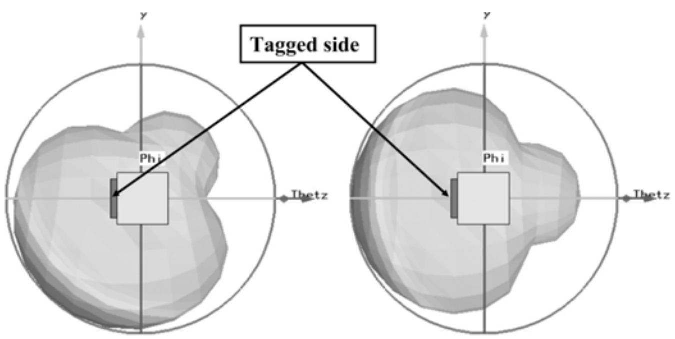


Figure 3. Simulated horizontal radiation pattern of the a) Enhanced tag, and b) Thin Propeller tag, when they are applied on a cardboard package containing a metal block.

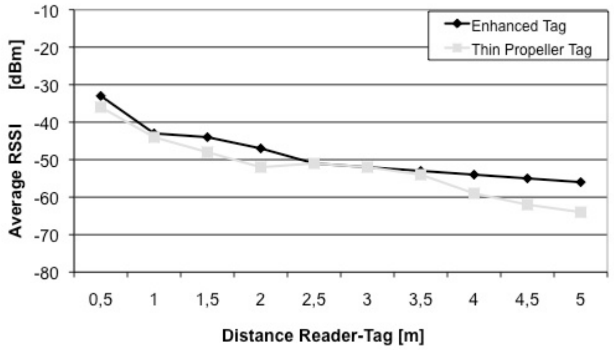
On the contrary, in the Enhanced tag case, an almost 45° oriented radiation pattern is found, resulting from the combination of two mutually orthogonal lobes. This way, also reader antennas orthogonal to the tag-plane can communicate with the tag.

In order to validate the working principle of our Enhanced tag and to test its potentiality, we have evaluated its performance by varying the boundary conditions. More specifically, the tests consist in the measurement of the RSSI, in three different situations: tag without any marked item (i.e. in free space condition), tag attached to a secondary package of an item containing metals (i.e. metallic bomb-spray), and tag attached to a secondary package of an item containing liquids (i.e. a small bottles containing syrup). The tests have been carried out in a semi-anechoic chamber and have been repeated by varying the orientation of the reader antenna with respect to the tags. It is worth mentioning that the measurements of the RSSI values, performed by using the Alien's ALR-8800 RFID reader connected to two Alien's UHF far field reader antennas (ALR-8610-AC), are accurate estimates characterized by a 95% confidence level with maximum relative error equal to 5% and have been obtained in static conditions (tag and reader in the same fixed position for the entire measurement time). In such a validation test, a performance comparison between the Enhanced tag and the Thin Propeller tag has been carried out, obtaining a first rigorous tag characterization, even if under elementary conditions.

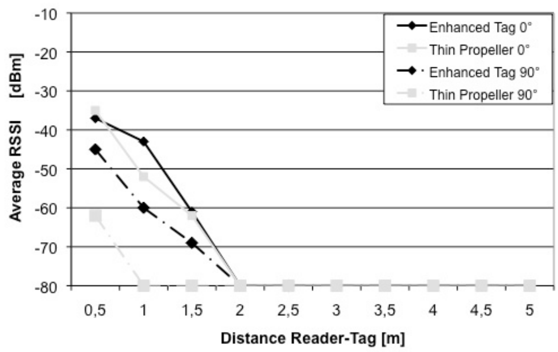
In Fig. 4, a performance comparison between Enhanced tag and Thin Propeller tag, in terms of RSSI measurements expressed in dBm, by varying the distance between reader antenna and tag antenna in FF condition (distance greater than 0.5 m) is reported. In particular, the measurements shown in Fig. 4.a, Fig.4.b, and Fig.4.c consider respectively the three described test conditions: free space, presence of liquids, and presence of metal. Furthermore, after verified that the maximum gain direction of a tag attached to an item is orthogonal to the face of the item the tag is attached to, the RSSI has been measured in two different situations: maximum gain with tag and reader antennas aligned (indicated with 0° in the figure caption) in one case, and the orthogonal case (indicated with 90° in the figure caption) in the other one. In Fig. 4.a, for instance, just two curves are shown, as there are not substantial differences for the two alignment conditions. Such curves clearly show that in free space condition both tags are characterized by a high reading range between reader antenna and tag antenna and that performance are comparable. As observed, when the tag is not attached to any item, RSSI values are quite remarkable in the whole investigated range. Despite the Enhanced tag has not been specifically designed to work in free space, its structure guarantees evident advantages also in this case. Nonetheless, as well known, in practical cases, tags are attached to objects that could modify the radiation properties of the tag antenna. Indeed, results, reported in Fig. 4.b and Fig. 4.c, demonstrate that the two lobes of the radiation pattern (collapsing in two almost overlapped omni-directional patterns in free space condition)

give the Enhanced tag interesting redundancy properties, thus resulting in higher RSSI values at almost every investigated distance.
More specifically, the effect of liquids (Fig. 4.b) and metals (Fig. 4.c) on the Enhanced tag performance is evident, even though, the communication between tag and reader is guaranteed. It can be also be observed a performance degradation in presence of a misalignment of 90°. Moreover, when comparing the data in presence of metals (Fig. 4.c), it is apparent that the Enhanced tag is undoubtedly more efficient than commercial tags, thus confirming that ad-hoc antenna solutions can play a relevant role in electromagnetically critical operating conditions.

Vice versa, Fig. 5 shows the same performance comparison between Enhanced tag and Thin Propeller tag but in NF conditions. More specifically, the RSSI values have been measured by varying the distance between two NF reader antennas and by positioning a tagged secondary package respectively empty (Fig. 5.a), containing liquids (Fig. 5.b), and metals (Fig. 5.c). For such a purpose, two Impinj Mini Guardrail NF antennas have been used. In the free space configuration, where there are not electromagnetically hostile



(4.a)



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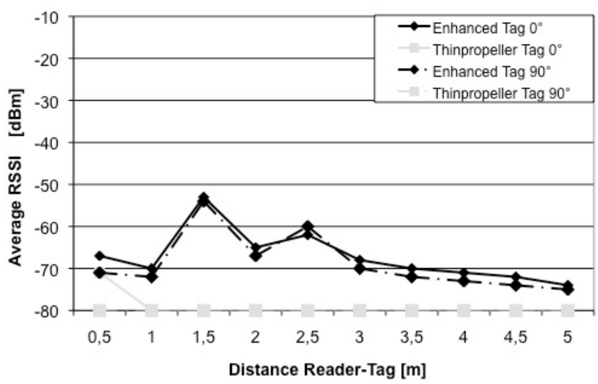
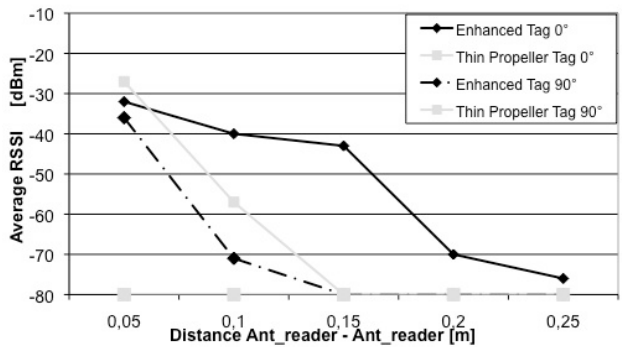
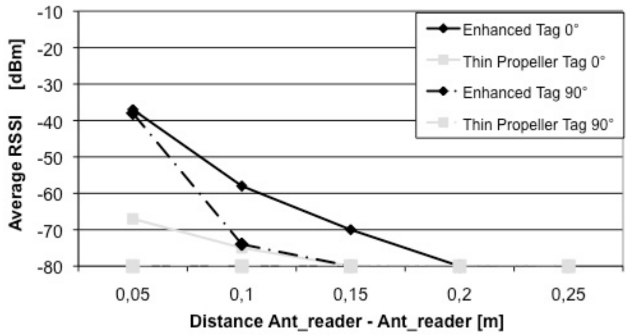


(4.c)

Figure 4. A performance comparison between Enhanced tag and Thin Propeller tag in terms of RSSI measured in dBm in Far Field condition by varying both the distance (reader-tag) and the orientation, in three different conditions: 4.a) free space, 4.b) presence of liquids, and 4.c) presence of metals.



(5.a)



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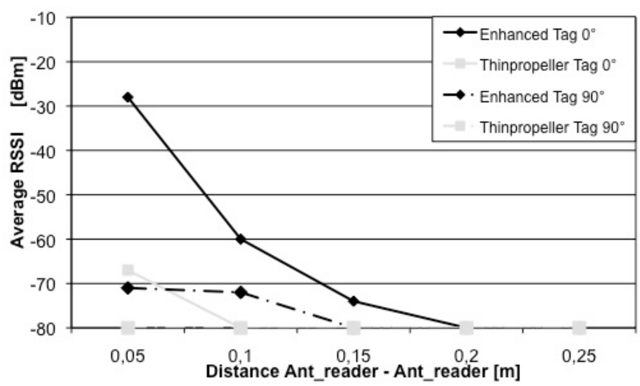

(5.c)

Figure 5. A performance comparison between Enhanced tag and Thin Propeller tag in terms of RSSI measured in dBm in Near Field condition by varying both the distance (antenna_reader-antenna_reader) and the orientation in three different conditions: 5.a) free space, 5.b) presence of liquids, and 5.c) presence of metals.

materials, the performance of the Enhanced tag is relevant in both the orientations. Even more interesting are the results obtained by testing the Enhanced tag in presence of packages containing liquids and metals respectively. Results are impressive: when the Enhanced tag is aligned with the reader antennas, it works properly for each investigated distance in the range from 0.05 m to 0.15 m. Moreover, when it is completely misaligned, it still guarantees readability up to 0.10 m, which is definitely an adequate working distance in an items line context. On the contrary, the Thin Propeller tag shows very poor performance in such a working condition. In particular, in presence of metals the Thin Propeller cannot work even in very short range (i.e. 0,05 m).

The impressive performance of the Enhanced tag, shown by previous comparisons, demonstrate that the use of the proposed tag guarantees very efficient item-level tracing also in critical operating conditions.

VII. Test environment

Test environment, shown in Fig. 6, has been realized in order to simulate the main steps of the pharmaceutical supply chain. The laboratory is equipped with one items line, one cases line, and one border gate. The transition of items on the items line and cases line is particularly interesting since the operating conditions are considerably stressed by high scanning speeds, possible misalignment and multiple reading of tags.

The items line consists of a conveyor belt whose speed can be varied in the range from 0 to 0.66 m/s, in order to guarantee real requirements of pharmaceutical manufacturing processes. For such a purpose, the following devices have been used: two Impinj Mini Guardrail reader antennas and one Impinj Speedway UHF reader. Similarly, the cases line consists of a conveyor belt, equipped with a line speed regulator in the range from 0 to 0.66 m/s, one UHF reader (Impinj Speedway), and a tunnel with four near field UHF antennas (Impinj Brickyard). In this case, each reader antenna is in the centre of each tunnel side. The width of the tunnel is equal to 0.6 m. The reader antennas are suitable for the frequency range 865-868 MHz. Further characteristics are: 50 Ω impedance, 6 dBi as maximum far field gain and -15 dB as Return Loss. Finally, the border gate uses a single UHF RFID reader (Impinj Speedway) and four far field UHF reader antennas.

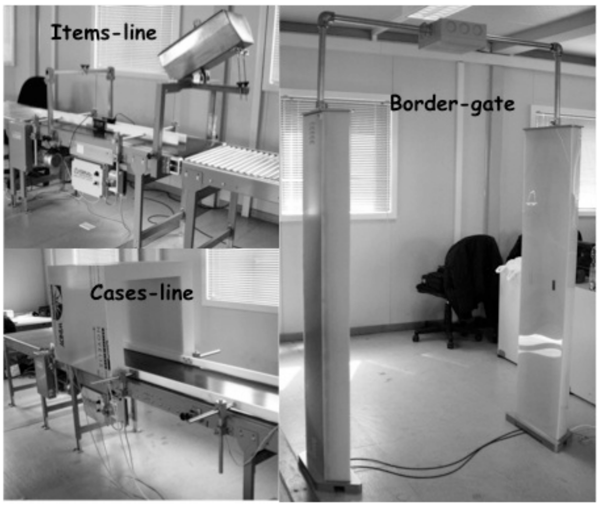

Figure 6. Test environment composed of an items line (top left), a cases line (bottom left), and a border-gate (right).

An effective evaluation of RFID reliability in a pharmaceutical supply chain cannot neglect the effects on the performance caused by hostile factors such as: the potential misalignment between tag antenna plane and reader antenna plane, the multiple reading of tags, the distance between tag antenna and reader antenna.

The misalignment problem is mostly relevant in the items line. To test such a misalignment impact, three different operating conditions should be tested. They are characterized by a mutual orientation between the plane where the tag antenna lies and the plane where the reader antennas lie: 0°, +90°, and -90° are considered. In particular, this last represents the worst case and allows the performance evaluation under unfavorable conditions. Vice versa, the 0° case is the ideal condition. Finally, the -90° case is characterized by the contact between tag and conveyor belt. Instead, in the +90 ° case the tag is attached to the up-side of the item, so that the potential interference with the conveyor belt is avoided but the distance with the reader antennas depends on the size of the item.

Another problem to be analyzed deals with the collisions among tags, impacting both the cases line and the border gate. For the cases line homogeneous cases (consisting of a single product type) have been tested. Moreover, also the configuration of the cases plays an important role. In order to simulate realistic conditions, three different configurations have been adopted for each case:

- Configuration I: the case was prepared placing the items with their tag antenna oriented toward the reader antennas and avoiding the overlapping of tag antennas.
- Configuration II: the case was prepared placing the items with their tag antenna oriented toward the center of tunnel (i.e. opposite to the reader antennas) and trying to obtain the overlapping of tag antennas.
- Configuration III: the case was prepared considering four different random dispositions of items. These dispositions were alternated in progress during the test bed.

In order to better clarify the compositions of cases, in Fig. 7 the configurations I and II are schematically reported. The overlapping of two different tags is represented by a double “x”.

In order to evaluate the current limits in item-level tracing systems of the most performing commercial UHF RFID tags, a preliminary technological scouting has been carried out. Note that for item-level tagging applications, the choice of the tags is affected by different requirements as: small size of the tag itself, compatibility with EPCglobal standard, high scanning speed, low cost, and high stress of tag label during product life cycle. As already stated, particular attention is focused on passive UHF tags that can be split into two sub-sets: NF and FF tags. In this work, eight different types of

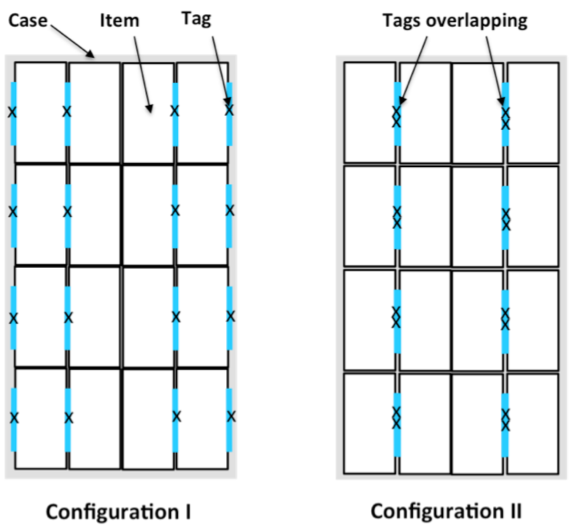

Figure 7. Some examples of case compositions.

passive UHF tags, six FF and two NF, have been tested. All the preselected tags are characterized by the same memory (96 bit), operating frequency (860-960 MHz) and compliance with the standard EPC Class1Gen2. On the contrary, the main differences are on antenna geometry and on the size of tag. The layout antenna of the eight preselected RFID tags is reported in Fig. 8.

More in detail, the following tag types have been considered:

- RSI Cube 2: it is a small near-field tag, whose size is 25.4 x 25.4 mm, with a NXP Ucode G2XL chip, designed for pharmaceutical and applications where small form factor is required;
- Impinj Paper Clip: it is a small near-field tag with Impinj Monza3 chip, whose size is 19.0 x 12.7 mm, designed for pharmaceutical and applications where small form factor is required;
- Impinj Thin Propeller: it is a far field tag with Impinj Monza3 chip and with an antenna, whose size is 8.0 x 95.0 mm, that is a high-performance dipole configuration. It guarantees large working bandwidth and is designed for warehouse, logistics, case, carton, and garment applications.
- Impinj Jumping Jack: it is equipped with Impinj Monza3 chip, a high-performance FF antenna and a NF antenna. Its size is 44.5 x 88.9 mm and it is designed for long-range, multi-orientation warehouse, logistics, carton, baggage, and garment applications.
- UPM Dog Bone: it is a high performance tag for a wide range of RFID Supply Chain Management RFID Apparel and RFID Transportation applications. It is equipped with a Impinj's Monza3 chip. Its size is 27 x 97 mm.
- UPM Web: it is a high performance tag for RFID item-level use, whose size is 34 x 54 mm. Reliable reads/writes when tags are in close proximity to each other. It is equipped with a NXP U-Code G2XL chip.
- UPM Short Dipole: it is equipped with a NXP U-Code G2XL/G2XM chip. It is designed for a wide range of RFID Supply Chain Management. Its size is 15 x 97 mm.
- Alien Squiggle: it is equipped with a Alien Higgs-3 chip. It is designed for a wide range of RFID Supply Chain Management. Its size is 12.3 x 98.2 mm.

VIII. RESULTS

A. Performance comparison with NF and FF UHF commercial Tags

In order to analyze strengths and weaknesses of commercial FF UHF tags and to evaluate the effectiveness of the designed Enhanced tag in the pharmaceutical supply chain, several experimental campaigns have been performed. In particular, a performance comparison of the Enhanced tag with the eight different commercial UHF tags, above described, has been carried out in terms of successful read rate.

Experimental campaigns have been mainly focused on particular operating conditions of two steps of the pharmaceutical supply chain: the items line and the cases line. As previously reported, these steps are particularly adequate to carry out an effective validation of novel RFID tags.

In all tests, the speed of the conveyor belt has been set to 0.66 m/s and 0.33 m/s respectively for the items line and cases line. The transmission power of the reader RFID has been set to 1W. Furthermore, the RFID tag is applied on the secondary package (made of cardboard) of the medicine product. Two different types of products have been used: ophthalmic solution in aluminum sachets and metallic bomb-spray.

The first part of the experimental campaign has been carried out on the items line. In this test, the misalignment problem has been stressed. In particular, the three different operating conditions (i.e. 0°, +90°, and -90°), previously described, have been considered.

The second part of the experimental campaign has been focused on the cases line. In such a test, each case was composed by homogeneous items. In particular, the bomb-spray case was prepared with 14 items on one layer, whereas the ophthalmic solution case was prepared with 36 items on three layers.

All the results, reported in this paper, are characterized by a confidence level equal to 95% with maximum relative error of 5%. Such estimations have been calculated applying the very well-known independent replication method [22]. This means that for each configuration (i.e., line, speed, alignment, type of drug, etc.), the successful read rate has been computed

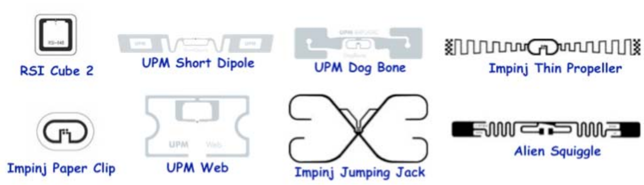

Figure 8. Layout of the eight preselected commercial passive UHF RFID tags.

considering a number of replications large enough to guarantee the desired statistical constraints. For instance, the estimated value of the successful read rate for the cases-line test, has been obtained by averaging data collected during more than 200 case scans (carried out automatically through our test bed environment).

Fig. 9 presents the performance comparison when a single item of ophthalmic solution, enclosed in aluminum sachets, (i.e. liquid and metal) is scanned on the items line. The graph clearly shows that the Enhanced tag is able to reach the optimal performance, i.e. a successful read rate equal to 100%, in every critical operating conditions. More in detail, the graph shows that although the performance of all tested tags are comparable under optimal conditions (orientation equals to 0°), in critical conditions (orientation equal to -90° and +90°) the performance of commercial tags decreases so abruptly to achieve in most cases a percentage of successful read rate equal to 0%. Instead, the Enhanced tag reaches, also in these conditions, 100% of successful readings. The results clearly show also that the NF UHF tags are not able to solve performance problems in critical operating conditions (e.g. presence of misalignment)

In Fig. 10, the same performance comparison, using metallic bomb-spray, is shown. The graph confirms the excellent performance achieved by the Enhanced tag in all operating conditions on the items line. In this case, however, we observe that the performance obtained by some commercial tags are comparable to those reached by the realized tag (100% of successful read rate).

Vice versa, the second part of the tests is aimed at comparing the tags performance in another challenging step of the supply chain: the cases line. Fig. 11 shows the performance comparison, in terms of successful read rate, of the Enhanced tag with the eight commercial tags by varying the composition of the ophthalmic solution case (i.e. Configuration I, Configuration II and Configuration III). It is worth noting that, commercial tags have never reached successful read rate higher than 70%, while in all the configurations the Enhanced tag has achieved the maximum performance. The results have also demonstrated the very poor performance of the NF UHF tags in any conditions of the cases line step.

Finally, Fig. 12 shows the performance comparison when the case is composed of 14 items of bomb-spray. In this case, only one commercial FF UHF tag (i.e. Jumping Jack) presents good performance especially in Configurations I and III. On the contrary, other commercial tags have shown very low performance. This permits to assert that, also in this case, the Enhanced tag guarantees successful read rates better than the other tags.

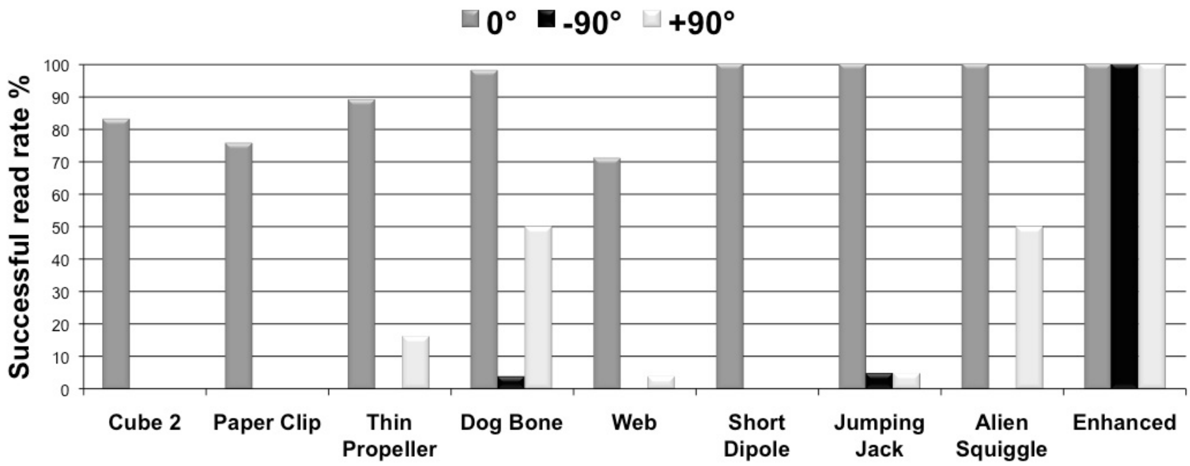

Figure 9. Tag performance comparison on the items line by varying the tag-reader antenna misalignment in presence of liquids and metals (Ophthalmic solution).

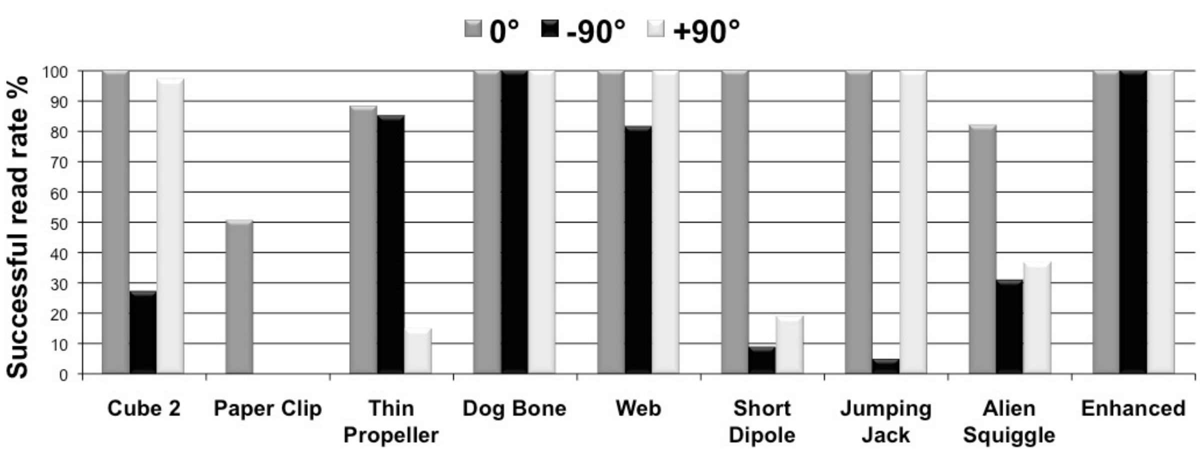

Figure 10. Tag performance comparison on the items line by varying the tag-reader antenna misalignment in presence of metals (Bomb-Spray).

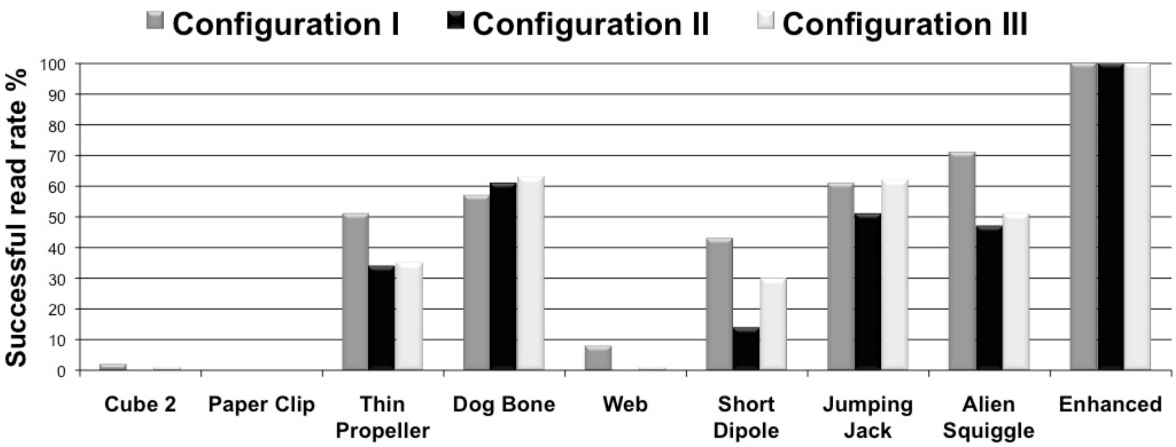

Figure 11. Tag performance comparison on the cases line by varying the tag-reader antenna misalignment in presence of liquids and metals (Ophthalmic solution).

B. Platform-tolerant tests: Tetra Pak material

In order to further emphasize the Enhanced tag robustness also in applications in which it is not specifically designed, an additional platform-tolerant test has been performed. In particular, further tests similar to the previous have been carried out considering, instead of pharmaceuticals, packages of milk. In this case the external package is entirely in Tetra Pak thus the operating conditions in which the tag is forced to work becomes even more critical. In fact, the Tetra Pak composition (that have an high percentage of metal), jointly to the presence of the liquid, drastically disrupts the electromagnetic propagation and, hence, hampers the tag identification.

In order to appreciate, also in this case, the effectiveness of the defined Enhanced tag, a performance comparison with one of the most powerful commercial tags (i.e. Dog Bone tag) has been carried out.

Once more, the measurement campaign has been carried out according to the same guidelines of the previous case considering both the items line and the cases line. In the items line the 0°, +90° and -90° configurations of the tagged Tetrapak package have been tested. Only the configuration I, instead, has been used in the cases line, taking into account a case with a 3 x 3 disposition of the single milk items.

Table 1 summarizes in detail the performance comparison between Enhanced tag end Dog Bone tag in the items line and in the cases line steps considering the Tetra Pak milk package.

Also in this case the results are impressive: in the items line the Enhanced tag exhibits always 100% of successful readings regardless of the package orientation. The commercial Dog Bone tag, instead, shows good results only in the optimal condition. In all other cases it is never identified.

Even in the cases line the Enhanced tag is much more robust than Dog Bone. In fact, as we observed in the same Table 1, the Dog Bone is never read, whereas the Enhanced tag achieves a successful read rate higher than 60%. This clearly demonstrates the qualities in terms of robustness and reliability of the proposed Enhanced tag even in contexts in which it has not been specifically designed.

IX. Conclusion

In this paper, the main features of an Enhanced FF UHF tag, designed and realized in order to work properly in the whole supply chain, have been considered. First of all, the properties that a RFID tag should own in order to properly

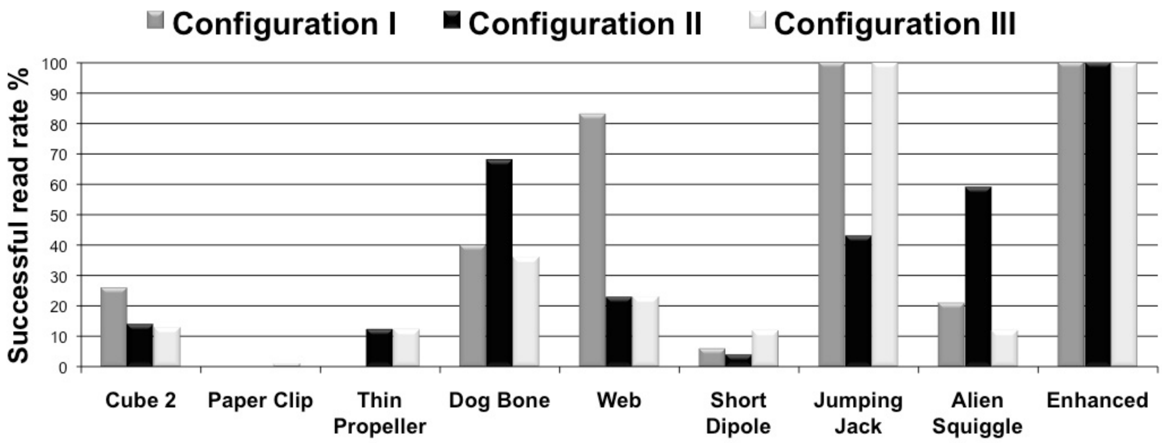

Figure 12. Tag performance comparison on the cases line by varying the tag-reader antenna misalignment in presence of metals (Bomb-spray).

TABLE 1 – PERFORMANCE COMPARISON BETWEEN ENHANCED TAG AND DOG BONE TAG APPLIED ON TETRAPAK PACKAGE

	Items line			Cases line
	0°	+90°	-90°	Conf. I
Enhanced tag	100%	100%	100%	61%
Dog Bone tag	93%	0%	0%	0%

work in every step of the supply chain have been pointed out, and the proposed tag has been designed following the indentified guidelines. In order to validate the Enhanced tag, a performance comparison with eight selected commercial UHF tags has been carried out considering critical conditions as the presence of liquids and metals, the misalignment between tag and reader antenna and the most severe supply chain steps such as items and cases line. The experimental results have shown that the Enhanced tag reaches the 100% of successful read rate in every critical condition and with the most critical pharmaceutical products. Finally, a very severe test has been carried out, aimed at evaluating the performance of our Enhanced tag on Tetra Pak packets containing milk. This application is one of the most challenging because of the very massive presence of both metal and liquids without any air in the middle. Very surprisingly, the performance are quite good also in this case, undoubtedly demonstrating once more that when a tag is designed by taking into account the peculiarities of the tracing systems, high performance can be obtained even in particularly critical conditions

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