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High Performance UHF RFID Tags for Item-Level Tracing Systems in Critical Supply Chains

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1. Introduction

The need of a traceability system implemented at item level is becoming more and more essential in many business processes and, among the different potential enabling technologies, passive Radio Frequency Identification (RFID) (Finkenzeller, 2003) is undeniably the most adequate candidate. Indeed, its simplicity of use as well as its very attractive cost-benefit ratio, give a strong appeal to RFID.

Among the many application sectors, the pharmaceutical supply chain, with millions of medicines moving around the world and needing to be traced at item level, represents a very interesting test-case. Furthermore, the growing counterfeiting problem raises a significant threat within the supply chain system. Moreover, several international institutions (e.g. Food and Drug Administration, European Medicines Agency, European Federation of Pharmaceutical Industries and Associations) are encouraging the use of innovative solutions in healthcare and pharmaceuticals, to improve patient safety and enhance the efficiency of the pharmaceutical supply chain.

In order to select the most adequate 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 (De Blasi et al., 2009; Uysal et al., 2008).

The choice between the two main RFID solutions, High Frequency (HF) or Ultra High Frequency (UHF), can be aided by several recent works, which highlight how passive UHF RFID systems provide better performance than passive HF ones, see for example (Uysal et al., 2008). Hence, UHF seems to be the most promising technology for item-level traceability on the whole supply chain. The success of UHF can be mainly attributed to the assertion of the EPCglobal (Thiesse et al., 2009) international standard. Furthermore, UHF has several advantages over HF and LF technologies: the capability to enable multiple simultaneous readings of tags, the capacity to offer very high read rates, in addition to the much longer reading distance.

Unfortunately, performance of UHF systems depends on several parameters (Bertocco et al., 2009), which are 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 moving objects, quantity of tags to be read, etc.). In such scenarios, the choice of an 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 (Rao et al., 2005; Catarinucci et al., 2010) 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 (Catarinucci et al., 2010).

In addition to the RFID checkpoints peculiarities, another important aspect is the effect on the tag performance of the platform where the tag is attached. Unfortunately, commercial FF UHF tags still suffer of many drawbacks (Nikitin & Rao, 2006). First of all, they suffer of performance degradation in presence of electromagnetically hostile materials, such as metals and liquids (Catarinucci et al., 2010; De Blasi et al., 2010). Another issue regards the strong dependence of the system performance on the mutual position between reader antenna and tag antenna, which may vary randomly for each item. Consequently, from the electromagnetic (EM) point of view, very strict requirements must be satisfied by the tag antenna.

The sum of the requirements to be met by a single tag, functioning properly in every step of the supply chain, will be extended in the next sections.

Consequently, the first part of this chapter describes the main features of the pharmaceutical scenario, mainly focusing on item-level tracing systems, RFID devices performance, related works and experimental measurement campaigns of commercial UHF RFID tags.

Taking into account the analysis of such aspects, the main causes of performance degradation are individuated and a guideline for the design of a new kind of RFID tag, working properly in each step of the pharmaceutical supply chain and regardless of the kind of traced product, has been drawn in the second part of this chapter. Moreover, a new enhanced tag has been realized by following the guideline, tested, and finally results have been discussed.

2. Related works

The current vision of the RFID market shows, in addition to UHF FF tags already widely used, also the presence of UHF NF tags. These last are based on inductive rather than 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 both NF reader antennas and small loop antennas restrict the NF tags reading range to only a few centimeters. Nevertheless, the smaller size of NF tags and the higher tolerance to the scenario – inductive field penetrates through liquids and dielectrics – make them useful in some applications where the size is crucial and marked items are electromagnetically complex.

It is important for the scientific community to understand the capabilities and limitations of the emerging passive UHF technology, and just as importantly, to 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 (Catarinucci et al., 2010) (e.g. data reliability, read rate in critical conditions, lack of unified standard for interoperability), (ii) software weakness (Barchetti et al., 2010) (e.g. scalability, single-point of failure, integration with information systems), (iii) relatively high costs of tags, software customization and systems integration, (iv) security issues (Staaake et al., 2005; Mirowski et al., 2009), (v) lack of scientific literature on the evaluation of potential effects of RFID exposure on molecular structure and potency of drugs (Acierno et al., 2010).

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

(Aroor & Deavours, 2007), for instance, evaluates performance of several commercial passive UHF tags under critical operating conditions (e.g. presence of liquids and/or metals) by using an experimental approach. In order to simplify both measurements and result analyses, an end-user metric has been chosen. In particular, performance of tags is measured in terms of maximum reading distance in a given environment. The tests have demonstrated that no commercial FF UHF tag can be properly read when it is directly applied to metal. Further results have shown that the water presence degrades the tag performance significantly. The tests have also demonstrated that larger tags guarantee better performance. In the same work, a series of experiments has also been carried out by using some NF UHF tags. The results have clearly demonstrated that NF UHF tags do not solve the problem associated with the presence of neither the metal nor the water. On the contrary, it has been highlight that the presence of metal or water has even much more drawbacks in NF rather than FF UHF tags.

(Bertocco et al, 2010) experimentally investigates 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.

(Ramakrishnan & Deavours, 2006) describes a benchmark suite useful to give good indications about how well UHF solutions work in real world scenarios. These benchmarks are able to compare the reading performance of different tags in terms of distance, quality, and real rates in various situations.

(Fuschini et al., 2010) is another work that aims at investigating the 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.

(Tae-Wan Koo, et al., 2010) is a very interesting work focused on the need to improve the performance when an UHF tag is applied on a metallic object.

(Bertocco et al., 2009) highlights the importance to evaluate the performance of UHF RFID systems in real-world conditions by using suitable test bed 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.

(De Blasi et al., 2010) 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 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.

3. Test environment to emulate a pharmaceutical supply chain

3.1 Reference scenario

The pharmaceutical supply chain, shown in Fig. 1, is a complex scenario with millions of pharmaceutical products moving around the world each year. Three are the most significant actors of such a supply chain: (i) the *manufacturer* who produces the package of pharmaceuticals, (ii) the *wholesaler* who buys and resells big quantities of medicinal products, and (iii) the *retailer*, which in general is a pharmacy or hospital.



Fig. 1. An abstract vision of the pharmaceutical supply chain.

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. Such orders often refer to small quantities of many 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 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 each other 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.

3.2 Test bed components

The controlled test environment, shown in Fig. 2, has been realized in order to simulate the main steps of the pharmaceutical supply chain. Such a test environment, in fact, makes it possible to carry out effective experimental campaigns to evaluate the performance of UHF RFID-based tracing systems, even in particularly stressed operating conditions.

The test environment, based on the three main components above described (items line, cases line and border gate), makes possible unbiased and repeatable comparisons among technologies.

More specifically, the items line consists of a conveyor belt whose speed can be tuned in the range from 0.00 to 0.66 m/s, in order to guarantee real requirements to be met by pharmaceutical manufacturing processes. The conveyor belt has a double containment edge to keep products in the same position along the belt. In the middle of each containment edge, a near field reader antenna has been installed and connected to a high performance UHF RFID reader compatible with the EPC Class1 Gen2 standard. 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 0.00 to 0.66 m/s, a double containment edge to keep cases in the same position along the belt, one Impinj Speedway reader, and two roller conveyors. In the middle of the line, four small near field reader antennas (Impinj Brickyard) have been placed inside a metallic tunnel. Each reader antenna is in the centre of each tunnel side. The width of the tunnel is equal to 0.6 m. Further characteristics are: 50 Ω of 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.

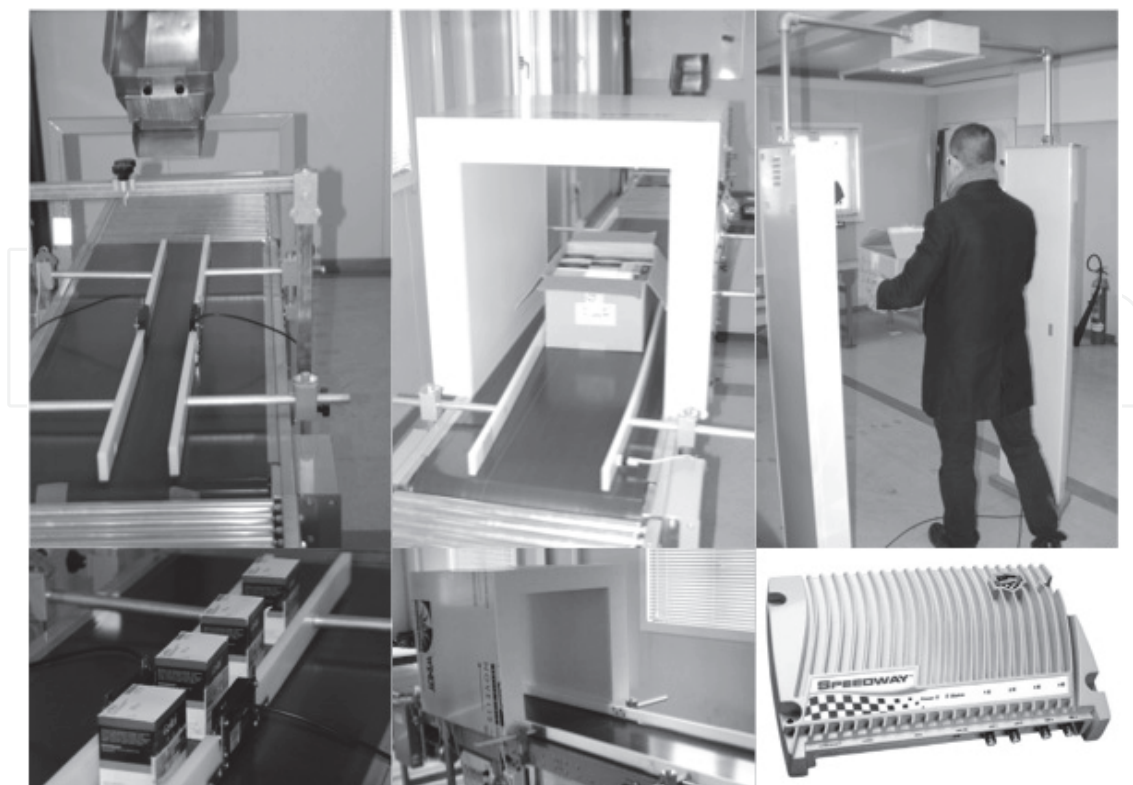


Fig. 2. Test environment composed of an items line (left), a cases line (middle), and a border gate (top right).

In order to effectively simulate the pharmaceutical supply chain, it is very important to take into account real heterogeneous drugs, so to significantly represent the global market of drugs, that is characterized by a wide heterogeneity of products, which differ for several factors as, for instance, medicine state (i.e. solid, liquid, gas, etc.) and material of the primary package (e.g. glass, metal, plastic, etc.). A complete taxonomy of most popular drugs may be done by considering these factors.

The first classification, which takes into account only the medicine state, splits all pharmaceutical items into four main categories:

- Solid: tablets capsules, granules, etc.
- Semi-liquid: creams, suppositories, etc.
- Liquid products: syrups, oral liquids, solutions, etc.
- Gas: pressurized gasses.

Another useful classification can be done in terms of material of the primary package. Plastic is the most widely diffused material because of the large use of bottles, blister packs, and film layers. Nevertheless, even the use of metal is fairly common: aluminium blister packs and sachets are possible examples. Another common material for pharmaceutical products is glass that is very valuable especially for the liquid products. Classical applications of glass packaging are bottles for liquids, ampoules, and vials.

Based on the above information and discussions, Table 1 summarizes a simple taxonomy of pharmaceutical products according to their physical properties.

It is worth observing that this classification is very important to perform significative tests because different materials interact with RF waves differently. In particular, liquids cause the RF waves attenuation by absorbing their energy, whereas metals do not let RF waves

pass through by reflecting them. Moreover, in both cases, the impact on the radiating properties of RFID tag antennas is relevant. The reported taxonomy, hence, becomes a compulsory instrument to select the most adequate drug for the specific laboratory test, so as to evaluate the impact of hostile materials on the performance of the RFID systems in the UHF band.

Product Type		Package Material		
		Metal	Glass	Plastic
Solid	Tablets in Blister	X		
	Tablets in a Bottle			X
	Granules in Sachets	X		
	Powders in a Bottle		X	
Semi-liquid	Cream	X		X
Liquid	Syrup		X	
	Single injectable solution in syringe		X	
	Multiple injectable solution in syringes		X	
	Oral solution			X
	Ophthalmic solution	X		
Gas	Bomb Spray	X		

Table 1. Classification of pharmaceutical products

3.3 Description of the working conditions

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 misalignments between tag antenna plane and reader antenna plane, multiple reading of tags, distance between tag antenna and reader antenna.

The misalignment problem is mostly relevant in the items line. To test such a misalignment impact, four 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°, -90° and 180° are considered. In particular, this last represents the worst case and allows the performance evaluation under unfavourable 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 both homogeneous cases (consisting of a single product type) and heterogeneous cases (containing products of different types) should be 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. 3, the configurations I, II and III are schematically reported. The overlapping of two different tags is represented by a double “x”.

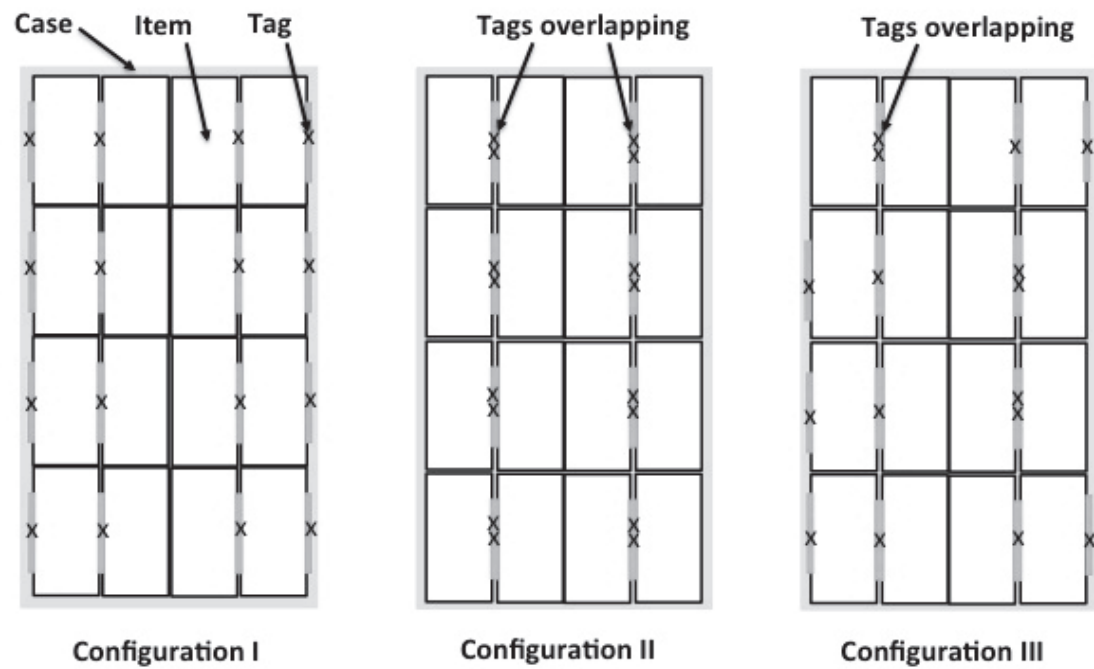


Fig. 3. Some examples of case compositions.

Further tests related to cases line and border gate should be carried out also on sets of heterogeneous drugs. More specifically, cases filled with a mix of 50 items in the cases line and mix of 200 items in the border gate will be considered in out measurements. Three different combinations of items into the case (cases line test) and into the plastic bag (border gate test) have been prepared considering the following percentages:

- MIX1: 40% solids, 40% liquids, and 20% semi-liquids;
- MIX2: 50% solids, 30% liquids, and 20% semi-liquids;
- MIX3: 60% solids, 20% liquids, and 20% semi-liquids.

4. Experimental results of commercial RFID UHF tags

4.1 Commercial RFID tags

In order to carry out an effective performance comparison among commercial RFID tags, able to evaluate the current limits in item level tracing systems in the whole supply chain, a

preliminary technological scouting is very important. 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 chapter, experimental results derived by testing eight different types of passive UHF tags, six FF and two NF, are reported. All 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. 4.

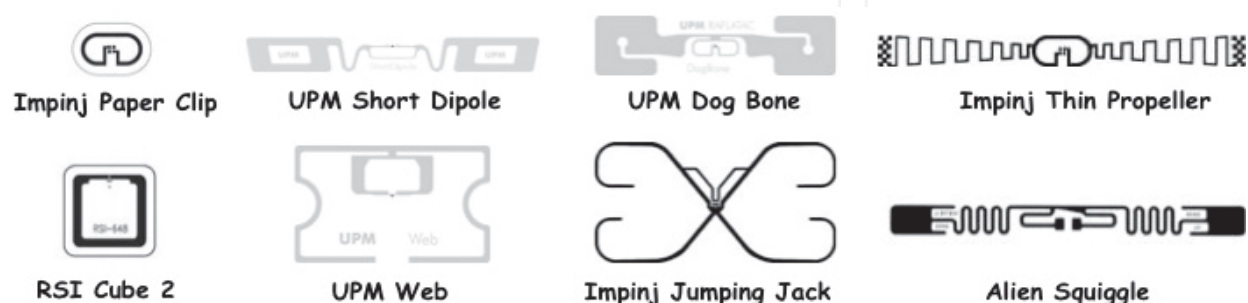


Fig. 4. Layout of the eight preselected commercial passive UHF RFID tags.

More in detail, the following types have considered:

- RSI Cube 2: it is a small near-field tag, whose size is 25.4 x 25.4 mm, with the 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 the 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 the 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 the 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 the 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 the NXP U-Code G2XL chip.
- UPM Short Dipole: it is equipped with the 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 the 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.

4.2 Results in ideal conditions

The first part of the experimental campaigns is focused on a performance comparison between NF and FF commercial UHF tags applied on different drug types in each step of the supply chain. The following RFID tags have been used: RSI Cube 2 and Impinj Paper Clip as NF tags, while, Impinj Thin Propeller, Impinj Jumping Jack, and UPM Dog Bone as FF tags. In the first test, the most favourable working conditions in the items line are reproduced. Indeed, the mutual orientation between the plane where the tag antenna lies and the plane where the reader antennas lie is 0°. Results reported in Fig. 5 show that the NF tag Cube 2 ensures optimal performance for every drug type, even in presence of critical materials such as liquid and metal. Likewise, also the two FF tags have given good results, even though a slight effect due to the presence of metal and liquid, above all in the bomb spray and ophthalmic solution cases, is observed.

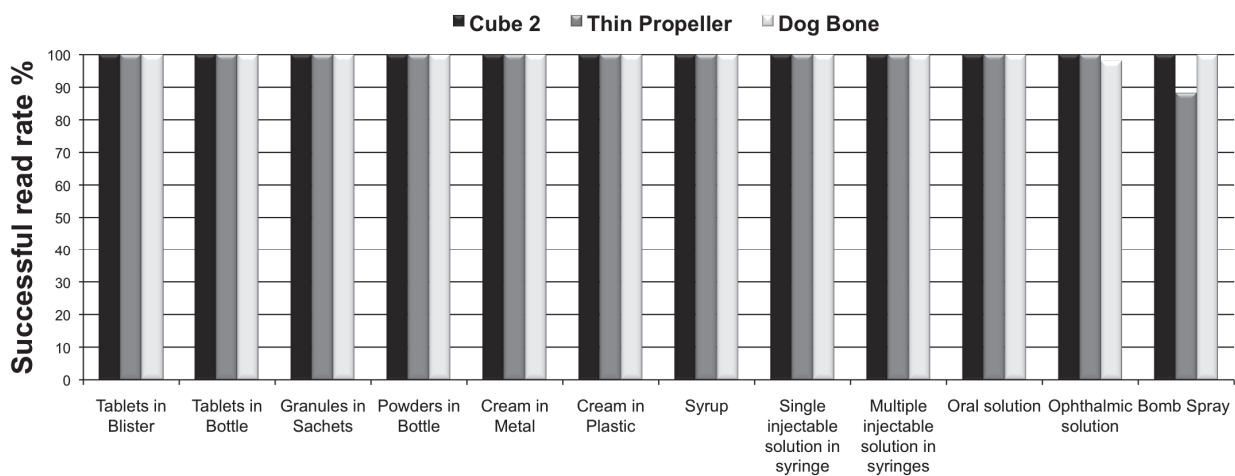


Fig. 5. A performance comparison on the items line by varying the drug type and the tag type considering normal operating conditions (mutual orientation 0°).

In a second test, the worst conditions are reproduced: a mutual orientation between the tag plane and reader antenna plane of +180° has been considered. This has been done by switching off one of the two reader antennas and by applying the RFID tag on the package face opposed of the active reader antenna. The experimental results, reported in Fig. 6, clearly show that FF UHF tags perform better than NF ones. The results where even the Dog Bone tag is not characterized by a successful read rate of 100%, have been obtained mainly in presence of granules in aluminum sachets, ophthalmic solution in aluminum sachets, syrup, and bomb spray. For these cases, though, the Cube 2 tag has shown very poor performance, reaching values of successful read rates near to 0%.

In order to evaluate the reliability in presence of multiple reading of tags at the same time, several experimental campaigns have been carried out. More specifically, eight different types of product, chosen among the four categories previously defined, have been used to perform tests on homogenous (single type of product) and heterogeneous (mix of products) cases (see section 3.3).

Homogenous cases have been analyzed considering a random disposition of items within the case. In particular, the type of case composition is the Configuration III previously described. Fig. 7 shows the experimental results obtained by testing again the NF Cube 2 tag and the two FF, Thin Propeller and Dog Bone, tags. The histogram clearly demonstrates that

the performance of FF UHF tags is better than the NF Cube 2 tag. Furthermore, this test shows that all the analyzed tags are not able to guarantee good performance in presence of materials that are hostile to electromagnetic propagation. In particular, the experimental results show very poor successful read rate when the homogenous case is composed of items such as bomb spray or ophthalmic solution.

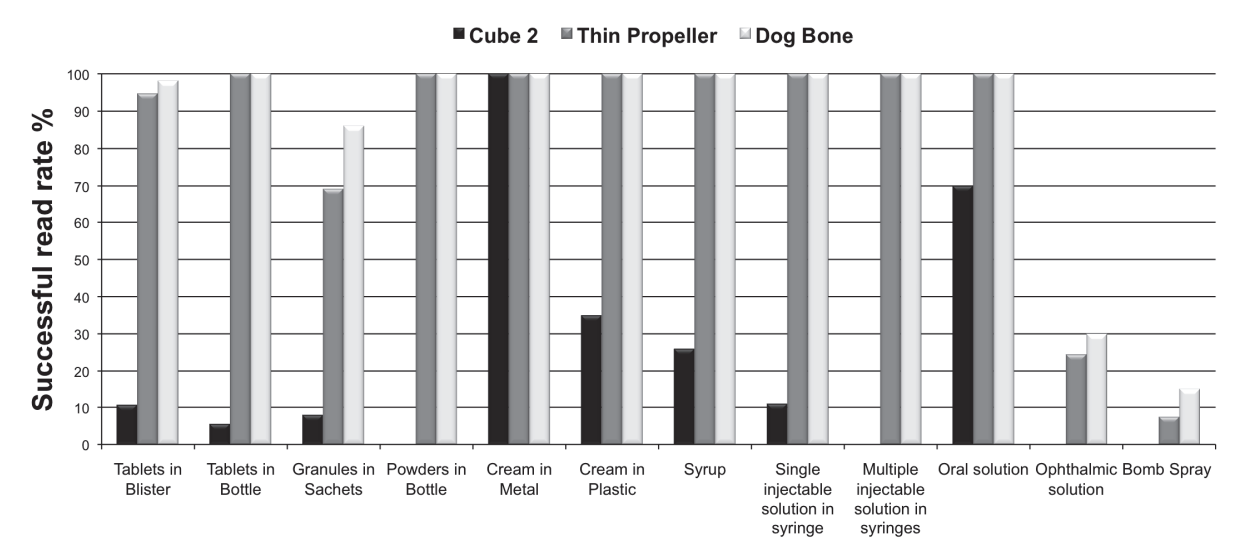


Fig. 6. A performance comparison on the items line by varying the drug type and the tag type and considering extreme operating conditions (mutual orientation +180°).

Further tests allowed the evaluation of the performance, also in this case in presence of multiple reading of tags, but considering the heterogeneity of drugs. In particular, Fig. 8 shows a performance comparison in the cases line by varying the configuration of the case in terms of drug types. The three different and previously described realistic compositions have been considered (MIX1, MIX2 and MIX3). The experimental results clearly show that optimal performance (100% of successful read rate) can be obtained using the two types of commercial UHF tag.

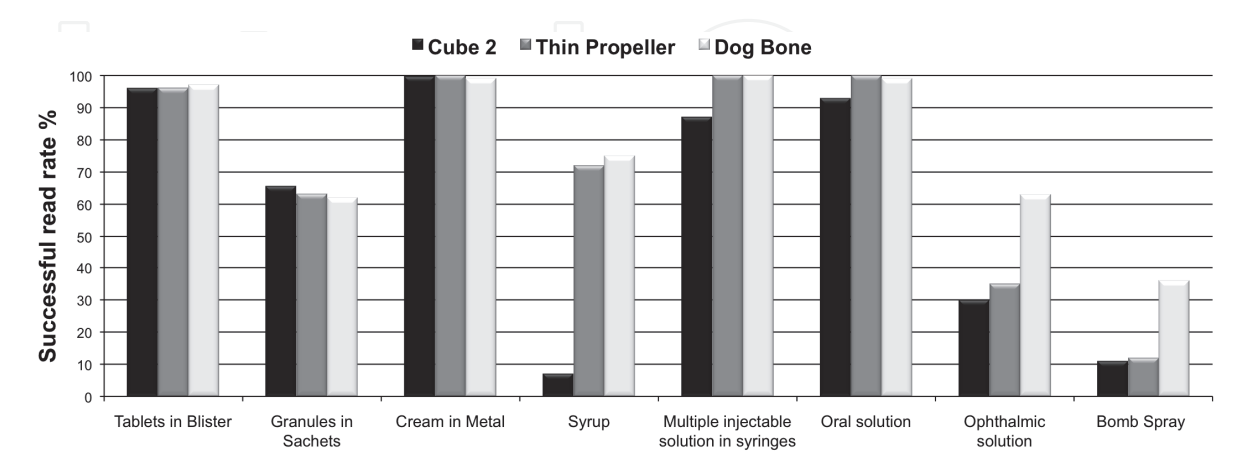


Fig. 7. A performance comparison on the cases line by varying the drug type and the tag type considering homogeneous cases and a random disposition of the items within the case (Configuration III).

Finally, the last test for the first part of the experimental campaigns is aimed to evaluate the reliability of commercial UHF tags in the border gate. An adequate number of 200 heterogeneous items contained in a big plastic bag has been considered. For this test, the same three previous different compositions, in terms of drugs type, have been considered. The experimental results of Fig. 9 show that a NF UHF solution is definitely not suitable for item-level tracing systems in this step of the supply chain.

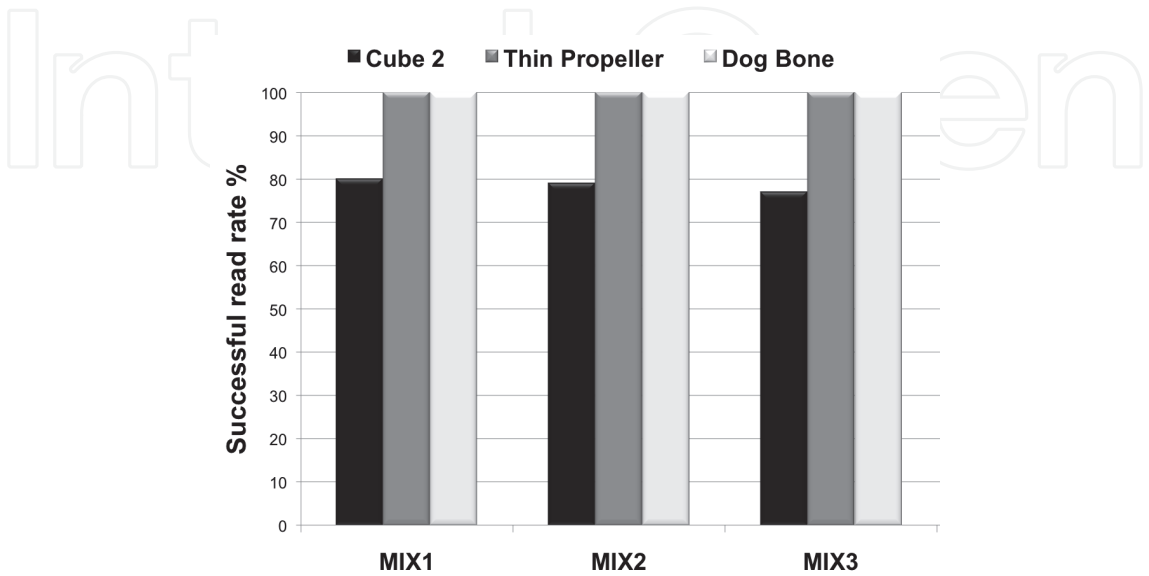


Fig. 8. A performance comparison on the cases line by varying the tag type and the composition of the case containing heterogeneous drugs.

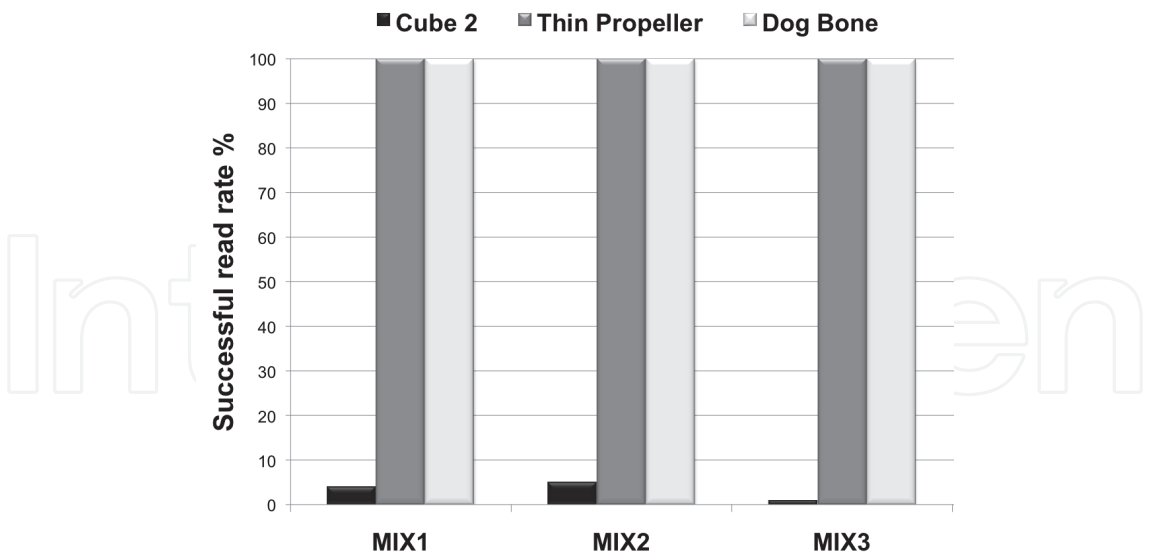


Fig. 9. A performance comparison on the border gate by varying the tag type and the composition of the plastic bag containing heterogeneous drugs.

The first part of the experimental campaigns has demonstrated that the use of commercial UHF RFID tags represents a well suitable solution for the traceability at item level at least in presence of non-critical operating conditions.

4.3 Results in critical conditions

As above stated, when the operating conditions do not present particular criticalities, all the selected FF tags work properly. Nevertheless, the performance degradation observed when the tags have been tested on products containing relevant quantities of liquid or metal is evident. For such a reason, this section focuses on the tag performance evaluation under more severe operating conditions. The products resulted as the most critical in the previously conducted tests, the bomb spray and the ophthalmic solution, have been considered. As previously stated, in fact, when the item to be traced is composed of metal and/or liquid, the tag performance could decrease considerably. This is substantially due to the fact that the horizontal-plane radiation pattern of the tag antenna, that is almost omnidirectional in free space conditions, varies significantly because of the presence of such materials.

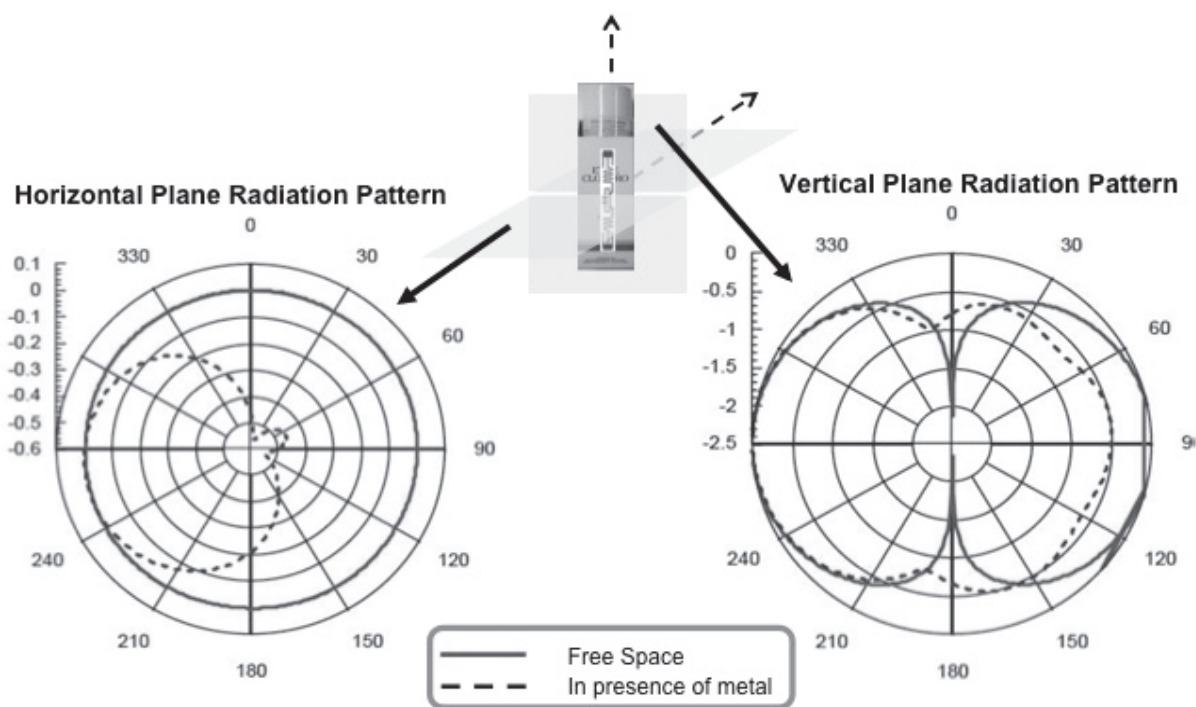


Fig. 10. Horizontal radiation pattern in free space condition (continuous line) and in presence of metal (dot line) of the Alien Squiggle Tag.

In Fig. 10, for instance, the horizontal plane radiation pattern of the Alien Squiggle RFID tag both in free-space conditions and in presence of metal are reported. It can be observed that, for many directions, the potential link between tag and reader is not possible anymore when the tag is attached on the bomb spray case. This effect becomes relevant when there is a 90° of misalignment between the planes individuated by the reader antenna and the tag respectively.

The results reported in Fig. 11 and in Fig. 12, for instance, are referred to the successful read rate measured in the items line respectively for the ophthalmic solution case and the bomb spray case. In order to stress the misalignment problem, tests have been carried out by considering the three different operating conditions previously described and characterized by a mutual orientation between tag antenna and reader antenna equal to 0°, +90° and -90° respectively.

Results are quite relevant: despite the very good values obtained in case of alignment, in general it emerges that no tag guarantees satisfactory performance levels in both cases and for each orientation.

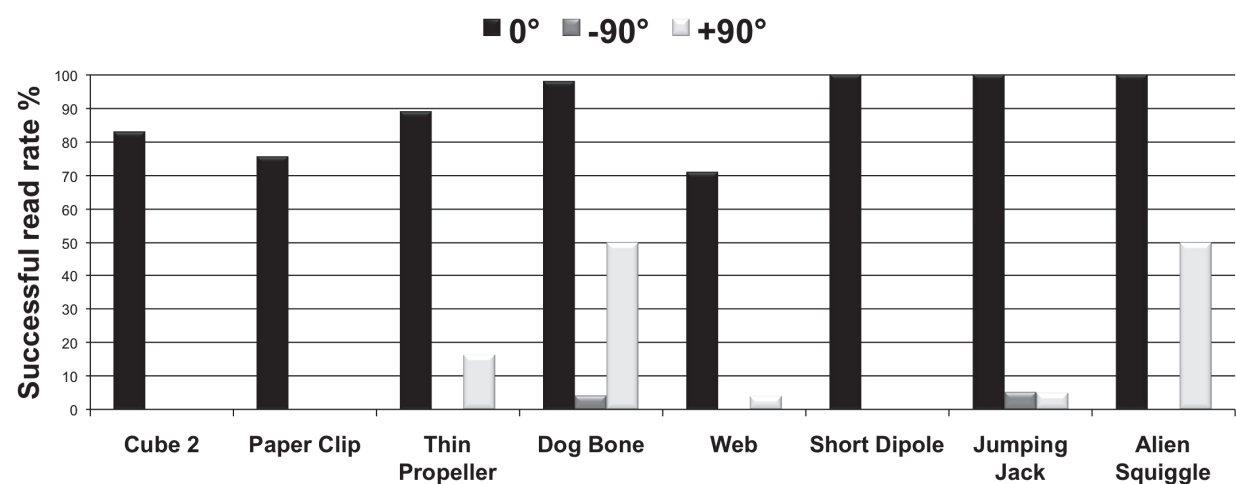


Fig. 11. A performance comparison on the items line by varying tag type and the tag-reader antenna misalignment in presence of liquids and metals (ophthalmic solution).

Even more interesting are the results obtained by testing the tags in the cases line. As an example, Fig. 13 and Fig. 14 reports the successful read rate evaluated by packing together 36 secondary packages of ophthalmic solution and 14 of bomb spray respectively, in the three configuration previously described and named respectively Configuration I, Configuration II, and Configuration III. It can be observed that the strong presence of metal and liquid substantially inhibits the communication between reader and the NF tags. Moreover, also when FF tags are considered, very low performance are obtained in each configuration, demonstrating once more that general purpose commercial tags are not appropriate for the implementation of complex item level tracing systems. It is substantially due to the fact that such tags have been designed not taking into account the peculiarities of the scenario where they must be utilized.

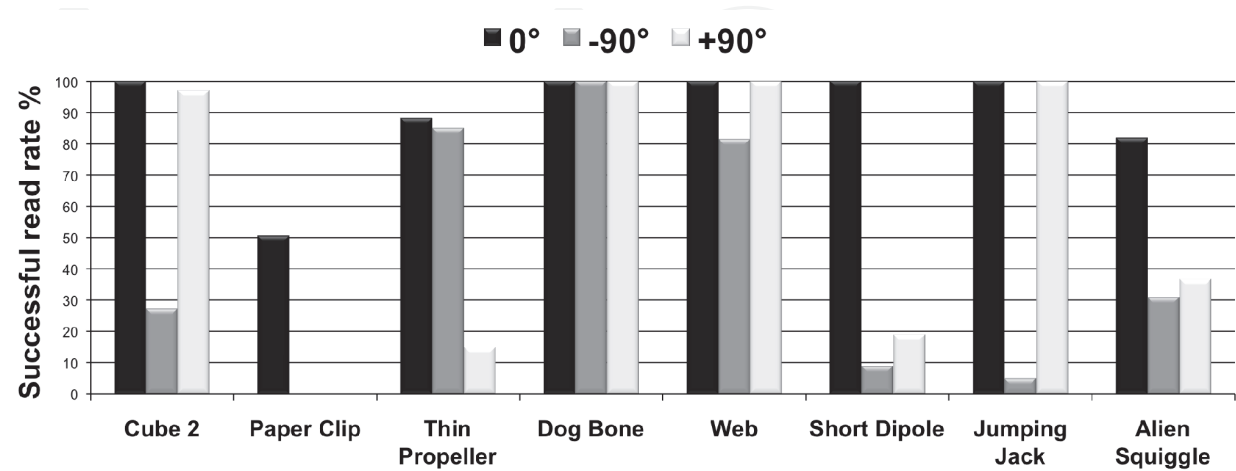


Fig. 12. A performance comparison on the items line by varying tag type and the tag-reader antenna misalignment in presence of metals (Bomb spray).

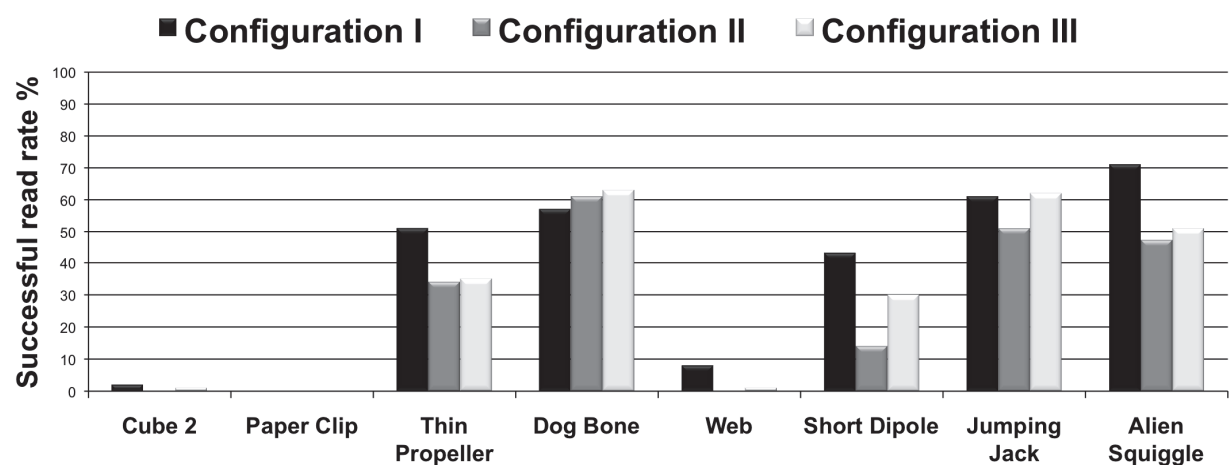


Fig. 13. A performance comparison on the cases line by varying tag type and the homogenous case composition in presence of liquids and metals (ophthalmic solution).

In the next section, a requirement analysis for a tag appositely designed to work in a complex supply chain, such as the pharmaceutical one, are individuated and described and are used to drive the development of a new high performance UHF RFID tag.

5. Requirements and guidelines in tags design

On the basis of the results shown in the previous sections, the realization of a tag designed ad-hoc for the specific supply chain scenario is a must. Consequently, this section focuses on the analysis of the pharmaceutical supply chain peculiarities and on the individuation of the properties that a tag should own in order to guarantee high performance in all supply chain steps, even when used to track items containing electromagnetically critical materials, such as liquids and metals. It is worth observing, though, that the pharmaceutical sector is only one of the many scenarios where a similar study could be of interest.

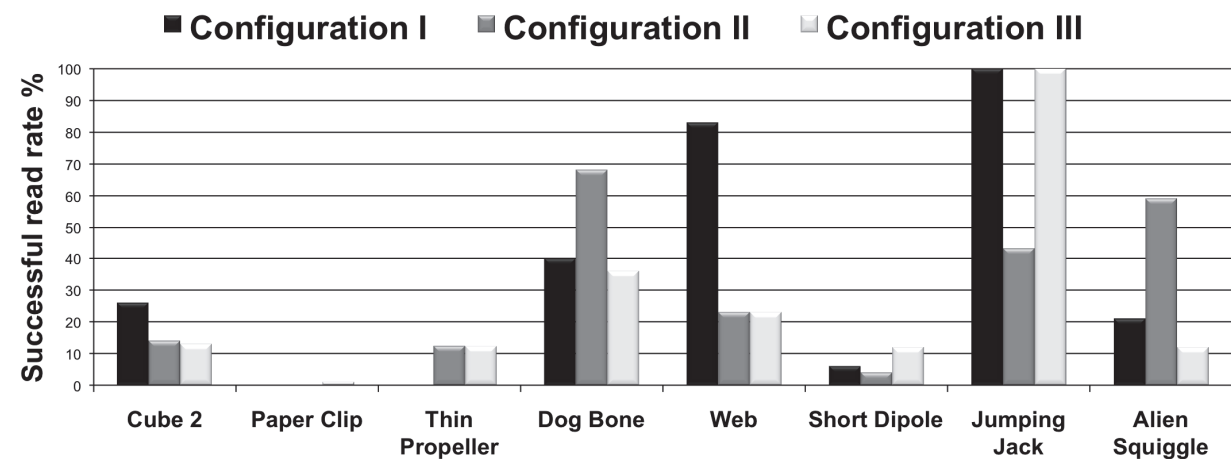


Fig. 14. A performance comparison on the cases line by varying tag type and the homogenous case composition in presence of metals (Bomb spray).

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. 10, 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.

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.

On the items line step, the packages are read one by one and no multiple-readings related problem arises; 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 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.

6. Design of new passive RFID UHF tags: the prototypal enhanced 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. 15 is reported the comparison, in terms simulated horizontal plane radiation pattern, between the Enhanced tag (Fig. 15a) and the commercial Thin Propeller tag (Fig. 15b), 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.

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.

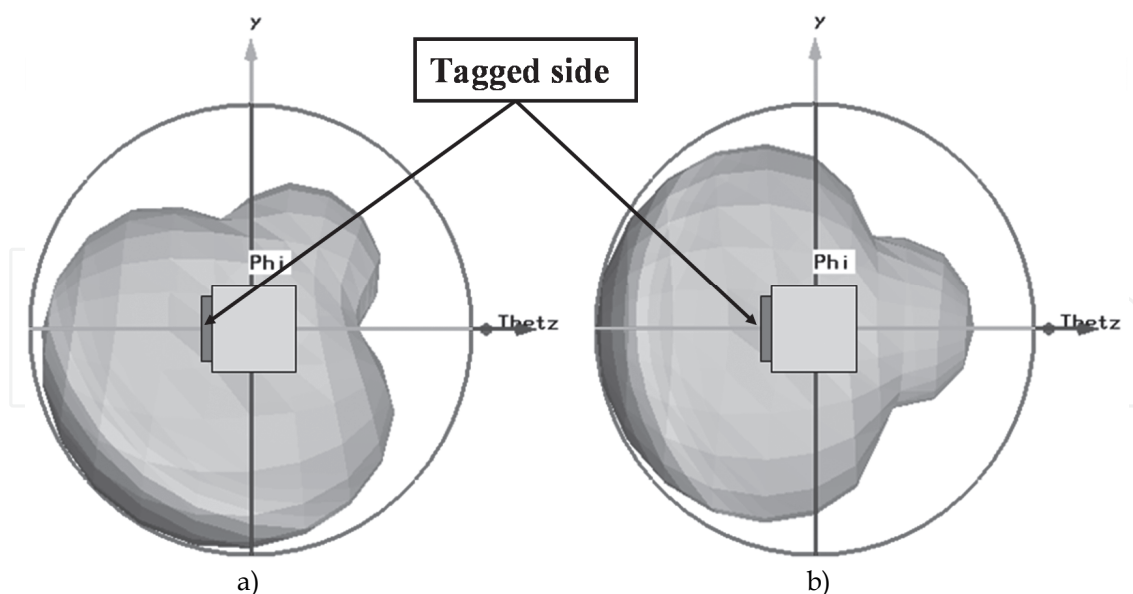


Fig. 15. Simulated horizontal radiation pattern of the a) Enhanced tag, and b) Thin Propeller tag, when they are applied on a cardboard package containing a metal block.

7. Experimental results of the enhanced RFID UHF tag

In order 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 some of the above described commercial UHF tags has been carried out in terms of successful read rate. In particular, taking into account the performance analysis carried out on commercial FF and NF UHF tags, the following four tag types with higher performance have been chosen in the comparison with the Enhanced tag: Jumping Jack, Cube2, Dog Bone, and Thin Propeller. One for the NF group and the others for the FF group.

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° , $+90^\circ$, 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 off 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%.

Fig. 16 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).

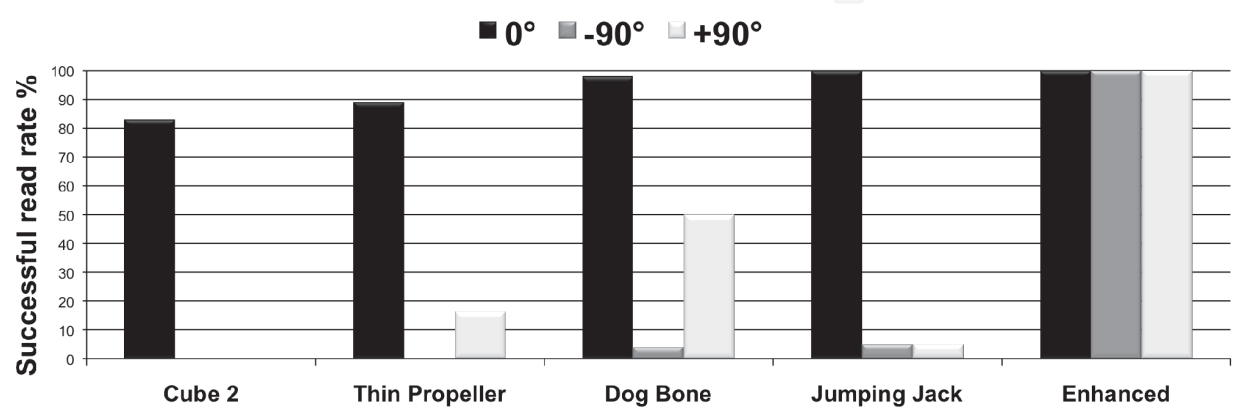


Fig. 16. A performance comparison between high-performance commercial tags and the Enhanced tag on the items line by varying the tag-reader antenna misalignment in presence of liquids and metals (ophthalmic solution).

In Fig. 17, 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, the performances obtained by some commercial tags are comparable to those reached by the realized tag (100% of successful read rate).

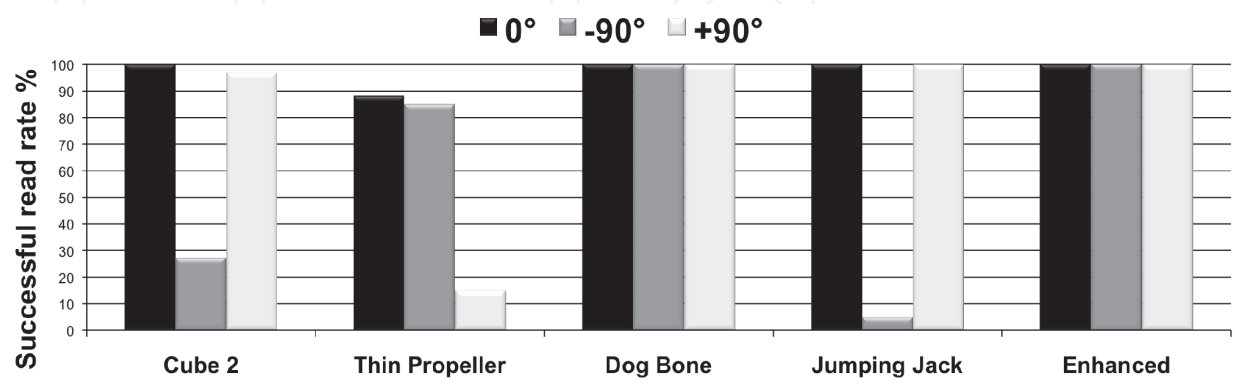


Fig. 17. A performance comparison between high-performance commercial tags and the Enhanced tag by varying tag type and the tag-reader antenna misalignment in presence of metals (Bomb spray).

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. 18 shows the performance comparison, in terms of successful read rate, of the Enhanced tag with the four commercial tags (i.e. one for NF and three for FF) 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 when used in a cases line. Finally, Fig. 19 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.

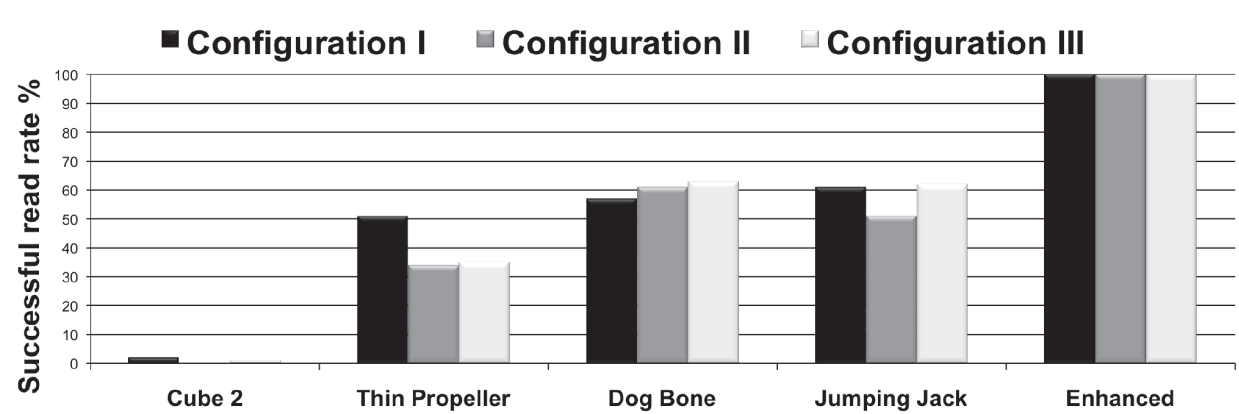


Fig. 18. A performance comparison on the cases line between high-performance tags and the Enhanced tag by varying the homogenous case composition in presence of liquids and metals (ophthalmic solution).

In order to further emphasize the Enhanced tag robustness also in even more critical applications, an additional test has been performed. In particular, packages of milk have been considered. They are characterized by an external package made in Tetra Pak, where the percentage of metal is relevant, and by the presence of liquid. To test the effectiveness of the Enhanced tag, a performance comparison with one of the most powerful commercial tags (i.e. Dog Bone tag) has been carried out.

Also in this case, the measurement campaign has been carried out by considering both the items line (configurations 0°, +90° and -90°) and the cases line (only the configuration I with a 3 x 3 disposition of the single milk items).

Table 2 summarizes in detail the performance comparison between Enhanced tag and 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 read rate regardless of the package orientation. The commercial Dog Bone tag, instead, shows good results only in the optimal condition. In all other cases it cannot be read.

Even in the cases line the Enhanced tag is much more robust than Dog Bone. In fact, as can be observed in the same Table 2, 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 different from those the tag has been designed for.

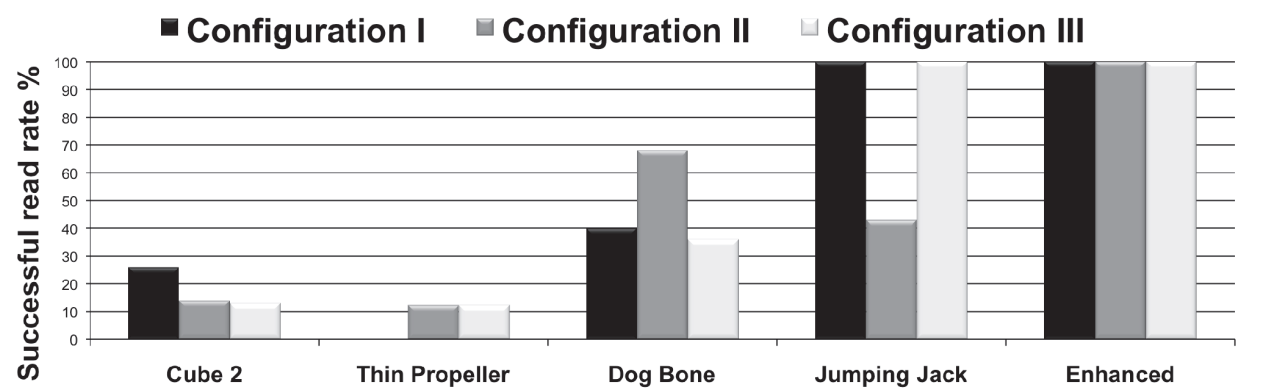


Fig. 19. A performance comparison on the cases line between high-performance commercial tags and the Enhanced tag by varying the homogenous case composition in presence of metals (Bomb spray).

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

Table 2. Performance comparison between Enhanced tag and Dog Bone tag applied on Tetra Pak package.

8. Conclusion

In this chapter, the problem of the effective RFID-based traceability performed at item level has been addressed. The pharmaceutical supply chain has been considered and its criticalities, in terms of kinds of goods to trace and peculiarities of the checkpoints RFID, have been individuated and discussed. The inadequateness of the use of commercial general purpose tags has been proved through an exhaustive performance evaluation campaign, aimed at evaluating the successful read rate in each step of the supply chain for numerous tagged products. Six different commercial Far Field UHF tags and two Near Field UHF tags have been tested; these last are the less reliable, but also the Far Field ones exhibit strong limits when used to trace products containing metals or liquids. Consequently, by taking into account the traceability scenario, the requirements that a tag should own in order to overcome such limits have been individuated and, on such basis, a new enhanced tag has been realized. Its performance has been rigorously evaluated and the obtained impressive results demonstrate that, if the tag is designed considering the peculiarities of the specific tracing system, a successful read rate of 100% can be obtained, regardless of the supply chain step, the composition of the traced product, and the operating conditions. 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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