Radio Frequency Identification (RFID) Power Budgets for Packaging Applications

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Executive Summary

A radio link budget for a packaging radio frequency identification (RFID) application is demonstrated. The power requirements to obtain a read, and the calculation of read range are discussed. The regulations limiting RF emitted power and UHF bands for North America, Europe, and Japan are covered. The detrimental radio effects of various commonly used materials are applied to a radio link budget. The benefit of using battery-assisted passive tags is demonstrated and shown to be an effective solution in some applications.

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Introduction

Radio frequency identification (RFID) has become a topic of great interest in the past few years. An increasing number of corporations are focusing on optimizing their supply chain efficiencies, and RFID is seen to have benefits. The application that has been driven by Wal-Mart, the Department of Defense, and a few other RFID drivers is case and pallet load tagging for internal distribution [1]. Wal-Mart mandated that their top 100 suppliers comply with case and pallet level tagging (915 MHz) by January '05 [2]. This mandate has greatly accelerated adoption and development of new RFID technology. The vast majority of Wal-Mart's top 100 suppliers are merely meeting the mandate, and not benefiting internally from RFID use. However, they are buying tags, and reader/writers and other RFID technology for their packaging lines and distribution centers [3]. Through the more widespread use of RFID, a large amount of the hype and exaggerated promises are starting to fade away, giving more publicity to actual real world application issues that complicate usage [4]. The limiting factors affecting RFID performance are obstacles/interference that inhibit power from reaching a passive tag.

An Overview of RFID

An RFID system consists of a reader or interrogator, and a tag/transponder [5]. The reader is a device that transmits a radio signal using a single or multiple antenna system and receives the data captured from a RFID tag. The received data is then sent to a personal computer (PC) for analysis and identification. A RFID tag can be of many shapes and forms. In most cases, the RFID tag consists of an antenna and an attached integrated circuit (IC), affixed to a substrate. In order for a passive RFID tag to communicate with an antenna/reader system, it must use a form of electromagnetic coupling. In the case of Ultra-High Frequency (UHF) tags, far-field backscatter coupling is used for communication.

Communication can be established between a passive RFID tag and reader in two ways. The first is a phenomenon called inductive coupling. Inductive coupling operates in the near field, and the electromagnetic energy induces a current in the tag antenna, charging the IC and completing the circuit to communicate with the reader.

Inductive coupling only functions at a useful distance for LF (125 kHz) and HF (13.56 MHz) bands [6]. The second method for communication is modulated backscatter coupling. Backscatter operates at UHF (>100 MHz) and higher frequency bands. Backscatter functions using far-field electromagnetic waves [7]. When the tag is introduced to the read field, the tag antenna gathers enough power to activate, and returns what can be considered an echo. This echo communicates the data contained in the tag's on-board memory using signal modulation, and enough power to be recognized by the reader antenna [8]. This paper will mainly focus on the environmental affects on power link budgets for UHF (915 MHz) passive tags.

RFID Read Requirements

There are two conditions that must be fulfilled for a reader to communicate with a RFID tag. 1) The tag must be activated by sufficient power, and 2) the signal that is reflected by the tag must be strong enough to be successfully detected by the reader [9]. At the first glance, these requirements seem simple to fulfill. There are many factors that are a detriment to RFID tag readability, especially in the packaging and distribution environment. Tagging shipped goods for tracking through distribution is becoming a more common practice [6]. In the years leading up to the Wal-Mart mandate, RFID was the subject of much hype and speculation. Many people in the industry had a vision of RFID changing the face of distribution and the retail supply chain overnight [4]. The hype has begun to die down now that more people have seen first hand the many factors that degrade RFID performance.

Regulations

Governments regulate the amount of power that can be radiated by RF devices, which limits the power given to the tag, therefore limiting readability. Japan currently is proposing to limit RF power in the UHF (950 MHz) band to 4W effective isotropic radiated power (EIRP) [10]. Europe has more crowded electromagnetic frequency band use, and therefore has more constraining regulations in place [11]. As shown in the table below, the power that a reader in North America can emit (4W EIRP) is 8 times greater than the power allowed in Europe (500 mW EIRP) [12].

Table 1:

Geography	UHF Frequency Allocation (MHz)	Total Power	Power Limit
North America	902 – 928	1 W	4 W EIRP
Europe	868 – 870	125 mW	500 mW EIRP
Japan	952 – 954	1 W	4 W EIRP

Data Compiled from [11, 12, 13]

Tag Power Requirements

The tag read range is limited solely by power restrictions and obstacles placed on the system. A tag typically requires about 100 μW (-10 dB) of power to communicate. When a typical radio link budget is examined, the maximum theoretical read range of a passive UHF tag is around 5.8 m (19.4 ft) [14]. This distance is derived from the Friis Equation:

$$R \leq \frac{\lambda}{4\pi} \sqrt{\frac{EIRP_{reader} G_{tag}}{P_{tag}}}$$

- R is read range
- P_{tag} is power required at tag antenna
- G_{tag} is tag antenna gain
- λ is the wavelength of the frequency in use

[11]

A nearly 6 m (19.7 ft) read range does sound rather attractive, however; even 3 m (10 ft) proves to be an optimistic read range in most radio link budgets. According to one study, at 3 m (10 ft), after taking into account losses attributed to distance, after the tag is powered, only a 7dB margin remains [15]. “This 7dB margin is not adequate for real world situations,” [15]. Real world situations prove to be challenging because many commonly used packaging materials and products cause communication power losses.

Material Obstacles for UHF (915 MHz) RFID

In addition to the effects of proximity, many other factors greatly diminish RFID tag readability. Many materials commonly used in packaging can cause RF shielding, reflection, cancellation, and dampening [7, 14, 16]. “As the electromagnetic field propagates through various materials, the dielectric loss and conductive losses in the material attenuate the field of the reader as well as the response signal of the tag,” [16]. These losses become of great concern in a pallet load of tagged items where tags are hidden, and must be read through a variety of different materials [16].

In a study performed by Dan Dobkin and Steven Weigand, it is shown that passive UHF tags within 1-2 mm (0.04-0.08 in) of metal have a read range of nearly 0. However, when tags were placed within 1 cm (0.4 in) of metal, performance was improved, but still degraded. It was found in their research that metal causes a change in the tag antenna impedance, which caused detuning of the return signal, making the tags unreadable in close proximity. However, this data was gathered using commercially available tags, and they found that the Alien Technology’s M-Tag was not nearly as effected as the I-Tag, which shows the benefit of tag antenna design to reduce impedance change in proximity to metals [17].

Further studies have been performed to show the detriments of various materials on RFID performance. In experimentation done at the Georgia Institute of Technology, a “radio assay” was performed using materials common to the real world environment in which RFID is expected to operate [7]. Using a formula based on the Friis equation, two formulas are proposed in which the first formula calculates the power that the tag will receive, and the second formula calculates the amount of power that is backscattered from the tag. For the quantitative analysis of radio effects based on differing material properties, a penalty value has been assessed for various materials, and integrated into the formula. The penalty values that are attained are for the material that the tag is attached to. By performing the assay, an “Average Gain Penalty” has been calculated for corrugated board, acrylic, wood, water, ethylene glycol, beef and metal [7].

Table 2:

Average Gain Penalties for Various Common Materials

	Corrugated Board	Acrylic	Wood	Water	Ethylene Glycol	Beef	Metal
Average Gain Penalty (dB)	0.9	1.1	4.7	5.7	7.4	7.4	9.4

[7]

When looking back at the typical radio power budget for 3m (10ft), the 7dB margin starts to look rather small when subtracting the penalty for each instance of these common materials. These gain penalty values only show one side of the communication budget; the penalty is doubled for the return signal from the tag as well [7]. However, according to Intelleflex, “the margin for reverse link (from tag to reader) is very large, at +61 dB” [15]. Therefore, the weakest link in the communication is the power necessary to activate the tag, not the strength of the returning signal.

Polarization

Another obstacle that must be overcome in an RFID system is antenna orientation and polarization matching for both the reader and the tag. In most cases, the orientation of the reader antenna(s) and tag antenna(s) cannot be precisely matched, causing loss in transmitted power. This can lead to unpredictable read range even in environments that are free of material and radio interference. However, using circular polarization in the reader antenna can minimize this problem of orientation. A circular antenna uses “2 dipoles that are fitted in the form of a cross, 90 degrees apart,” [9]. This polarization reduces the effect of unpredictable tag orientation, however comes at a cost of 3 dB in antenna power loss [9]. Antenna polarization can cause power loss in the link budget, and its effects must be understood in a successful RFID environment.

Typical Power link budgets for a packaging/supply chain RFID application

The data in tables 3-6 was determined by experimentation referenced from an article published by the Intelleflex Corporation. However, in tables 4-6, power link budgets have been compiled illustrating the loss due to the presence of typical packaging and product related materials. The data has been combined to show the benefits of battery-assisted UHF tags in a lossy environment; that is having or involving the dissipation of electrical or electromagnetic energy.

Table 3:

Passive and Active UHF tag power budgets at 3 m (10 ft)

Budget Component			
Forward Link (Reader to Tag)			
	Passive Tag	Battery-Assisted	Units
Reader RF output Power (US)	+30	+30	dBm
Modulation correction	0	-3	dB
Reader Antenna Gain	+6	+6	dBi
Path loss at 3m	-41	-41	dB
Tag antenna gain	+2	+2	dBi
Received power at tag	-3	-6	dBm
Power to activate tag	-10	-42	dBm
Margin at forward link	+7	+36	dB
Read	Yes	Yes	

[15]

Table 4:

Tag in close proximity to corrugated board, and a wood pallet, 3 m (10 ft) from reader antenna

Budget Component			
Forward Link (Reader to Tag)			
	Passive Tag	Battery-Assisted	Units
Reader RF output Power (US)	+30	+30	dBm
Modulation correction	0	-3	dB
Reader Antenna Gain	+6	+6	dBi
Path loss at 3m	-41	-41	dB
Corrugated Container	-0.9	-0.9	dB
Wood (pallet)	-4.7	-4.7	dB
Tag antenna gain	+2	+2	dBi
Received power at tag	-3	-6	dBm
Power to activate tag	-10	-42	dBm
Margin at forward link	+1.4	+30.4	dB
Read	Yes	Yes	

Data compiled from [7, 15]

Table 5:

Tag in close proximity to a water filled container, a wood pallet, and corrugated board, 3 m (10 ft) from reader antenna

Budget Component			
Forward Link (Reader to Tag)			
	Passive Tag	Battery-Assisted	Units
Reader RF output Power (US)	30	30	dBm
Modulation correction	0	-3	dB
Reader Antenna Gain	+6	+6	dBi
Path loss at 3m	-41	-41	dB
Corrugated Container	-0.9	-0.9	dB
Container filled with Water	-5.7	-5.7	dB
Wood (pallet)	-4.7	-4.7	dB
Tag antenna gain	+2	+2	dBi
Received power at tag	-3	-6	dBm
Power to activate tag	-10	-42	dBm
Margin at forward link	-4.3	+24.7	dB
Read	No	Yes	

Data compiled from [7, 15]

Table 6:

Tag attached to a metal container at 3 m (10 ft) from reader antenna

Budget Component			
Forward Link (Reader to Tag)			
	Passive Tag	Battery-Assisted	Units
Reader RF output Power (US)	+30	+30	dBm
Modulation correction	0	-3	dB
Reader Antenna Gain	+6	+6	dBi
Path loss at 3m	-41	-41	dB
Metal	-9.4	-9.4	dB
Tag antenna gain	+2	+2	dBi
Received power at tag	-3	-6	dBm
Power to activate tag	-10	-42	dBm
Margin at forward link	-2.4	+26.6	dB
Read	No	Yes	

Data compiled from [7, 15]

Link Budget Benefits for Battery-Assisted RFID Tags

As shown in Tables 3 - 6, the presence of common packaging materials can make reading passive UHF tags difficult at a typical distance. However, the battery-assisted tags are able to read with a large margin (>25 dB). The battery only needs to supply 100 μW to replace the power normally taken from the electromagnetic field. The Class 3 Semi-passive tags that Intelleflex offers require less than 1 μW (-42 dBm) to activate. This is nearly 100 times less than necessary for a typical passive tag. While integrating a battery into an RFID tag adds cost, the benefits of readability may outweigh the cost in some high profit margin product tracking applications [15, 18]. A battery-assisted tag may prove to be beneficial to replace passive tags where redundant passive tags are being attached to a single package. Additionally, by reducing the power needed for a read so drastically, some applications may require fewer readers, offsetting the increased tag cost [18].

Summary

Many materials inhibit power transmission to passive UHF RFID tags. There are a number of factors that can be manipulated to increase tag readability. Increasing the distance between the package/product and the tag can help with power loss. Matching the polarization of the reader antenna and the tag antenna is also critical in the link budget. Passive RFID tags have a useful read range of less than 3 m (10 ft) in real world applications. The weak link in the power link budget for passive UHF RFID is the reader to tag activation power. Battery-assisted tags can greatly increase tag readability in difficult environments. It has been shown that these aforementioned factors must be considered when implementing an effective RFID system for the packaging and distribution environment.

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