The Art and Science of UHF Passive Tag Design

And Selecting The Tag That is Best for Your Requirements

Alien Technology® is unique in the industry in having over 15 years of experience designing UHF passive RFID inlays, the semiconductor chips on them, as well as the readers that interrogate the combination. This expertise enables Alien to provide a level of RFID inlay and tag design that others cannot. Here we examine the multifaceted challenges of tag design and what aspects of this are important for tag purchasers to understand.

Problem

- Passive UHF RFID tags are already well on the way to replacing bar codes
- A much greater level of expertise is required to choose the best performing tag design for a specific application (vs selecting a bar code) … but the benefits are much greater too (and the ROI is now proven)
- Few choosing tags for their application understand enough about how Radio Frequencies work in the context of RFID
- Understanding the technical trade-offs in modern day tag design is an often overlooked aspect of tag selection

Background

Over the past few years RFID tags have continued to replace barcodes in many applications. This document does not dwell on the business rationale why, although the diagram below hints at one of the many reasons, namely that RFID tags identify a specific object and not just a class of objects. Briefly, other reasons include the fact that RFID tags store additional data, this data may be written and updated in the field and that tags do not require line-of sight to function.

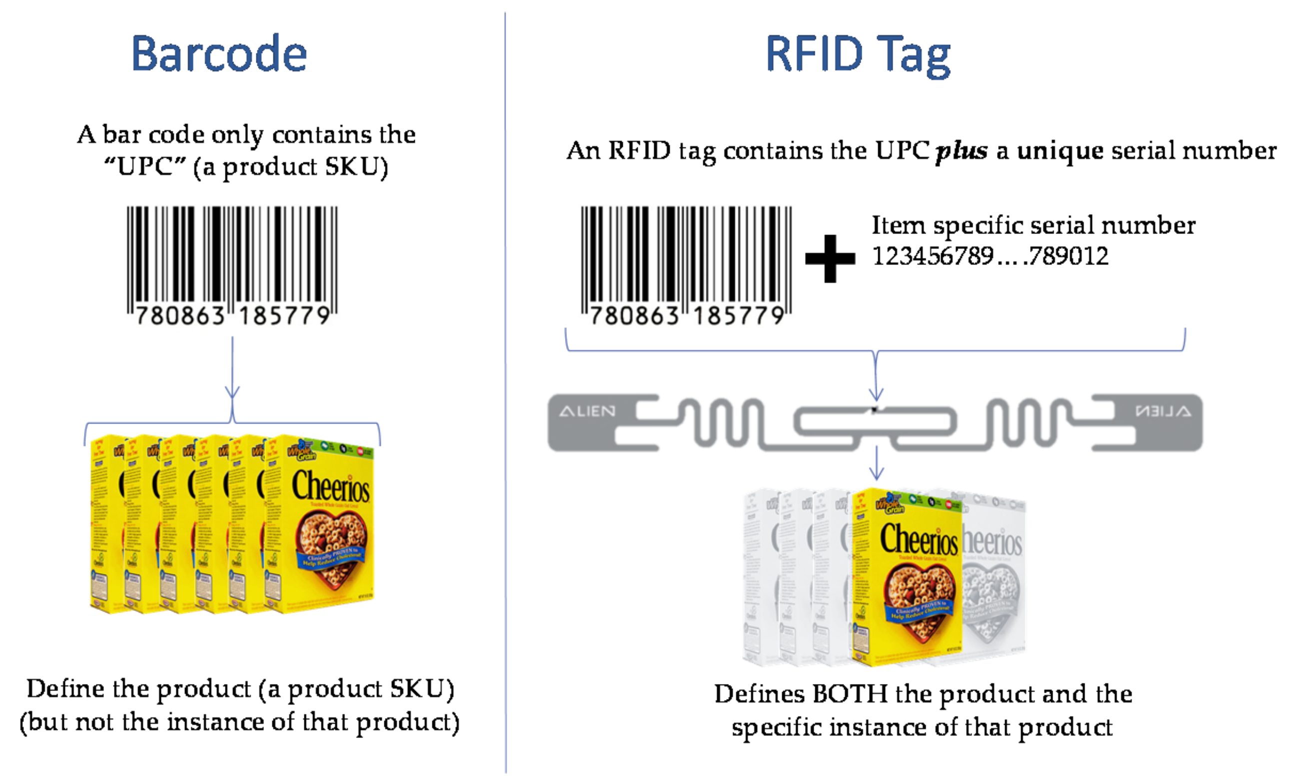

Figure 1 – RFID Tags are Replacing Bar Codes – They Contain Item Specific Information

The Return-on-Investment is now regarded as a well proven fact and better understood than a few years ago. The technology has also improved to the point that it is no longer a question of if the technology works but how do I get it to work *best* in a specific application? This paper discusses tag design issues that are also important for a purchaser of the technology to understand allowing a more informed purchasing decision.

> *RFID is extremely fast and extremely accurate and nobody is doubting whether RFID can reduce labor. But finding the right tag to fit the product used to be extremely painful, and when it's painful it becomes expensive.*
>
> Zander Livingston, CEO of Truecount

Bar codes are in their most simple form are fairly simple to understand and users do not need to know much about how the stripes (1D barcode) or blocks (2D barcodes) are created or decoded. A "reader" has to "see" the code and "observe" the light and dark variances, interpret these and present the data in human readable form. There is not much to understand about them. This did not stop early bar code users making mistakes such as printing on surfaces without enough contrast, inverting the light and dark areas or printing them on uneven surfaces that made them problematic to read. Also if they become scuffed, marked or soiled, it is pretty easy to understand that this may be a problem for the reader.

Terminology:

- (Tag) Antenna – The aluminum antenna used to collect power and transmits/receives signals to/from the UHF passive RFID chip. Note that the RFID reader also has one or more antenna of its own.
- Inlays – The antenna + chip combination
- Tags – The inlay applied onto a substrate (usually a plastic or paper) to allow its use when applied to an object
- Labels – The tag with an extra layer of printable material added with the inlay sandwiched between allowing printing onto the surface
- Conversion – The process of taking the inlay and manufacturing a tag or label
- RF – Radio Frequency
- ISM band - industrial, scientific and medical (ISM) radio bands (bands requiring no special licenses providing the adhere to certain frequencies and power limits)
- FHSS = Frequency Hopping Spread Spectrum (rapidly switching a carrier among many frequencies using shared knowledge between transmitter and receiver)
- LBT = Listen Before Talk
- ETSI defines the European RFID requirements. It uses a form of LBT.

As we move to the world of Radio Frequency Identification, we move to the world of "RF". Understanding RF is a degree level subject and not something that many RFID implementers necessarily understand well. For those that want a good general backgrounder on the subject may also choose to read "RFID for Dummies" by Patrick J. Sweeney, II. This paper examines the roll of tag design and the trade-offs that must be made by the tag designers and what the impact is to the tag. This in turn should be understood by those who are involved in the tag selection process for a specific application allowing them to make a more informed and educated decision about what is best in their application.

Trade-Offs

An understanding of basic Radio Frequency physics is an important skillset that should be used by those selecting tags for their application. However, an in-depth knowledge is not required although a solid understanding of the challenges of RFID tag behavior and tag design will contribute to a better tag purchase choice. This is what this paper seeks to accomplish.

From a high level these trade-offs include:

- Forward-link vs backscatter
- Operating frequencies (for forward and reverse links)
- Substance to be tagged and the environment this tagging is taking place in
- Size vs performance
- Tag design vendor (IC vs tag interaction knowledge)
- UHF Passive IC type/supplier
- Tag quality (design and materials)

With a background on these trade-offs, the number of "surprises" experienced during the implementation phase will only be reduced. Often it is useful to keep in mind the differences between barcodes and RFID tags. Fundamentally this all boils down to barcodes being a one-way optical (line-of sight) communication of a single number compared to RFID that is always a bi-directional (even when only reading) radio-frequency communication of many words of information.

Tag Design Considerations – A Multidimensional Problem

Before purchasing tags, it is important to understand the basic anatomy of a tag and some of the key elements that influence tag design and the implications of these design trade-offs on tag usage. As the adage goes, "if it is too good to be true, it probably is". No tag can be all things to all applications so understanding these trade-offs is useful. For the purposes of this paper we focus on Passive UHF RFID.

	Passive	Battery Assisted Passive "BAP"	Active
Power Source	From the reader at read time	Internal battery	Internal battery
Power Availability	Only on reading	On reading (continuous for sensors)	Continuous transmit
Read distance	Short (up to 10m)	Medium (10m+)	Very Long (100m+)
Data Storage	Small (100's of bits)	Medium (K bits)	Huge (Mb's or MB's)
Life time	Indefinite	1-4 years	1-12 Months
Sensor support	None	Some	Many large sensors
Cost	A few pennies	Dollars	Tens/Hundreds $'s
Size	Very small and thin	Large	Huge

Figure 2 - Types of RFID Tags

A tag includes the RFID IC and antenna on a substrate to allow the combination to be applied to a tracked object. However, the antenna has *three* functions and there are actually *two* different resonant elements ("sub-antenna" if you like) within most UHF passive RFID tag designs (except near field tags that have only one). What are these three functions?

First, the inlay must be able to receive RF power from the reader to "power up" the chip. As there are no batteries involved in Passive RFID tags, the power to allow the RFID chip to do anything must come from somewhere. It comes from the reader, 20 or 30 feet away. The challenge is to create a potential difference across the aluminum antenna, enough to power these very specialized RFID chips. If you think your cell phone has a low-power chip design, that is nothing compared to these passive RFID chips. **RFID chips are powered and active, doing their job, at thousands of times less current than a cell phone or tablet in sleep mode[1]**. So an RFID reader is not just a reader, it also transmits RF radiation to supply power to the tags. This power transmitted by the reader varies dramatically depending on reader type (handheld readers often supply less power than fixed readers), country (countries use different power limits in order to manage interference between devices) and the environment (e.g. reader to tag distance and what lies in between). A range might be considered to be as low as ¼ Watt and as high as 4 Watts radiated power (at the reader antenna so much lower when received by the tag).

Second, the tag must receive and interpret a signal (containing a command or commands telling the tag what to do). This is actually piggy-backed on the same power signal provided to the tag by the reader. This signal is defined by the ISO 18000-6C protocol[2] adopted by the EPC Class 1 Generation 2 standard[3].

[1] UHF Passive RFID consumes 1-3 micro Amps vs a smart phone sleep mode 74 milli-Amps. See Table 4 here: http://www.scribd.com/doc/116401727/Power-Consumption-Analysis-of-a-Modern-Smartphone
[2] http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=59644
[3] http://www.gs1.org/gsmp/kc/epcglobal/uhfc1g2

The third and final function is for the tag to transmit information back to the reader. For this to happen, the tag modulates the signal received from the reader as defined by ISO-18000-6C and using back-scatter radiation[4], reflects a modulated version of the received signal back to the reader. There are two terms used to describe where a tag-reader combination is limited: *forward-link limited* (the tag is always able to backscatter sufficiently to the reader if it receives enough power on the forward-link to power the RFID chip) or *reverse-link limited* (the tag receives enough power to power the chip but insufficient capability to backscatter information back to the reader).

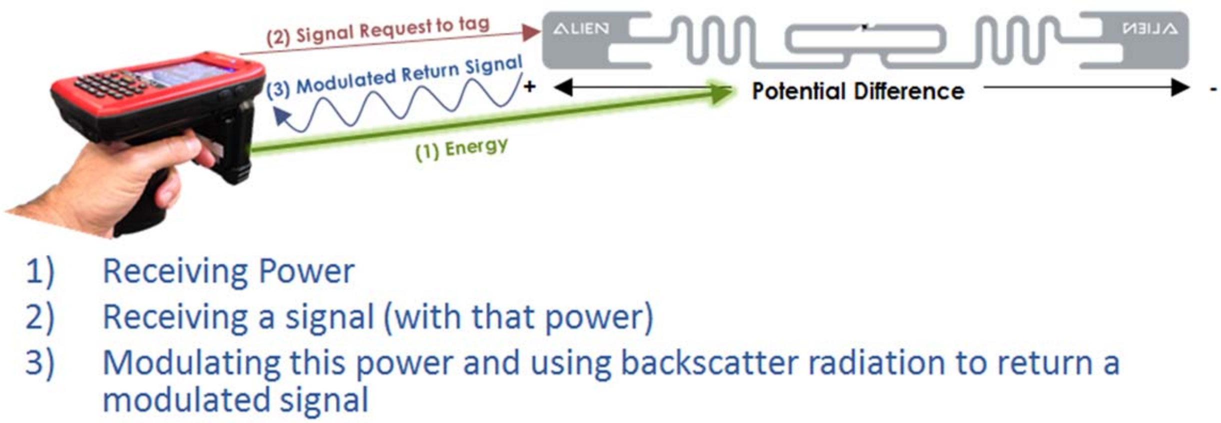

Figure 3 - Three Tag challenges

One of the many complexities is that these UHF passive RFID tags actually have 2 resonating elements to the design. As will be shown later, together, they are key components in providing sufficient bandwidth to the solution.

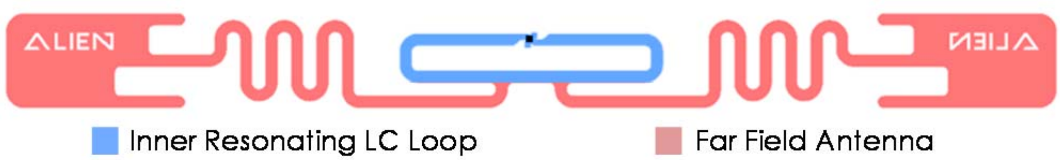

Figure 4 – The Two RFID Resonators Built into a Single UHF RFID Antenna

This is further complicated by the patchwork of worldwide UHF passive RFID frequencies[5] in use (all within regional ISM bands) and other restrictions within each region (and sometimes individual countries) such as maximum allowable transmitted power. As long as these limits are adhered to then the RFID solution (primarily the readers) do not need licenses (just as a WiFi router does not require a special license). The primary regions are:

- United States - 902-928MHz (4W EIRP FHSS)
- Europe - 865-870MHz (2W ERP ETSI)
- China 840-844MHz and 920 – 924MHz (2W ERP FHSS)
- Japan – Was 950-956MHz moving to 916-924MHz (4W EIRP LBT)

[4] http://www.eetimes.com/design/microwave-rf-design/4018929/RFID-Basics-Backscatter-Radio-Links-and-Link-Budgets
[5] http://www.gs1.org/docs/epcglobal/UHF_Regulations.pdf

Combining all regions into a single tag design is common today but as can be seen, this tag design has to span 840-956MHz, a very broad range indeed. The reality is no tag design can address all regions equally well. As a result, an understanding of where and how a tag will be used is important. Many tags do have to be used worldwide through a complete international supply chain. However, sometimes there is only one region where the tags are to be used that may exhibit a more challenging environment. For example, provisioning a tag in Asia during the manufacturing of the tagged item may be easier because the environment is well controlled and tag writes are done at low power close to the tag on a conveyer. However, when the tags are in use, the use-case may be much more problematic e.g. thousands of tags, packed on clothes on shelves on a retail show floor or warehouse in Europe.

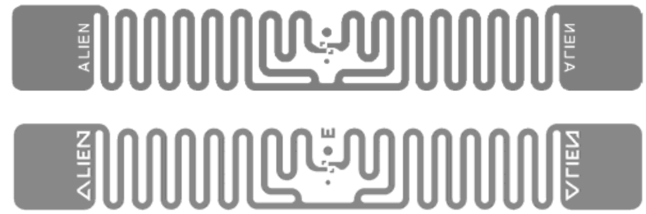

Figure 5 – Example of world tags with regional optimizations (North America, Japan. China focus world tag top; Europe focus world tag bottom)

Application Materials – What is the Tag Applied to and What is Between the Tag and the Reader?

The application the tag needs to operate in is probably one of the most discussed topics today but can still be problematic if not well understood. There are two major aspects here, the substance the RF signal will traverse and the material the tag is applied to. Both are absolutely critical.

The relationship between the reader (the readers antenna) and the tag is often dynamic but understanding what may be in between will dictate the amount (if any) of the RF signal will reach the tag. These materials can be divided into the following:

1. RF-Lucent (RF travels through easily): air, oils etc
2. RF-Opaque – Two types:
    - Conductive materials: Block or reflect energy e.g. metals/foils
    - Absorbing materials: water or high-water based objects e.g. wood and people.

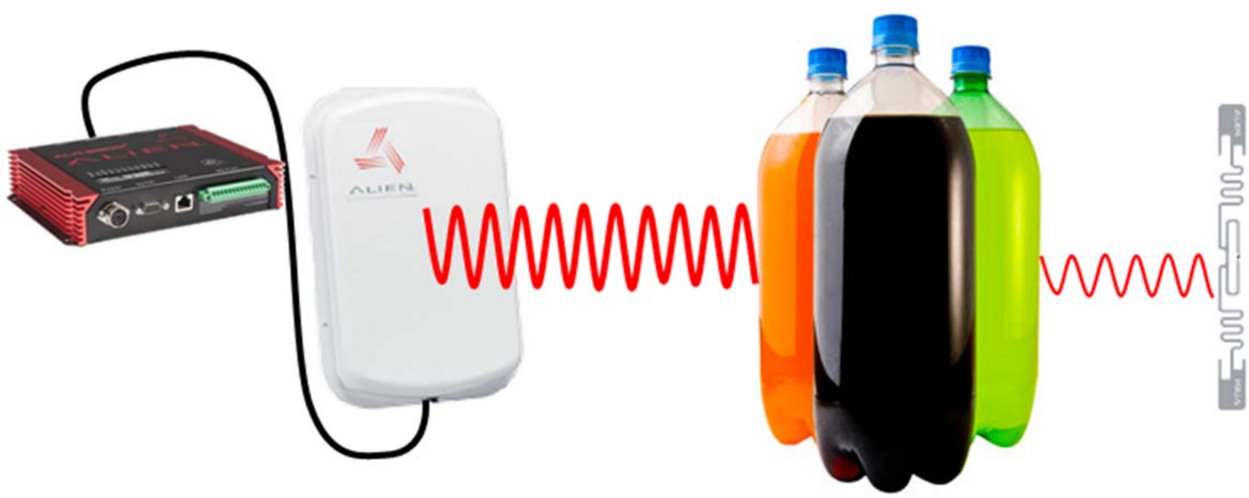

Figure 6 – What is Between the Reader and the Tag? Will it Absorb or Reflect RF Radiation?

Water based objects do a good job of absorbing RF radiation so should not be placed between reader and tag (try placing the reader antenna above the objects with the tags on top). Wood and paper will also absorb RF radiation based on the moisture content…so care needs to be taken. Interestingly, oils conduct RF radiation very well so while Baby Oil will not cause any problems, a bottle of Baby Shampoo will (it is mostly water).

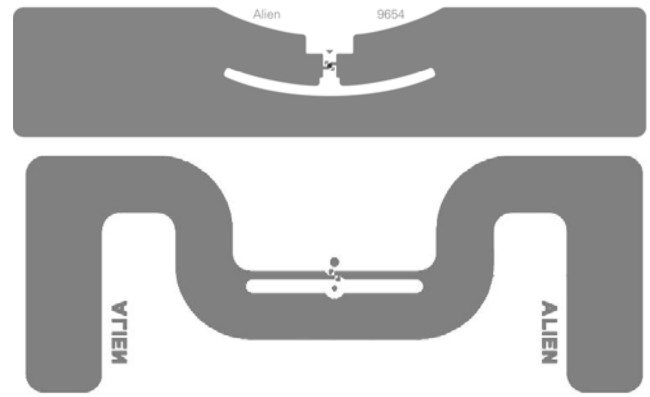

Figure 7 – Example Two High-Dielectric Tags (top, glass windshields, bottom high-density plastics containing metal and water e.g. automotive batteries or tires)

Tags can be applied directly onto many materials (with a few important exceptions). However, understanding the properties of this material is also important (e.g. dielectric properties; what else is inside the materials being tagged). If this is a plastic, how dense is it? A glass windshield; does it have metal as part of the tinting? If this is a plastic container, what is inside? Is there metallic foil inside (like a cigarette packet)? Engaging in a conversation directly with an educated tag supplier can help. Some companies provide more specialized tags for application with different materials.

One material that will always be troublesome is metal. Applying a UHF passive RFID tag directly to metal is akin to taking the tag, connecting both ends with a wire and then trying to create a potential difference across the antenna. Clearly this is impossible as the tag antenna is shorted out. It will never be powered up because of the lack of potential difference across it.

Figure 8 – Appling a Tag Directly to Metal is Akin to Shorting a Battery

To solve RFID being applied to metal, a small insulating material needs to be placed between the tag and the metal. This only needs to be enough to allow the tag to have the potential difference across the antenna such as a thin foam-like material. Foam backed RFID tags are often used in this application. In metal environments, make sure there aren't other metal objects between the antenna and the tag since metal acts like an RF mirror reflecting the RF radiation back to the reader before it is able to reach and power the tag. While dealing with metals is clearly challenging, these RF properties can also be used as a benefit. With a small standoff from the metal, the metal *behind* the tag, can reflect more energy into the tag thus enhancing the tag performance. So careful placement, tag choice and stand-off distance are important.

Turn-on-Threshold and Backscatter

Some of this discussion can be better understood by looking at some graphical representations of two of the main properties of the inlay and IC combination. The (relative) read sensitivity is defined by the ability of the chip to "turn on" or to be powered. We call this Turn-on-Threshold (ToT). The lower the turn-on threshold, the better, since the tag powers on when receiving less power. This describes the forward-link of the tag that we mentioned earlier. Next is the level of back-scatter radiation (denoted by "BS" below) the tag is able to reflect back. The higher this is, the better, since this shows how efficient the tag is at returning a strong modulated return signal to the reader. It should be noted that readers forward and reverse link capability are also critical in defining the overall behavior (reader read/write sensitivity). It is a system issue of which the tag is part.

The graph below shows these for a tag measured "in air" (not applied to any material). We also show the four frequencies of most interest to us (yellow vertical lines).

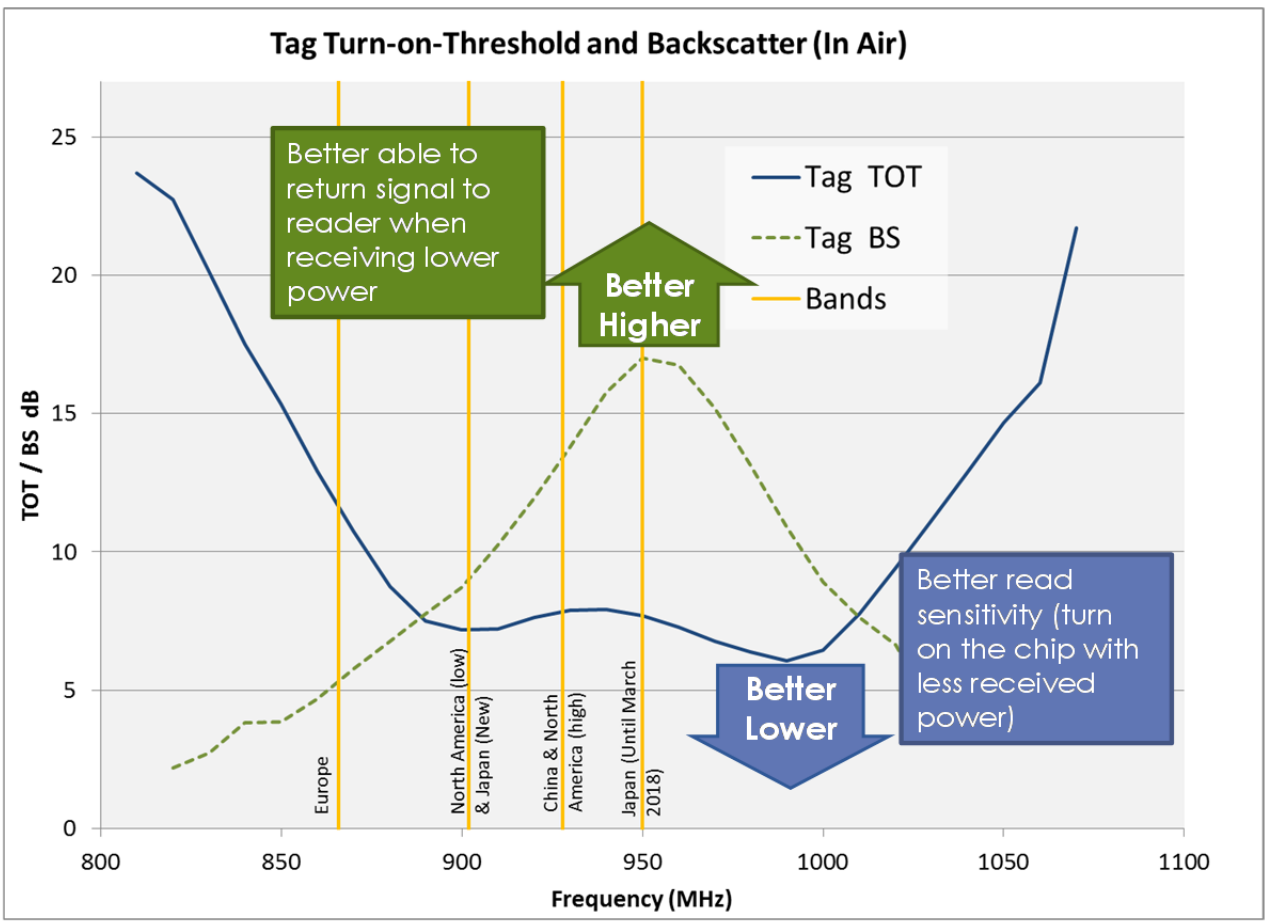

Figure 9 – Example UHF Passive RFID Tag ToT and BS When the Tag is Measured "in Air"

Note the following:

- There are two "troughs" or "upside-down peaks" to the turn-on-threshold (ToT). This is because the two resonating elements that coexist inside the RFID tag each have their own resonant frequency. The ToT is a complimentary combination of these two. This is important as it enables the tag to turn-on across a wide range of frequencies. This is how tag designers make a tag applicable to more than one region.
- The backscatter only has a single peak (as only one of the resonating elements provides the majority of the backscatter).
- The peak of the BS and the two troughs are not located in the center of the important frequencies shown in the graph. One of the ToT troughs is closer to 1GHz, way off from the low end 865MHz for Europe and even from the top of the North American bands at 928MHz and soon to be vacated 956MHz Japanese bands. This is deliberate in the design.

The experience of tag design comes into play in designing how close the ToT humps are, where the peaks and troughs are and most critically how and where these troughs move as the tag is applied to different substances. When the tag is applied to a material several things happen:

- Each ToT trough shifts left by *different amounts* depending on the material and how each of the two loops are designed;
- The two ToT troughs move down (relative to their "in air" values) and again they move at *different amounts* each dependent on their designs.
- The backscatter also shifts left (into the desired frequency) and also shrinks or expands dependent on the material the tag is applied to.

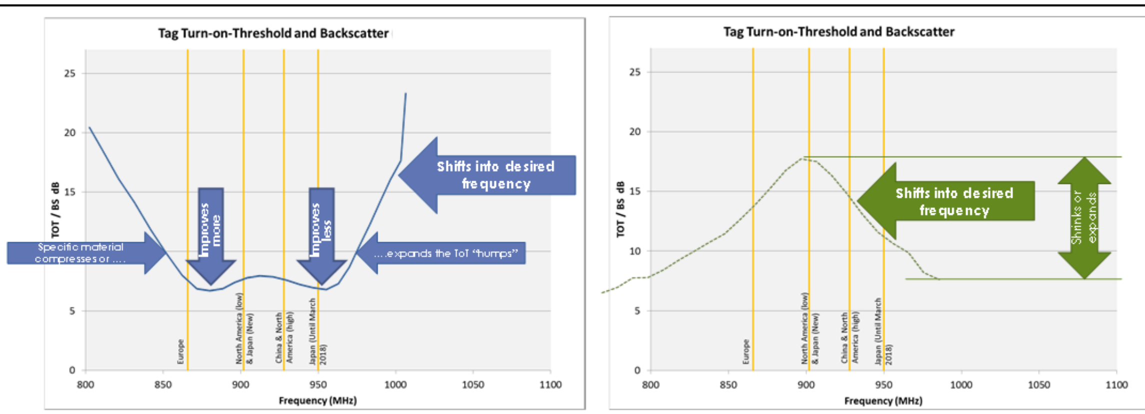

Figure 10 – The Shifting, Shrinking and Expanding of ToT and Backscatter When Tag is Applied to a Material

The net effect of these changes is shown in the graph below.

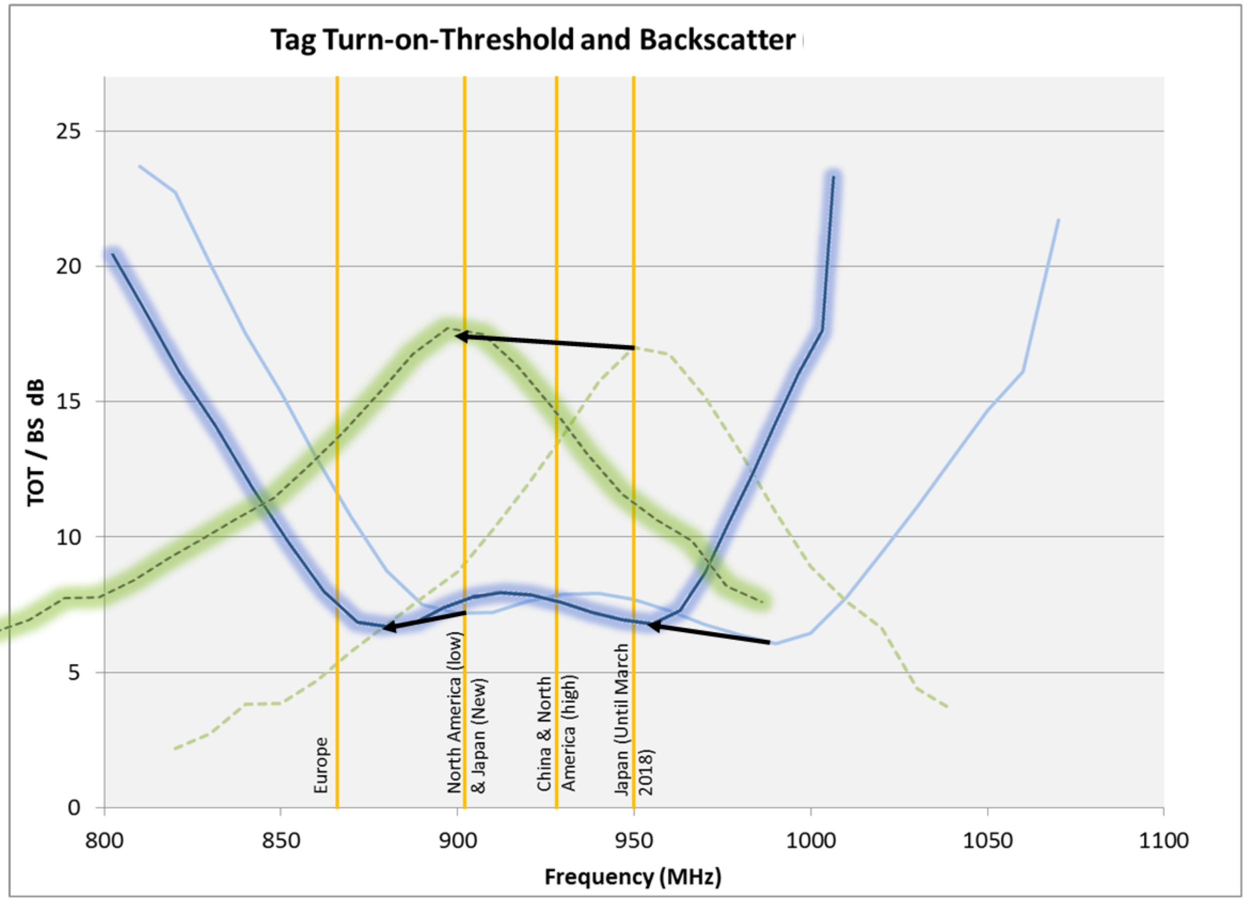

Figure 11 – Summary Showing the Overall Change of Tag ToT and BS When the Tag is Applied to Material

UHF Passive RFID Tag and IC Suppliers – What to Look Out For

A good tag designer can predict, model, simulate and design for these complex changes. The simulation tools need to be developed from the ground up and must take into account the complexities described here and many other subtle but important nuances. The best vendors are those that understand the subtle interactions between the RFID IC, the tags and the RFID reader itself. The best solutions will use this knowledge to build better tag designs that extract the best of that IC design and vice versa.

The whole design process is shown below and includes:

1) Initial simulation of the tag (both resonant elements)
2) Impedance matching the design to the specific properties of the selected RFID IC
3) Review the simulated radiation pattern
4) Review the simulated current distribution
5) Review the simulated Turn-on-Threshold and back-scatter charts (similar to above)
6) Build a prototype antenna sheet of bare aluminum antenna and hand mount the IC on 10 or 20 samples
7) Capture the performance of the prototype and re-plot on the same ToT/BS charts to confirm performance is as simulated (and if not, identify what needs to change).

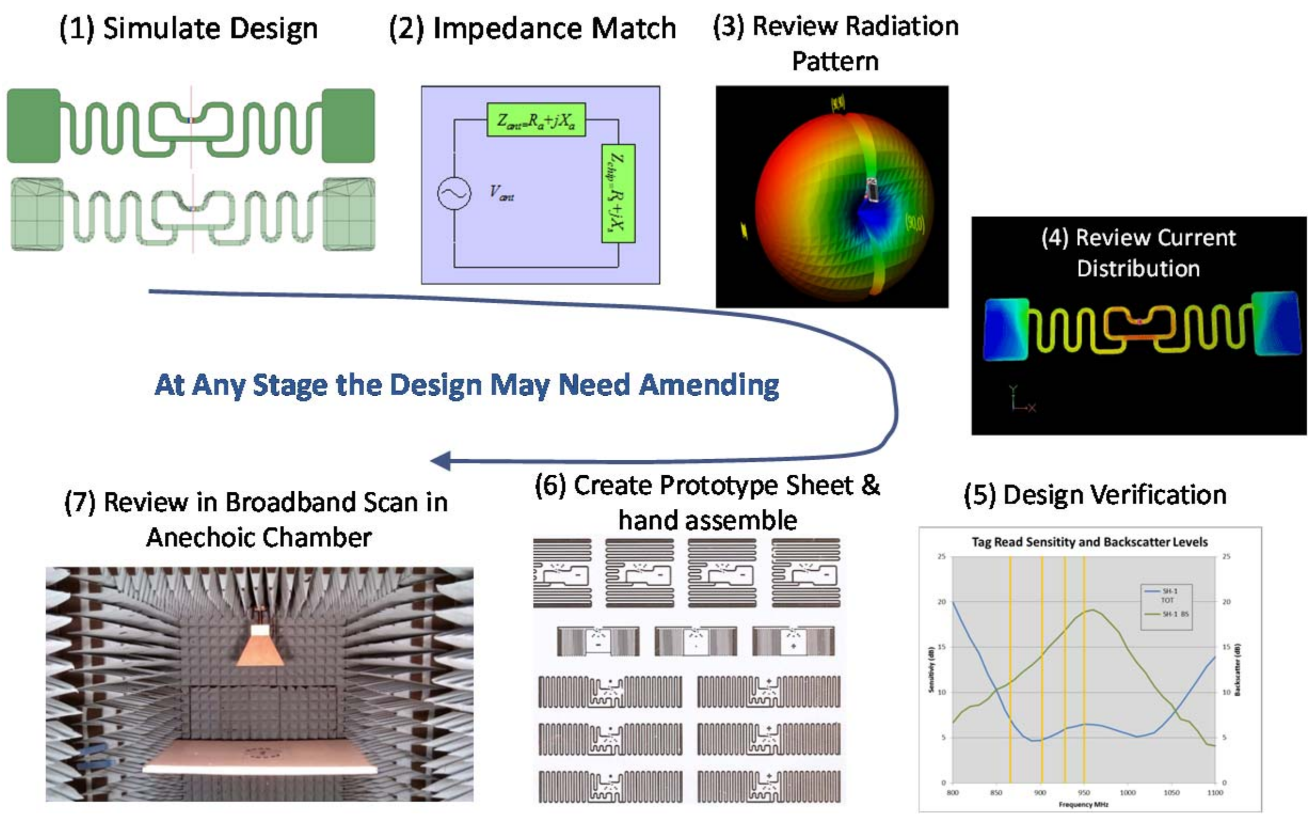

Figure 12 – Tag Antenna Design Process

The tag material and build quality is also important. A small misplacement of the IC onto the antenna can cause the overlap impedance to change dramatically and the tag behavior will “shift” and behave different to the target design. Also, if the antenna is damaged during manufacturing a similar result may manifest itself. A tag not working is bad but what if one of these problems stops the tags from being programmed properly? The wrong EPC number could be worse than a non-functional tag (a green T-shirt is read as a blue dress)! Just a few poorly manufactured tags can result in a large disturbance in a stressed supply chain (especially if this happens to a number of tags in a sequence that are applied to multiple product SKU’s).

Size Does Matter

The final aspect to consider is perhaps one that seems more intuitive. The larger the antenna, the better the antenna is at receiving a signal and power from the reader and the stronger the returned back-scatter signal will be back to the reader. The most important dimension is the dipole length that is usually (but not always) the horizontal dimension of the tag. As a general rule, if you can fit a larger dipole, you would normally see better performance (dependent on all the above mentioned factors such as material the tag is attached to etc.). So reviewing a variety of tags is useful.

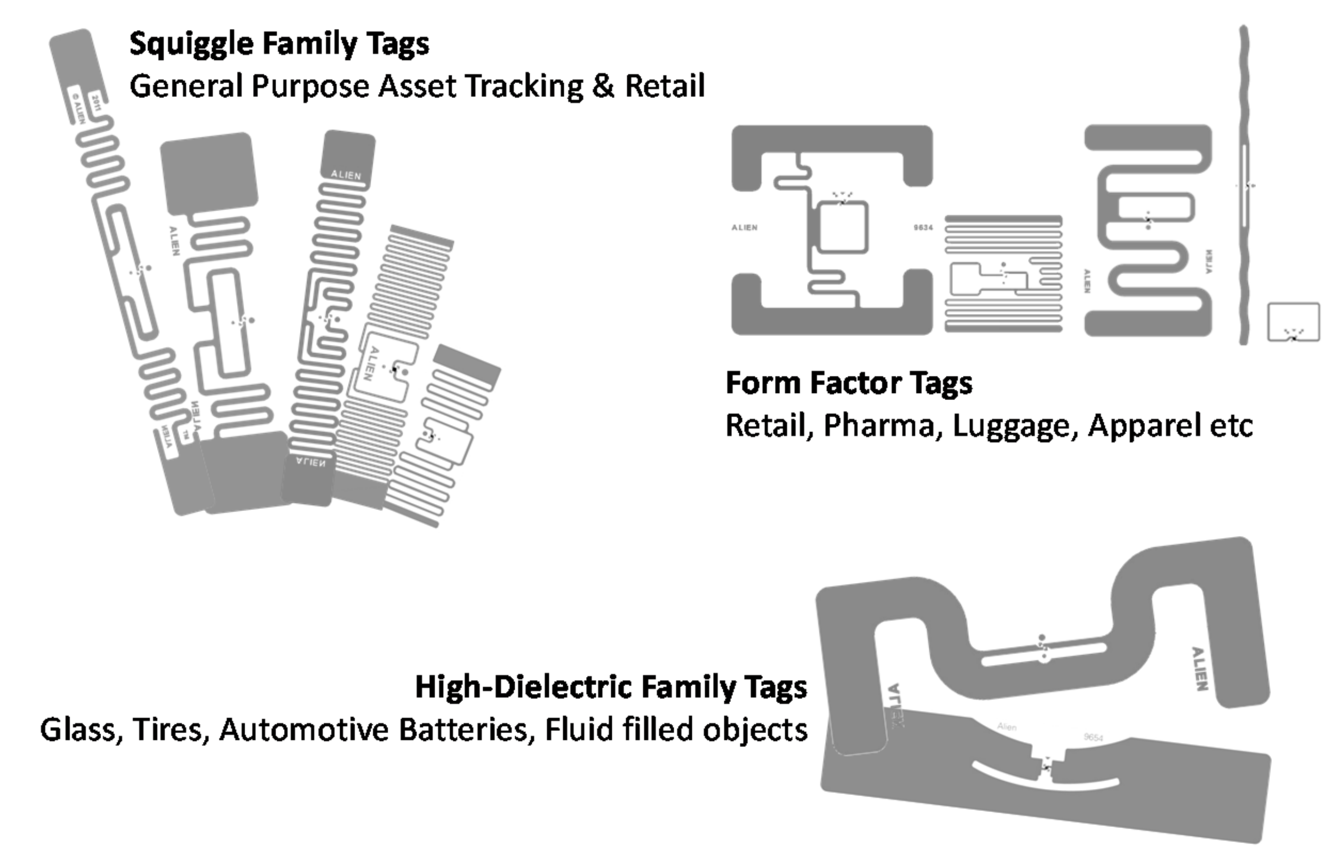

Figure 13 – Alien Technology Tag Portfolio – Tags for Most Applications, Form-factors and Use Cases

Conclusions

Tag design is a complex process involving complex trade-offs between elements including but not limited to:

- Forward-link vs backscatter
- Operating frequencies (for forward and reverse links)
- Substance to be tagged and the environment this tagging is taking place in
- Size vs performance
- Tag design vendor (IC vs tag interaction knowledge)
- UHF Passive IC type/supplier
- Tag quality (design and materials)

“Tag Design is like squeezing a balloon! You optimize for one aspect to the detriment of another”

No application is completely the same as another. While many times a general purpose world-wide tag will work sufficiently well, that should not be assumed and work should be done to understand the application, the usage model and the environment in which the tag will be used. The tag designer and tag supplier should be part of the evaluation since just a small amount of poor quality tags can create a large issue for an expensive supply chain. If in doubt, work with a company that can advise you on what will work best in your specific circumstances. Most ideal is a company that manufacturers UHF Passive RFID chips, tags and readers and can actually do a site survey for you or assist with your own.

Figure 14 – Optimal Tag Design – The Art of Applying The Science

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