Passive Radio Frequency Identification (RFID) – A Primer for New RF Regulations

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The following text is submitted with the intention of highlighting some RFID issues (in general) with respect to current and proposed regulatory environments. Although it is submitted from Matrics, a specific RFID vendor, the materials contained within address general RFID and regulatory architectures, not a specific product. The following text is a general education and a start to discussion points, and we welcome continued evaluation of details and further education on intricacies of the world of RFID.

What is Passive RFID?

Passive RFID refers to an RFID tag. Tags that are passive in nature obtain operational power from an active RF field emitted by a corresponding RFID interrogator (reader). This is most unlike typical devices that only communicate via RF and are actively powered by any number of methods including batteries, utility power, solar, etc. While a good amount of RF energy could be in an RF field – the realistic applications involve human interaction, and for safety reasons, limit the amount of energy a reader can emit. Although these limits vary worldwide and at different frequencies, current passive RFID systems are functional anywhere from about 1-10 meters. Tag operational power requirements can go as low as 200 microwatts absorbed from the RF field.

Since there is not enough field power to operate a traditional RF transmission, passive RFID tags communicate back to the reader with a technique called 'backscatter'. In effect, what the tag does is alter the impedance of the antenna match so that more or less energy is reflected. The reader's job then is to detect this change in reflected signal. Several schemes are used to encode digital information from the tag to the reader (baseband signaling is the most common), but all are based upon the backscatter technique.

Passive RFID Applications

Passive RFID tags enable many applications. Traditional RF communications devices are three-dimensional in nature due to component such as the power source. Passive RFID tags, comprising only an antenna (typically printed) and one very small ASIC can now be made into paper thin devices such as a 'smart' label, embedded into credit cards, and so on. Heights of passive RFID tags can be as low as a few hundred microns. New applications are enabled and created seemingly daily as this new technology evolves and market education takes place. As well as the low profile capabilities, even more attractive is the long life characteristic of a passive tag. Since these tags do not require limited duration batteries to operate, theoretical life span is virtually forever.

How Does RF Field Power Impact Passive RFID?

Passive RFID tags derive all of their operating power from the energy of the RF field as absorbed by their antennae. This field is generated by another antenna connected to the RFID reader. Simple physics shows that field power decreases in proportion to the distance located from the (reader) antenna. In implementation – the farther the tag is away from the reader, the less power it has available in the RF field. Operational distances very much impact (or enable) many RFID applications. Hence, regulated power levels directly affect operational distance and indirectly enable (or prohibit) certain applications as a result.

While substantial improvements have been made in the last decade, minimal operating power required by RFID tags has only recently fallen into the range of about .5 to 1 milliwatt region. This, in a typical US FCC Part 15 application (4 watts EIRP @ UHF), will yield an operational range of about 5-10 meters for UHF products, and around 1 meter for 13.56MHz and 2.4GHz ranges. In stark contrast is the current European regulations limiting field power in the 800 milliwatt EIRP region (also UHF), at approximately 1/5th the power available in the US, which shortens the operational range to the 1-3 meters range.

How Does Available Bandwidth Affect Passive RFID?

This is certainly the most complex of relationships to understand for regulatory impact upon the passive RFID products and applications. The basics, however, are simply stated – all passive RFID tag designs must facilitate the lowest powering scenario possible in order to provide the market with sufficient product performance to meet application demands. Understanding the many inter-related concepts are discussed in detail to include: modulation technique used, the bandwidth occupied by such techniques, the impact on RFID devices as well as other in-band devices, and finally, the impact of restrictions on certain types of applications.

Modulation Technique of Choice

The most popular choice of modulation techniques used across many frequency bands is amplitude modulation keying, or in a digital sense – pulse width modulated signaling. While this ancient technology has been superceded by many advancements, all of these newer models require a substantial circuit to be powered. These alternate designs are not yet possible to implement in the single or sub-microwatt region as required to maintain the tags' operational range for the market, with few exceptions and only in the lower frequency bands. Very simple circuits are designed in most all currently available products (tags) with extremely low power consumption to decode pulse width signaling. The unfortunate side effect of this style of modulation is two-fold: 1) that bandwidth usage is relatively high, and 2) data throughput (per Hz) is relatively low. These two issues remain to battle against each other – regulators desire nicely defined bands (sharp edges) which would typically limit a baseband frequency (data rate) used for modulation – or imply a more complex encode / decode design, while the applications desire faster tag read rates which imply wider bandwidth usage through higher data rates.

Bandwidth Usage

While there are many protocols in use to facilitate communications from readers to tags, and vice versa, baseband modulation in the UHF range seems to have been consistently situated at 10-80 kbps (10-80 kHz fundamental). Presuming all tags are designed with timing circuits, this exemplifies an effective operational data speed range of a product. Many products have encoded only two data speeds possible, while others may operate on many more levels. In the end, however, it is unlikely to find products outside this range of operation – as the result would be an inoperable product within any application. A quick review of general communications reveals a typical bit rate in the 16-80 kbps, and a 'tag read' number of bits in the order of 100-200 bits. A quick calculation reinforces an industry tag read rate in the range of 50-800 tags per second. This is the anticipated range for worldwide operations. The lower end is even a questionable practice for some applications – such as a dock door application reading a pallet of 200 tags in one second (remember – tags must be in very close proximity to be activated). The dock door example, working backwards, would yield the following results:

- 200 tags per second requirement, min.
- 100 bits per tag, min.
- Effective throughput = 20,000 bits per second, min.
- 20kbps = 40kHz, baseband requirement (typ bit '0' = min. width, bit '1' = 2x width = overall 2x factor on bits/Hz.
- 40kHz standard modulation (dual side bands) = 80 kHz fundamental bandwidth
- 3rd harmonic is necessary for a 'clean' signal to decode = 240 kHz (plus tolerances) channel requirement.

This would be representative of the standard practice in present RFID products in the UHF range (data rates in other ranges are similar). While some bandwidth can be removed by some exotic reader designs, these are not popular in production due to increased costs. These improved readers may result in about a 30-40% bandwidth savings in best cases.

From this example, it is easy to deduce that reducing bandwidth by a factor of 10 (25 kHz) would not be supported by the industry, as these would not fulfill most application demands. Thus, you will not find this kind of product design available even in a test case.

Modulation Depth and Channel Width Definitions

Some improvements can be made in overall bandwidth usage outside the fundamental frequencies that are required for standard applications. These improvements are easiest to make in the modulation depth emitted by the reader. While there may be many reasons for the need to limit emissions quickly outside the defined channel (discussed in the next section), limiting the modulation depth (also referred to as dip-depth) is a very effective way of reducing power outside the channel. While this is desirous by most, there are limits again imposed by the requirement to keep the decode method on the tag very low power (which implies simplicity).

Again – keeping in mind that there is a very simple design to the decoding of data on the RFID tag, some reasonable accommodations can be made into the 50-30% (reduction from CW) model for modulation depth. While 10% or even less would result in a better channel definition (cleaner / narrower), this would negatively impact the design in two ways. First, and most important, very shallow modulation is more impacted by general background noise and yields a less robust system that ultimately results in retried communications and slower system performance. Secondly, and less obvious, is that the demodulator design must accommodate a relatively large ripple as high harmonics from demodulation are required to be filtered out from the reader transmissions in order to keep the emissions low outside the channel. Use of a very shallow modulation from the reader can be dangerously close to the levels exhibited by the ripple. This will yield to improper demodulation of the data from the carrier – to the point where data can no longer be decoded.

Tag Response

There is much debate on this particular topic. Keeping in mind that the tag response is a modification of the reflection of the signal it receives (backscatter), there is not much power available to communicate back to the reader. With respect to the signal emitted by the reader, the backscatter response is much closer to the noise floor than the peak reader emissions. Different methods of encoding data are used by a variety of manufacturers, but basically all can be discussed in two types – in-band, and out of band.

In-band responses offer a very discrete channel of operation, which seems on the surface a clean design. However, many issues surround this method making RFID systems difficult to design in general. One large issue is that the reader must emit a very pure tone for a relatively long time so that the tag response(s) can be decoded. The reader, when sending data, is occupying the same frequencies as the tag responses. Unlike typical methods where transmission stops when changing from Tx mode to Rx mode, passive RFID readers must continue to transmit carrier to power the passive tags. Most tag backscatter is relatively low in frequency, and this forces the reader carrier to be extremely clean so as not to interfere with the tag responses. Another issue for design on in-band tag responses is that there must be some wasted time in switching from reader transmit to tag transmit modes, and back again. This time directly and negatively impacts system performance. Lastly, in attempting to keep the tag response in-band, the data bandwidth must be kept at approximately the same rate as the reader data rate – relatively slow, and it is typically implemented in a digital baseband type encoding (one cycle decode), which is less noise robust than other methods. Frequently, however, there will be products that implement a much higher data rate from the tag to the reader while staying in regulation. This is not as a result that the tag backscatter is 'in channel', but that the tag emissions are not substantial enough to produce prohibited power levels outside the reader channel. These systems are typically more robust as they frequently encode multiple signals to produce a bit – placing a better opportunity for decoding the signal.

Out of band tag responses have many benefits – such as the previous paragraph seems to suggest. Multiple duplicate signals encoded produce a better chance of a proper decode – Manchester encoding is an excellent example. Even more robust, though, is a particular frequency repeated in the 10's, even 20's of time. This gives a solid 'tone' onto which the reader can lock. 'Tones' can be easily and very discretely decoded while ignoring frequencies both lower and higher – net effect is much more rejection of interfering signals known not to be the desired tag transmissions. The trade-off, though, is obviously time (10x-20x lengthened time frame). Increasing the frequency of the response shows many improvements in overall system design, while keeping in mind that these emissions by the tag are very low in power. High frequencies allow the reader to receive at the same time it is transmitting -- since it's signature out of band is required to be very low by regulation, tag energy in higher frequencies become larger than reader emissions that can be substantially filtered. This full duplex signaling eliminates time spent changing from reader Tx to tag Tx and back. The signal also allows for a less expensive reader transmitter since inherent noise can exist in the channel as it does not impact the receiver channel from the tag backscatter. For the same reasons, a reader can be built to receive tag backscatter from a longer distance as compared to some real technology limits of in-band signaling and reader receiver technology.

As it turns out, in-band signaling for backscatter responses offers some large hurdles for reader designs that are not much of a problem for out of band designs. Out of band designs do have to take into account the effect of signals within the target backscatter receiver band, and also the interference of RFID systems into other systems operating in the chosen frequencies. It can easily be shown that RFID readers themselves emit a majority of the radiation that would interfere with their own receiver circuits. Thus placing signals to be received by an RFID reader outside the band in a majority of the cases is a much better condition.

The latter is of concern to regulators, however, the signal strengths need to be discussed as a primary factor over the actual frequency of operation. Signal strengths of these out of band signals from backscatter devices are confined to the realism that a number of conditions limit the power of backscatter:

- The tag cannot reflect 100% of the power received by the reader – backscatter is created by detuning the antenna and this in actuality can only achieve in the 10's of percentages of variance. The smaller the change the better, as tags require as much power absorbed as possible to maintain operational power.
- Tags are most likely to be located away from the reader antenna by several meters. Reflections from the tag in the first few feet are the only considerably powered out of band signals that could be generated.
- Passive tags are quite small circuits, without the ability to regulate power via resistance / heat dissipation design. Instead, the tags will detune the antenna so as not to absorb the excess power. This substantially inhibits the tag's ability to generate large variances of detuning and backscatter power under substantial power conditions (close to the reader).

- Backscatter is not a generated precise tone; in real designs it is a sub-modulation of a reflected signal, and more closely resembles a square wave control signal than a pure tone sine wave. Energy is evenly divided into the higher and lower frequencies by nature. The square wave effect further spreads energy out into even higher offset frequencies, but at extremely low levels as opposed to the than confining a majority of energy into a particular frequency.

In reasonable designs, backscatter energy is typically 40-60dB less (a minimum) than an RFID reader's output, and is most likely to be in the range of 'spurious emissions' than an offending signal. In fact, it is entirely likely that a rapidly rotating fan blade produces the same level of reflected signal out of a band as compared to a passive RFID tag. The US regulations (FCC) qualifies a passive radiator as an 'unintentional' radiator as they have investigated the emissions in general to be so trivial. The US / FCC maintains the position of not requiring any tests of emissions with RFID tags as it is not relevant.

If the backscatter is to be considered in a systematic approach, issues such as distance from reader to tag, and both reader and tag from test equipment receiving antennae must be specified in a test. Additionally, power levels of the reader and of the tag must be specified. And, since tag backscatter produces energy across many frequencies (a result of a more square wave than sine wave modulation), ALL tag types, both in-band and out of band, must conform to these levels.

All things considered, evaluating passive tag backscatter seems much more trouble than it is worth, further supporting the US / FCC viewpoint on the subject and also our recommendation.

Duty Cycle

Duty cycle is, at its essence, a means to control access to a medium in an effort to assure all devices have an equal chance (high probability for success) for access to a particular frequency for operations. While imposing duty cycle seems a good, simple design, it rarely is – just the opposite. The issue must be understood in more detail. Equal but restricted access to a medium assumes that: 1) competing devices can't 'play nice', and 2) there are more devices competing for bandwidth than there is bandwidth available. Again, to understand a good solution is to study the US / FCC model.

The FCC has chosen a frequency hopping approach. In design, transmitters must not consume a frequency for more than a short time (less than ½ second). However, at the end of this time period, they are not required to turn off (such is the case with duty cycle), but are required to hop to another random frequency. The end effect is that this method assures most efficiency with one AND many transmitters. With one transmitter, it is allowed to consume 100% utilization until its task is done (though it must do this over many frequencies). With many transmitters, the 'load' of collective bandwidth and waiting times is spread fairly evenly across all devices. In this case (many transmitters), it is likely that a transmitter, when forced to move to another frequency, finds this frequency used (let's assume all are used.) It must wait and retry until it can find an available frequency unused. Since the frequencies are picked at random, access becomes a matter in statistical averaging – assuring a relatively equal spread of usage and wait times among all transmitters in contention within the full band. To further assure good performance in all, the FCC has selected an overall bandwidth (at UHF) of 25 MHz, and typically (for RFID) 50 channels.

It is realized, however, that 25MHz may not be available in all regions. Certainly, the FCC model does not work with one frequency. There is most likely a method to determine where exactly the FCC model breaks with respect to the number of channels available. It highly depends upon the expected number of contending transmitters over the full frequency band – so it is a relative calculation. Still, with even very few channels (such as 4-6), the model works very well and is HIGHLY recommended in lieu of the duty cycle model. For comparative purposes, the impact of a duty cycle mode should also be understood.

Duty cycle restrictions, while somewhat simple in design, often remove the chance for best efficiency in usage. Duty cycle (traditional) designs impose a certain percentage of 'on' time vs. 'off' time. In ALL conditions, 'off' time may mean missed events and an unreliable system under certain applications. For example, take a 10% duty cycle over a one second interval. An RFID system could read tags for 0.1 second, and then it is to be dormant for 0.9 seconds. Two issues arise as follows (either or BOTH):

- A limited number of tags are read in the 0.1 second available. With RFID (low data rates discussed previously), this is likely to be less than a full population of tags. If this tag population is in motion, the remaining unread tags may very well be missed as they may be out of range in a 0.9 second time period of 'off'.
- Even with few tags in a population (or even one) – in some rapid transit (toll tag) applications – this leaves a large window of opportunity to miss reading the tag(s). It does not allow for a robust application, and may impose a condition like slowing a vehicle substantially so that a read is guaranteed. Further

exacerbating the situation, many RFID systems are configured to read a tag multiple times to ensure reliability with the tag collection process. This could extend a window of time into the multiple seconds whereby a vehicle is required to be within a small range (10-20 feet). This is relatively slow compared to normal driving speeds.

On another extreme, some duty cycle designs show a relatively long period of time, such as a one hour time period. Easily stated, this would theoretically allow a transmitter to occupy a frequency for even minutes of time (6 minutes is 10% on an hour). ANY other device being blocked for more than a few seconds poses reliability issues in any real time system such as RFID. Obviously, the longer time period is just not an acceptable solution.

Evaluating shorter time periods can be a long process with many impacting factors, but in all cases, a percentage of time is required by a transmitter to be inactive – even if in a small number or one transmitter environment. This does not utilize the full capability of the frequency band and is certainly not optimal in any environment but a very specific number of transmitters, which is unlikely to be a majority of actual installed applications.

So, as you can see a simple duty cycle restriction may be the easiest to specify, but certainly not the most flexible or most efficient use of bandwidth. Interestingly enough, efficiency of usage needs to be best, not sub-optimal, when dealing with a limited overall frequency band / small number of channels.

For these reasons, duty cycle designs should be avoided whenever possible, in favor of a more flexible design such as exhibited in the US / FCC designs for bandwidth contention.

Note

This document is meant as a discussions point for emerging regulations. There are some, but little details of RFID drawn out, and with no specific relevance to one vendor’s product. Matrics welcomes further discussions on both more details of Matrics products, and details in UHF RFID products across many vendors.

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