MOTOROLA

Second report of detailed container use cases and deficiencies in the ISO 18185-1, ISO 18185-7, and ISO 18000 standard

Presented for consideration
to ISO TC104/SC4/WG2

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I. Revision History

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1.0	7/11/2005	Motorola, Inc	Original release
1.1	7/15/2005	Motorola, Inc	Figure printing cleaned up. Section 3.2.2 updated
1.2	7/17/2005	Motorola, Inc	Formatting cleaned up Chapters 1, 2, and 6 updated

II. Supporting Documents

Conclusions drawn and interpretations made in this document are based on the following documents:

- ISO/IEC 18000-7 Information technology -- Radio frequency identification for item management -- Part 7: Parameters for active air interface communications at 433 MHz (IS 60.60 on 2004-08-31) http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=37978&ICS1=35&ICS2=40&ICS3=

- ISO CD 18185-1 Freight containers -- Radio-frequency communication protocol for electronic seals: Part 1: Communication protocol (CD 30.99 Report of detailed container use cases and deficiencies ISO TC104 SC4 WG2 in parts 1 and 7 of the ISO 18185 standard N228 Motorola, Inc. May 3rd, 2005 Page 18 on 2005-05-02) http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=41125&scopelist=PROGRAMME and sc4wg2n0216_DIS18185-1_20050428.doc

- ISO CD 18185-7 Freight containers -- Radio-frequency communication protocol for electronic seals: Part 7: Physical layer (CD 30.99 on 2005-05-02) http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=40812&scopelist=PROGRAMME and sc4wg2n0222_18185-7_20050428.doc

- ISO CD 17363 Supply chain application for RFID -- Freight containers (CD 30.20 on 2005-04-04) http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=38331&scopelist=PROGRAMME and http://www.autoid.org/2005docs/fb/JWG_05009_CD17363_20050225.doc found under http://www.autoid.org/ISO_JWG/iso_jwg.htm under the February 2005 heading.

- ISO WD 10374.2 Freight containers -- Automatic identification (working draft) http://www.autoid.org/2005docs/apr/JWG_05017_10374-2_drRev.doc found under http://www.autoid.org/ISO_JWG/iso_jwg.htm under the April 2005 heading. (original ISO 10374: http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=18435&ICS1=55&ICS2=180&ICS3=10 and amendment Amd 1:1995: http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=20452&ICS1=55&ICS2=180&ICS3=10)

- US FCC Part 15 Radio Frequency Devices (updated on 2005-01-26) http://www.fcc.gov/oet/info/rules/part15/part15_1_26_05.pdf

- WSC Use Cases http://www.autoid.org/tc104_sc4_wg2.htm with document number 104sc4wg2n0162_WSCApReSum.doc found under May, 2004.

- Sklar etc al Digital Communications: Fundamentals and Applications 2nd Edition, Bernard Sklar – UCLA, Prentice Hall 2001, ISBN: 0130847887

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1. Executive Summary

The purpose of this paper is to honor the request of the ISO TC104/SC4/WG2 committee to provide additional clarification and insight to the deficiencies presented by Motorola in document N228 dated 3 May, 2005 and at the TC104/SC4/WG2 meeting in London. While the short time to prepare N228 prevented detailed model building and simulations to be performed, this report overcame those limitations and focuses on the practical implications and limitations of ISO 18185 parts 1 and 7 as well as ISO 18000 part 7 in light of the required system reliability levels (99.99% read reliability and 99.9999% read accuracy).

This report focuses exclusively on the communication aspects of ISO 18185 and concludes that there is a need for more robust capabilities than provided by the current standard. It is concluded that more communication bandwidth and more efficient communication coordination is required in order to achieve the 99.99% reliability goal.

Aspects of security have not been considered in this report as a separate vulnerability assessment is chartered by the TC104/SC4/WG2 group to focus on those aspects.

Delays in reading electronic seals and tags

The report will show that the ISO 18185 standard, based on the ISO 18000-7 RFID interrogation protocol, performs adequately in small populations of tags or at reliability levels of less than 99.99%. Those readers resolving individual e-seals one at a time will in general have a high probability for resolution. However, readers operating in environments of as little as thirty seals or tags will have difficulty resolving these seal communications in a timely manner at the 99.99% reliability level.

This lack of expedient resolution will become a factor in scenarios both where seal resolution time is critical (moving transport), and where numerous seals and other 18000-7 RFID devices are within read range.

Limited ability to reduce reader power

This report specifically has taken into account the use of variable reader powers in order to focus the collection areas especially in multi-lane gate situations. Detailed analysis will be presented that proves the minimum reader power required to operate the system at 99.99% reliability level will still cause significant populations of seals and tags to respond in typical gate and yard situations.

In order to support all container use cases at the 99.99% reliability level (single 20ft on short chassis, dual 20ft with doors facing in, single 40ft container) reader power has to be increased significantly over the theoretical minimum level. No matter where readers are installed throughout gate structures, the sequence of events required in the ISO 18185 and ISO 18000-7 RFID interrogation protocols will force readers to operate at power levels that make significant tag and seal populations respond.

Interoperability and performance issues due to underspecified standards details

The definition of the interrogation collection algorithms in ISO 18185 and ISO 18000-7 is lacking specificity as to the communication timing tolerances and minimum tag and seal responsiveness after receiving the wakeup header. In the best case, reader installations are able to operate in multi-vendor product environments, but at significantly reduced performance levels (lower read reliability and/or increased collection times). In the worst case, interoperability issues will render a reader installation inoperable due to communication collisions arising from the lack of minimum timing and tolerance requirements.

This report highlights once more the need for a more robust communication protocol in order to support the pervasive use of electronic seals, container license plate tags, and potentially chassis license plate tags. The existing ISO 18185 and ISO 18000-7 RFID interrogation protocols may very well perform satisfactory among the small tag and seal populations expected during the initial roll-out. However, communication capabilities are inadequate to support system reliabilities at the 99.99% level in light of multi-vendor products and tagging/sealing of substantially the entire ISO container fleet.

2. Introduction

During the Committee Draft ballot discussions for the ISO 18185 electronic seal standard in Schaumburg, Illinois, Motorola raised significant issues about the communication technology currently used in the standard. Motorola was asked to document in a very short period of time the expanded container use cases and to describe the technical deficiencies of the current parts 1 and 7 of ISO 18185 and part 7 of ISO 18000. Document ISO TC104 SC4 WG4 N228, published May 3rd, 2005 is the report of that work.

The deficiencies Motorola identified in that report included the lack of system throughput necessary to resolve a number of tags, the lack of security within the air interface communication between reader and seal, and the lack of completeness necessary for a standard to become interoperable between products from differing manufacturers.

Motorola's arguments were found to be convincing during the discussion of N228 during the May 2005 sessions in London, and a consensus vote was taken to halt the present ISO 18185 parts -1 & -7 standard until further information could be evaluated to decide the future direction of this standard.

A sub-working group of TC104/SC4/WG2 was then created, and chartered to help define the parameters to be used to better represent real-world implementations of each of Motorola's scenarios. An initial set of parameters was created out of this work and passed throughout the TC104/SC4/WG2 group, and specifically to the user community, for comment and approval. Over the course of the following 6 weeks, members of the WG2 group debated various aspects of three use case scenarios and the parameters to be used within each. While waiting for agreed upon scenarios and parameters, Motorola started to build simulation models in preparation of the analysis. Detailed investigations were limited to the two weeks following the scenario and parameter agreement which were used to create this follow-on paper. Descriptions of the agreed upon scenarios and parameters can be found in Appendix A.

The following analysis further addresses the deficiencies and use cases pertaining to the lack of system throughput necessary to resolve a number of tags. Please refer to the ongoing ISO TC104/SC4/WG2 Vulnerability Analysis materials for further details about security improvement needs especially in the area of device authenticity determination.

3. Terms/Definitions

BER – Bit Error Rate

Collection Round – the set of signals comprising a collection command from the interrogator plus the numerous responses from the tags

Electronic seal – also known as an e-seal. A read-only, non-reusable freight container seal conforming to the high security seal defined in ISO 17712 and conforming to ISO 18185 or revision thereof that electronically evidences tampering or intrusion through the container doors.

Interrogator – a station which is part of the fixed infrastructure which issues collection commands and decodes tag responses. This has also commonly been referred to as a reader within the ISO standards discussions.

Identification Tag – see License Plate Tag

Iteration - round

License Plate Tag – also known as an identification tag. This is an RFID device which contains freight container identification information, based on ISO standard 10374.2.

Manifest Tag – also known as a Shipping Tag. This is an RFID device which contains shipping information about a freight container contents, based on ISO standard 17363.

NF – Noise Figure

$numTags_0$ - total number of tags in the 0^{th} iteration i.e. the starting population of tags that shall hear the first collection command

PER – Packet Error Rate

Reader – see Interrogator

Resolved – when an interrogator successfully decodes a tag a response to a collection command.

Round – collection round

Shipping Tag – see Manifest Tag

Slotted Aloha – a system for coordinating and arbitrating access to a shared communication channel. A time period is divided into slots, with a slot size equal to a fixed packet transmission time. When the packet is ready for transmission, it waits until start of the next slot, such that packets overlap completely or not at all. The method picks a timeslot and sends the information – there is no listen before talking algorithm.

Tag – a generic term used to describe an RFID device used for freight container applications such as an e-seal, a manifest tag, or a license plate tag.

4. Adaptive Windowing Limitations

Adaptive windowing applications are limited by the inability to know the population from which to select the optimum window size. Even if a windowing algorithm could know the population of tags apriori, the best case performance of a windowing algorithm is still limited. It shall be shown that the best case performance of an adaptive windowing algorithm resolving a population of N tags is still limited by the maximum throughput cap of Slotted Aloha at 1/e.

It shall be further demonstrated the expected number of iterations 'i' to reduce a population of N tags ($numTags_0$) to a percentage c assuming the best case window size is chosen for each iteration 'i' is.:

$$i = -2.180192 * \ln c$$

where:

$$c = (\text{number of tags not yet resolved after the 'ith' iteration}) / (numTags_0)$$

and:

$$i = \text{the 'ith' collection round}$$

It shall also be shown that the time that has elapsed, in units of slots of time (the slots being large enough to accommodate a response burst from the tag), not counting the time to put a tag to sleep, as a function of the 'ith' iteration is:

$$resolutionTime_i\ (slots) = e * numTags_0 * (1 - (1-1/e)^i)$$

It shall ultimately be shown that total amount of time to resolve a population of tags ($numTags_0$), given the best performing windowing algorithm, is:

$$totalResolutionTime = numTags_0 * (e * tagResponseBurstDuration + sleepBurstDuration)$$

4.1 Metric Definition and Metric Performance

The two goals for the performance of any best case window selection algorithm are:

1. Maximize the number of successfully resolved tags each collection round (i.e. iteration)
2. Minimize the amount of time taken to resolve the population each iteration

Therefore a metric to determine the best case window size for any collection round would be:

$$\text{Metric}_i = \text{Max}\left((E[\text{successfulResolutions}(\text{numTags}_i, \text{windowSize}_i)])/\text{windowSize}_i\right)$$

Where:

E[ ] = Expected value

successfulResolutions = the number of tags successfully decoded by the interrogator

numTags_i = the number of tags in the 'ith' collection round or iteration that still must be resolved by the interrogator

windowSize_i = the window size of the 'ith' collection round or iteration in units of slots

If the window size is minimized while maximizing the number of successfully resolved tags, the metric is maximized.

Experiments were generated where populations of containers within listening range of an interrogator, each container with a license plate tag and an e-seal (i.e. two tags per container) were resolved by an interrogator. A set of plots were generated below indicating performance of an interrogator attempting to resolve various populations of tags. The various populations can be denoted as {numTags_0:20, 40,. 60, 80, 100} where numTags_0 indicates the starting population which shall hear the first collection command issued by the interrogator. For each numTags_0 in the set of populations given above, a plot has been generated for the expected number of tags successfully resolved by the interrogator versus the window size (window size units are slots). The numbers were generated through a Monte Carlo simulation.

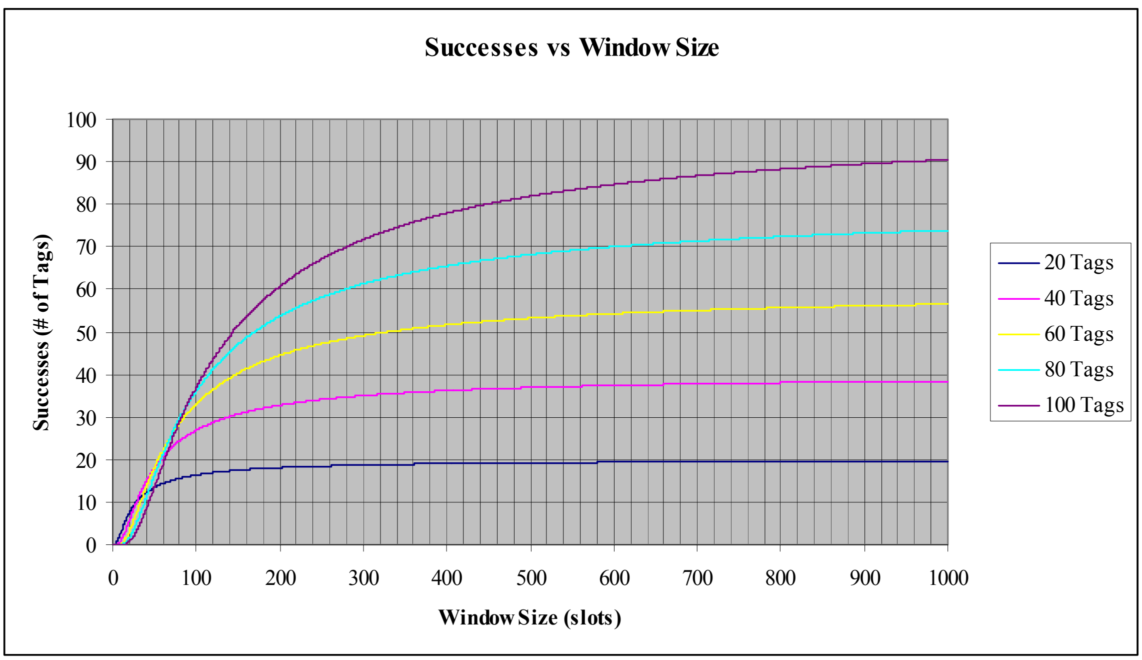

Figure 1: Successes vs Window Size for Various Populations

The metric for each of the populations above are plotted below:

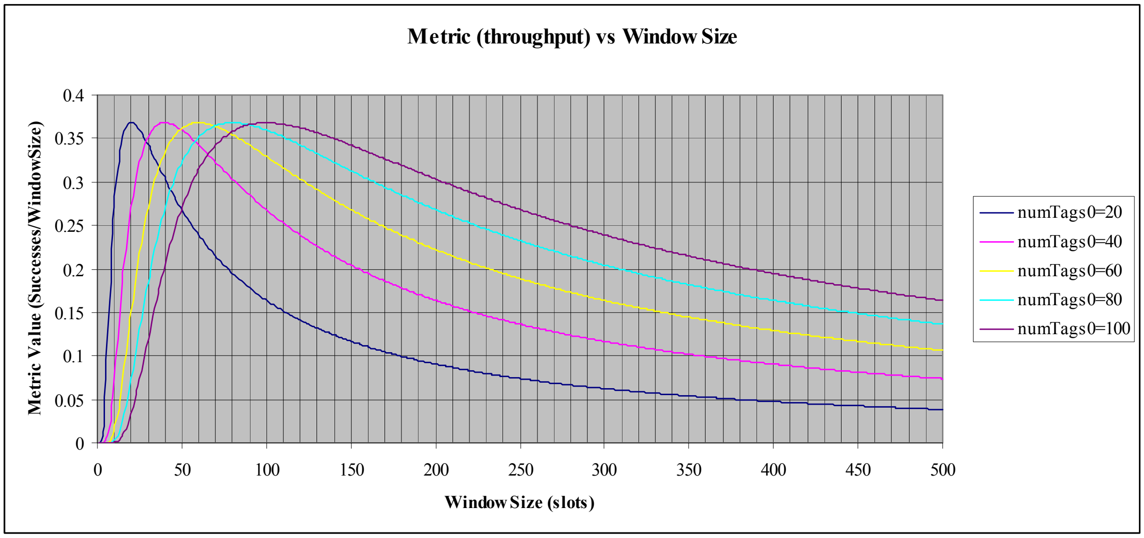

Figure 2: Metric vs Window Size for Various Populations

A familiar value arises when analyzing the metric's maximum value because of what the metric actually means. The $Metric_i$ value is really the throughput value. The number of successes divided by the window length is a measure of throughput. Therefore by maximizing the metric each iteration, the throughput is maximized. Therefore the best a window selection algorithm can do is pick the window which maximizes the ratio of successes divided by the window size (in slots) i.e. maximize throughput each iteration. This best case performance is clearly impossible because there is no way for the interrogator to know the population apriori so even the poor performance of the ultimate in window selection algorithms is an impossible acme to reach.

4.2 Analyze the Metric Behavior

4.2.1 System Throughput

The maximum's of the ensemble exactly meet the expected maximum throughput value of 1/e =.368 for slotted Aloha. The plots above follow exactly to the throughput expected of Slotted Aloha where:

$$\text{Throughput} = G \exp(-1/G)$$

The variables:

$$G = numTags_i/windowSize_i$$

And:

$$windowSize_i = slots$$

Therefore the most that can be expected to be resolved for any iteration is 1/e times the population. Because the effective bit rate is only 27.7kpbs with one stop bit per 8, the overall throughput can be generalized:

$$\text{System throughput} = 27.7\text{kbps} * 8/9 * 1/e = 9 \text{ kbps}$$

This is the best case (average) **system** throughput that can never be achieved without knowing the population of tags apriori (i.e. $numTags_i$).

4.2.2 Resolution Delay

Because of the limited throughput, the population can only be reduced at 1/e each iteration. As a result, the final expected population decimation after the 'ith' iteration can be quickly generalized. If 1/e is decimated each iteration 1-1/e remains. Therefore:

$$(1-1/e)^i = c$$

where:

c = (number of tags not yet resolved after the 'ith' iteration) / (total number of tags in the 0^{th} iteration)

reducing:

$$i = -2.180192 * \ln c$$

Therefore the expected number of iterations to reduce a population of 10 tags to 1/10 of its population (i.e. 1) assuming the population was exactly known for each iteration would be:

$$i = -2.180192 * \ln (.1) = 5 \text{ iterations}$$

Of course this is the same number of iterations if a population of 100 is to be reduced to 10 (10/100=.1) or a population of 300 is to be reduced to 30 (30/300=.1).

If a population of 300 is to be reduced to 3 (3/300=.01) or a population of 100 is to be reduced to 1 (1/100=.01) the expected number of iterations, assuming the population was exactly known for each iteration, would be:

$$i = -2.180192 * \ln (.01) = 10 \text{ iterations}$$

And it then also follows that the expected number of iterations to reduce a population of 1000 tags to 1/1000 of its population (i.e. 1) assuming the population was exactly known for each iteration would be:

$$i = -2.180192 * \ln (.001) = 15 \text{ iterations}$$

The logarithmic progression can be seen: to reduce the population by a factor of 10 requires 5 additional iterations.

The amount of time it would take to resolve any population of tags is comprised mostly of the window size used in the collection round plus the amount of time to put each of the resolved tags to sleep. Given that the optimum windowing algorithm, upon knowing the population, shall choose an equal number of slots for the collection window size, the amount of time taken to complete 'i' optimum windows (not counting the time to put the resolved tags from the previous iteration to sleep) is given by the following derivation:

$$\text{resolutionTime}_i \text{ (slots)} = \text{numTags}_0 \sum_{n=0}^{i-1} (1-1/e)^n$$

where i = the 'ith' iteration

and numTags_0 = the starting population before the first iteration commences.

The equation above reduces to:

$$\text{resolutionTime}_i \text{ (slots)} = \text{numTags}_0 * (1 - (1-1/e)^i)/(1 - (1-1/e))$$

or:

$$\text{resolutionTime}_i \text{ (slots)} = e * \text{numTags}_0 * (1 - (1-1/e)^i)$$

Therefore for if $numTags_0$ = 3000 and after the 15th iteration, the $resolutionTime_{15}$ in slots is:

$$resolutionTime_{15}\ (slots) = e^* \ numTags_0 * (1 – (1\text{-}1/e)^{15}) = 8146 \text{ slots}$$

A slot must comprise of a minimum duration to contain the following elements of a tag (collection) response burst (i.e. responseBurstDuration):

Burst Component	Length	Units
Preamble	.001296	Seconds
Byte+StopBit	.000324	Seconds
Number of Bytes of Data	20	Bytes
CRC	2	Bytes
1/2rampUp + 1/2rampDown	.001	Seconds
Packet End Time	36	microseconds
Total Duration of Tag Response Burst Response	**.00946**	**Seconds**

Table 1: Required Tag Response Burst Duration (responseBurstDuration)

An example would be to calculate the $resolutionTime_i$ for 100 tags reduced to 1:

$$resolutionTime_{10}\ (slots) = e^* \ numTags_0 * (1 – (1\text{-}1/e)^{10}) = 269 \text{ slots}$$

Multiplying 269 slots by the responseBurstDuration time produces a result of 2.54 seconds (this does not count the time to put the tags to sleep).

Given the length of a burst above, the amount of time to complete 15 iterations (not counting the time to put the tags to sleep) would be 77.1 seconds.

The cumulative duration to resolve the original population of tags (which equals $numTags_0$) has been generalized and plotted below (note that responseBurstDuration is defined in Table 1). Each iteration can be equated to one collection command transmitted by the interrogator and a number of responses from the nearby tags being received by the interrogator as a result of the tag receiving the collection command. The numbers on the y-axis if multiplied by the responseBurstDuration time and the original population of tags which can hear the collection command ($numTags_0$) shall indicate the total amount of time that has elapsed up to the "i^{th}" iteration:

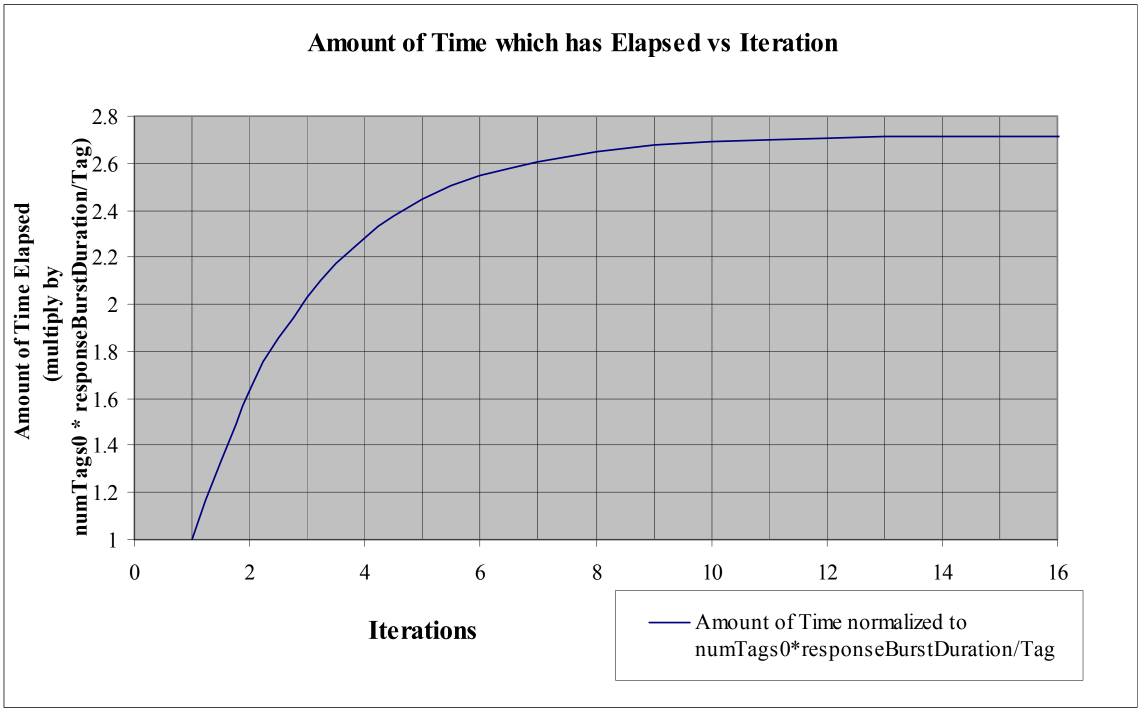

Figure 3: Expected Amount of Time Elapsed vs Iteration

Note that the above time doesn't include the time it would take to put each of the tags to sleep. That would be an additive factor of $numTags_0$ times the duration of the sleep burst.

Therefore the expected totalResolutionTime to resolve a population of tags given by $numTags_0$ counting both the window size used in the collection round plus the time to put the tags to sleep is:

$$totalResolutionTime = numTags_0*(e*responseBurstDuration+sleepBurstDuration)$$

This equation can be solved in order to derive the maximum $numTags_0$ which can be resolved within in one second and therefore still be within the constraints of the FCC. First the sleep command length is calculated in the table below:

Burst Component	Length	Units
Preamble	.001308	Seconds
Byte+StopBit	.000324	Seconds
Number of Bytes of Data	12	Bytes
CRC	2	Bytes
1/2rampUp + 1/2rampDown	.001	Seconds
Packet End Time	36	microseconds
Total Duration of Sleep Command Burst	**.00688**	**Seconds**

Table 2: Required Sleep Burst Duration (sleepBurstDuration)

Therefore:

$$1 \text{ second} = numTags_0*(e*.00946+.00688)$$

$$numTags_0 = 30.7 \text{ Tags}$$

This represents the maximum population possible that can be resolved within 1 second, assuming the windowing algorithm knows the starting population ($numTags_0$) apriori. This is an important number when faced with the FCC imposition: after a tag sends its first response to a collection command, the tag has up to one second to continue sending responses before reverting to 30x the transmit time of silence time and with no less than 10 seconds of silence. *Therefore the largest population that can ever be resolved, due to this FCC restriction, is 30 tags.* Any system configuration that involves more than 30 tags ensures that the system will have less than 30/31 (96.8%) reliability. If the system must resolve 31 tags, the reliability shall be 30/31 = 96.8%. If the system configuration involves 50 tags, the system will have 50 tags to resolve which equates to 30/50 = 60% reliability.

Note that Figure 3 can be represented as a function of percent population. Taking the equation for $resolutionTime_i$ and substituting:

$$i = -2.180192 * \ln c$$

The following plot represents the substitution:

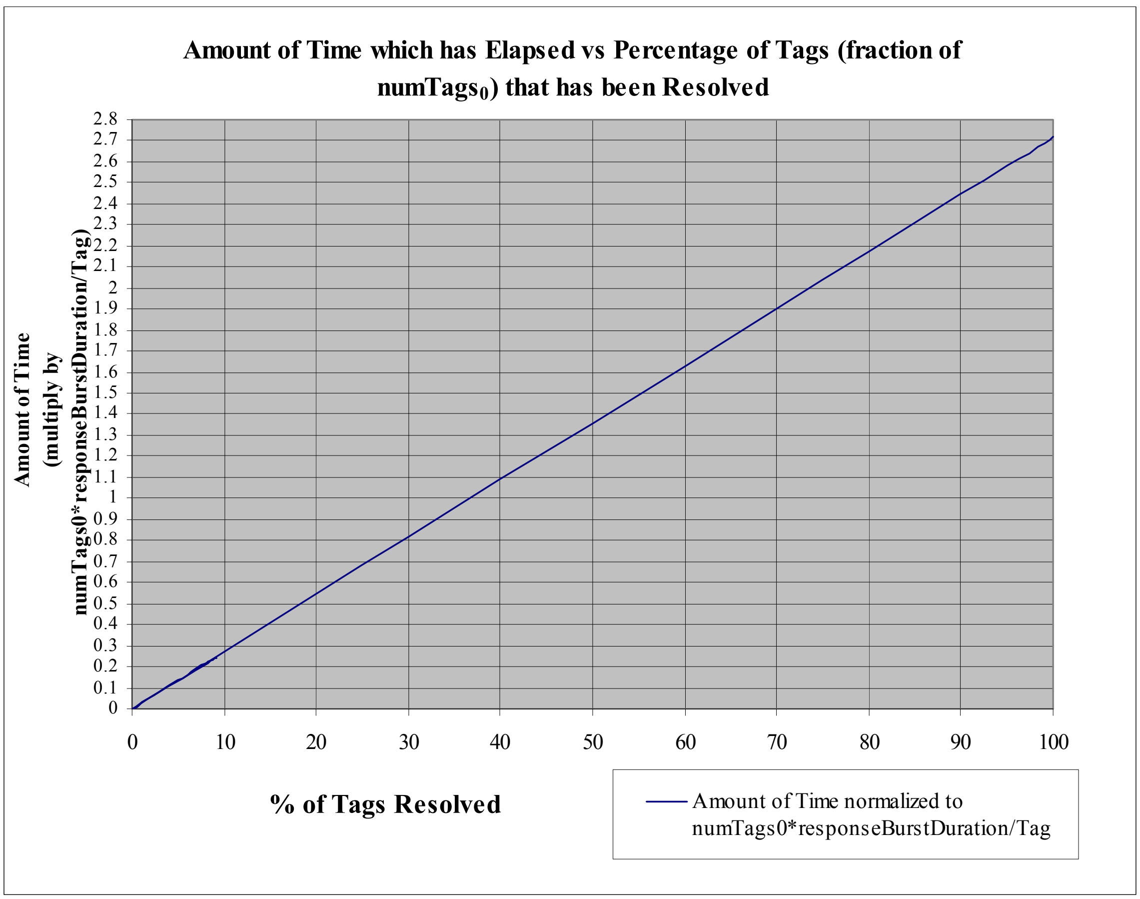

Figure 4: Amount of Time Elapsed as a function % Population Resolved

The above plot is another representation of the $resolutionTime_i$ function given earlier. An example of the use of this plot follows. What would be the amount of time taken to resolve the population to 10% of the original population ($numTags_0$)? With the best windowing algorithm, it could be expected that 2.45 times $numTags_0$ times the length of a response burst (responseBurstDuration) would be the time it would take to resolve 90% of the population (not counting the time it would take to put the population to sleep). If the burst length is 10msecs and $numTags_0$ equaled 41 tags, the expected time to resolve 37 of the 41 tags would be over 1 second.

Really the figure above is a linear curve normalized to "e". The curve is linear because the number of resolved tags plus the number of empty, multiply occupied slots is a linear function of the population. It is a linear function of the population because the windowing algorithm chooses the correct window size each iteration and the same ratio of tags are resolved each iteration.

After dividing out the above plot by "e", the values can be represented with the following plot:

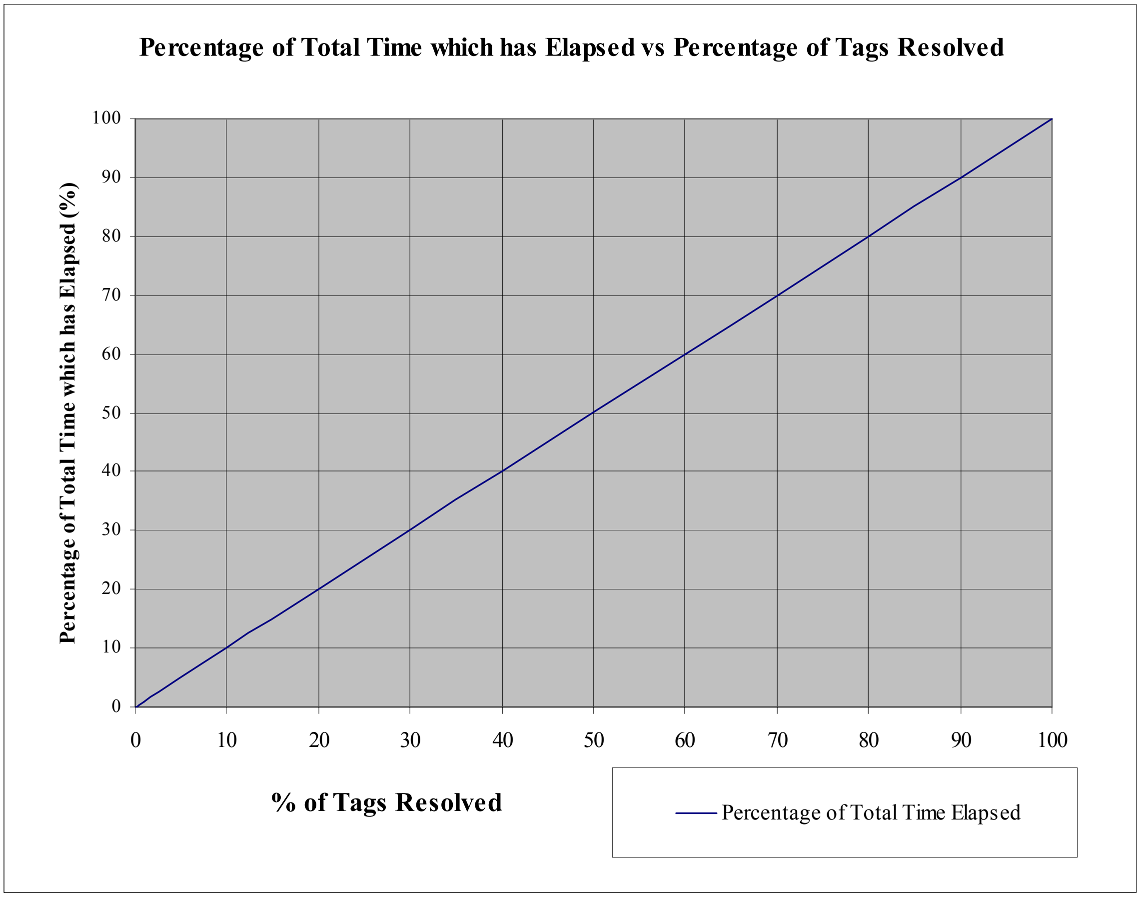

Figure 5: Percentage of Total Time that has Elapsed vs Percentage of Tags Resolved

Interpreting the plot above, if 0% of the population has been resolved, 0% of the total time has elapsed and 100% of the total time necessary to resolve the entire population (numTags0) must still be endured. If 50% of the original population has been resolved, 50% of the total time has elapsed and 50% of the total time which was required to resolve the entire population (numTags0) is still left to elapse. If 30% of the population has been resolved, 30% of the total time has elapsed and 70% of the total time to resolve the entire population ($numTags_0$) is still left. Note that the figure (Figure 5) above includes putting the tags to sleep.

The purpose of generating Figure 5 shall be made more evident later in the paper. Figure 5 shall be referred by subsequent discussions.

4.2.3 Poor Standard Definition limits Performance lower than Slotted Aloha

Section 4 of 18185-7 states that "The actual duration of a slot is determined by the interrogator collection command type and is a function of the tag transmission time". This isn't true. Only the window size is specified in the Collection Command not slot size. There seems to be no definition for slot size. Simply taking the slot size equal to a tag response is inadequate. If the slot size is not specified for the entire length of a burst, a tag can potentially interfere with more than one slot reducing throughput even further. Therefore the slot size must account for worst case R-to-T time, worst case PA ramp up time, etc. This is a serious issue.

5. Scenario Analysis

5.1 Tags on Containers Carried by Trucks Stopped at Gates

The fundamental problem of resolving tags on containers which have arrived on a truck and have stopped at the gate for interrogation by the reader is influenced by these primary factors:

1. RF Blocking caused by the container which comes between the interrogator and the tag (see below):

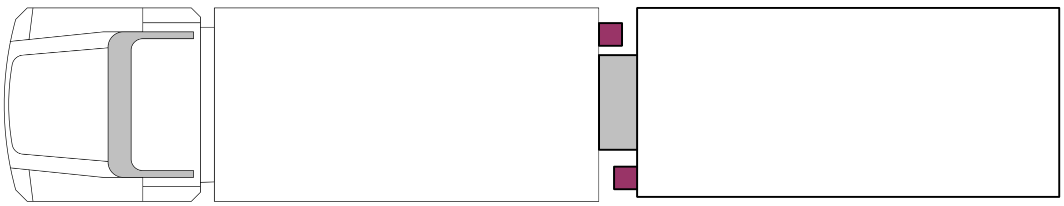

Figure 6: Two 20' Containers with Tags Opposing each other

Figure 7: One 40' Container with Tag at Far End

   Note that the tag positions do not lend themselves to be readily detected if the interrogator is at or near the front of the cab. The signal from the interrogator must be transmitted at sufficiently high power to enable the tag to detect the collection command.

2. The opposing factor to simply transmitting at high power is the risk of unintentionally waking up too many tags on nearby, stored containers causing them to respond to the collection command. If many tags respond to a collection command, a sufficient amount of time must be taken to resolve the responding population. The FCC mandated that a tag, upon initiating responses to a collection command, must finish within 1 second and then be silent for 30 seconds. Resolving too large of a responding population of tags may will push the resolution system time longer than one second. Pushing the resolution time longer than 1 second will incur suboptimal performance below 99.99%.

In order to better understand the system configuration, the following plot is the sensitivity using FSK at the 27.7kbps rate and a noise figure (NF) of 8dB:

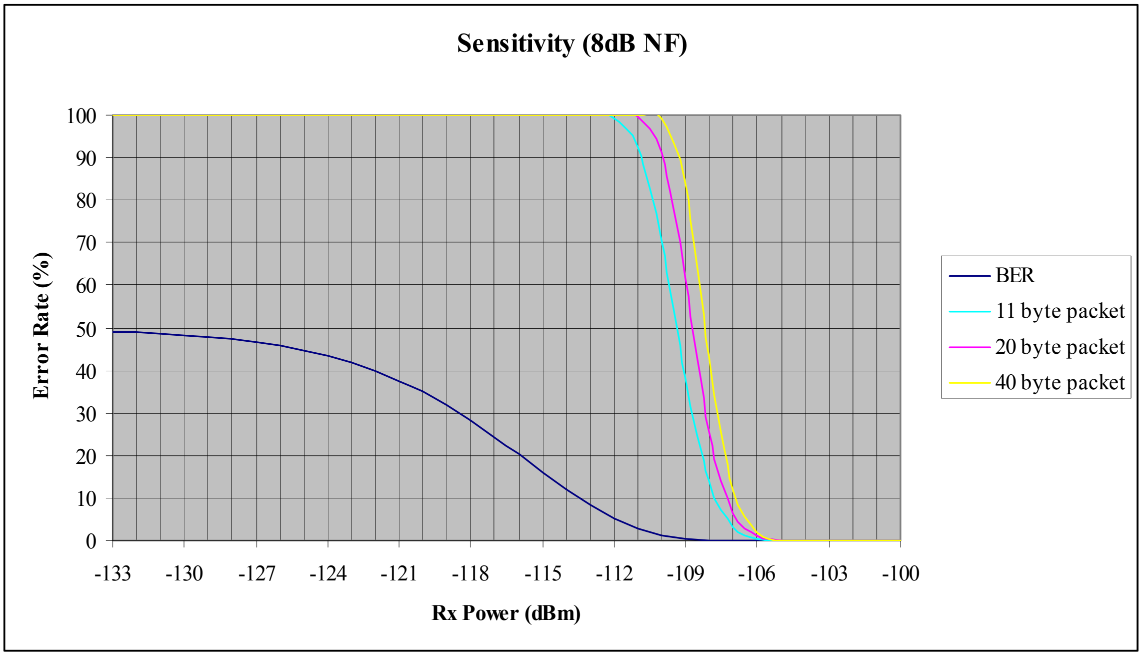

Figure 8: Sensitivity of Modulation w/ 8dB NF

The above plot is the BER and PER for various receiver powers (i.e. signal strength at the tag's antenna). An error rate is the probability that the bit or packet shall be in error. The steep decline is because there is no error correction and every bit must be correct in order to successfully detect a packet.

A more detailed graph of the one above is depicted below:

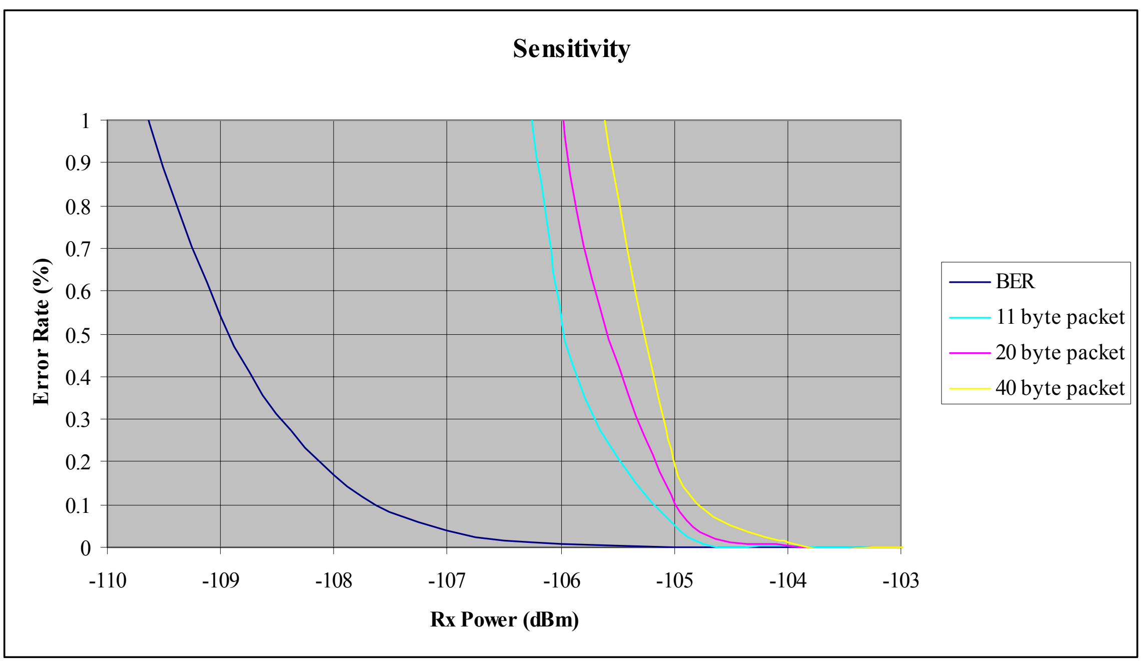

Figure 9: High Res Look at Sensitivity Curve

A logarithmic plot of the same data is plotted below:

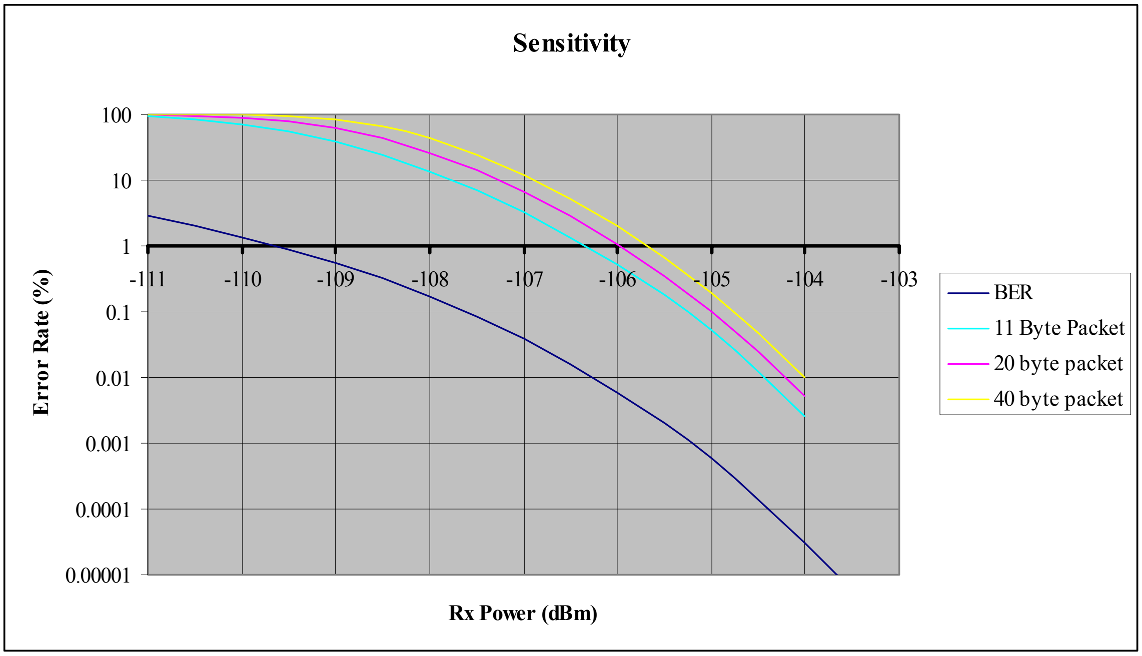

Figure 10: Logarithmic Representation of BER and PER Sensitivity

As can be discerned from the figure above, the sensitivity for 99.99% successful detection rate can be generalized at -104dBm. The PER goes to 0% when the receive signal strength is -103dBm.

In order to understand what transmit power is necessary, the following figure depicts the link loss due to both diffraction and free-space path loss. The diffraction loss occurs because more often than not, the RF signal shall not have a direct path between the interrogator and the tag. The RF signal must reflect or bend around corners. Free-space loss is the loss due to a weakening of a signal over distance. The two losses add together, against the transmit signal.

Note that the diffraction loss can be verified by real world measurements with tags on containers (which Motorola has done). Note that unfortunately diffraction loss requires more transmit power by the interrogator:

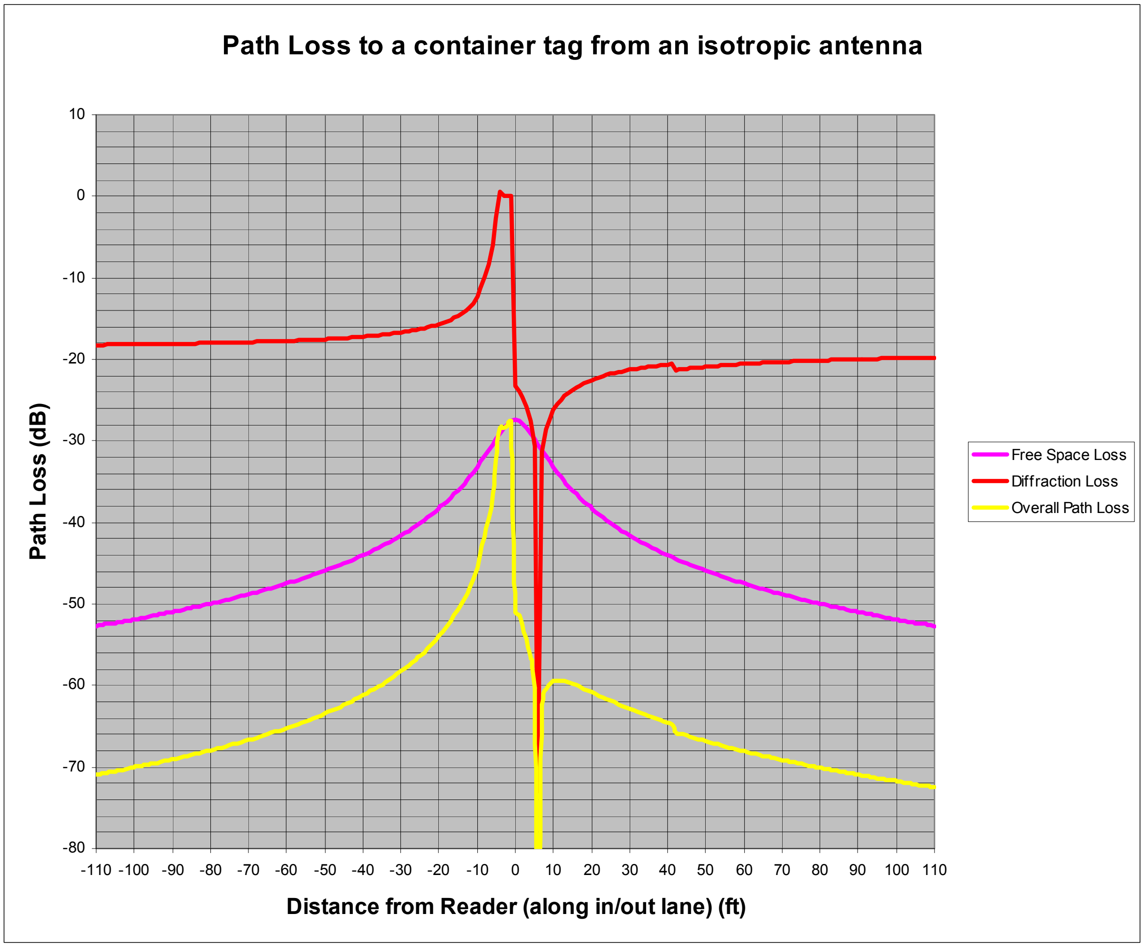

Figure 11: Free Space Loss, Diffraction Loss and Overall Path Loss

In order to transmit the interrogator signal at sufficient power and enable coverage, without violating any transmitter power limitations, a 7.7dB gain antenna with a 60 degree 3dB beamwidth can be implemented. Any more gain than this shall nullify the intention of keeping the power to the above specified limit. Of course nearby tags on stored containers will respond to this, depending upon the transmit power that is chosen.

The interrogator transmit power must be chosen to cover the worst case situation depicted in Figure 7. In this case, the tag is at the rear of a 40' container. Assume some nominal distance is necessary due to cab and chassis connector length (say 10'-15'). Therefore the distance needed to ensure 99.99% coverage is 50' to 55'. The link loss at 50' to 55', according to Figure 11, is -64dB. Assume the tag is within a few degrees of the boresite; therefore the tag benefits from 7dB gain of the antenna. Knowing the sensitivity of the tag is -104dBm the interrogator transmit power should be -47dBm. (Note that -47dBm + 7dB -64dB = -104dBm).

The collection command reliability contour can be plotted and depicted[1]: The plot is a function of freespace loss, diffraction loss, PER sensitivity, antenna gain pattern and transmit power. This indicates the amount of responsiveness of tags on nearby, stored containers to the collection command. If tags on nearby containers detect the collection command, they shall respond. The probability contour below indicates the probability of a response from a tag assuming the tag is positioned at that specific point from the interrogator and the interrogator is positioned at point (0,0):

[1] This plot generalized a 20dB loss for diffraction.

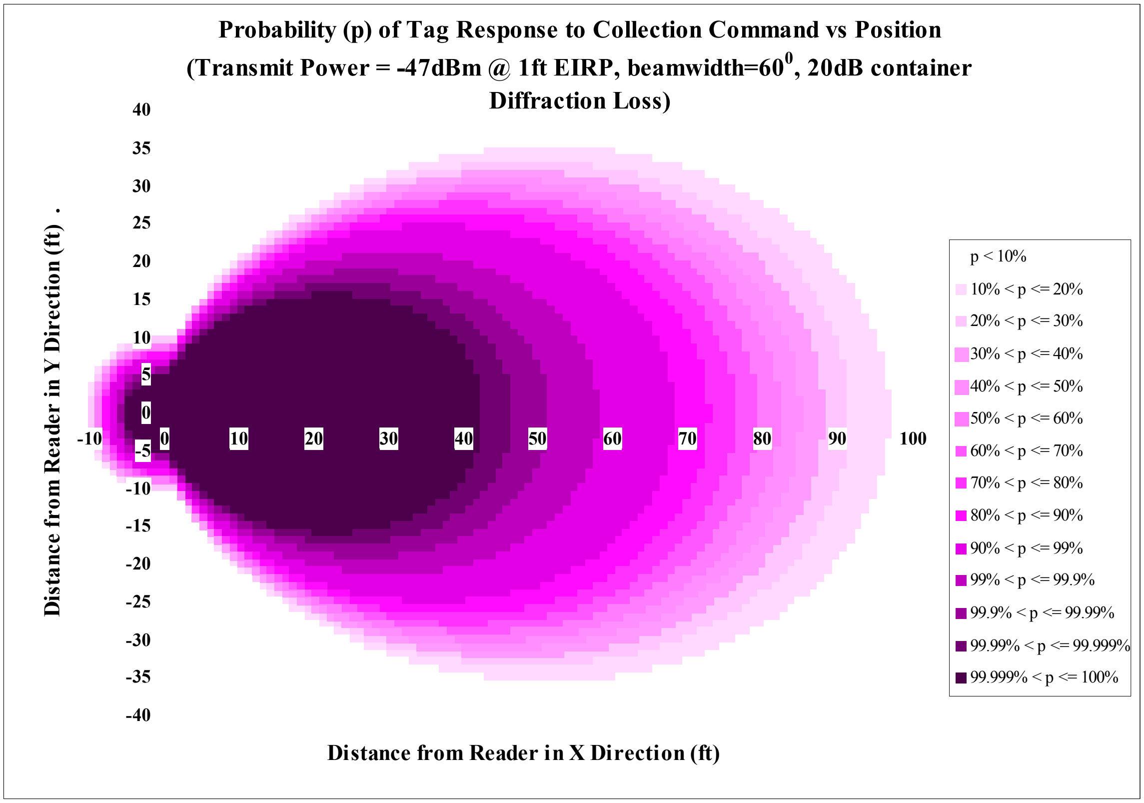

Figure 12: Probability of Collection Detection as a Function of Position from the Reader

If an integral (a summation) of the probabilities depicted Figure 12 is made over the entire area but only accounting for containers less than 100' away from the interrogator, the total number of expected responses can be calculated. The plot above is only for -47dBm, but the integral can be calculated over a range of transmit powers. For the plot that follows assume:

- Farther than 50' away (but nearer than 100' away) 20' containers are stacked 5 high. Therefore the number of stacks of 5 containers 50' away is ~100 stacks.
- Closer than 50' away tags in the gate area may respond as depicted in Figure 12.
- There is 20dB diffraction loss for each tag on the container.

The plot below indicates the number of responses to expect from nearby tags for a given interrogator's transmit power e.g. the summation of probabilities of a tag successfully detecting a collection command (assume one tag response per 20' container). The larger the number of neighboring tags responding to the collection command causes system performance to suffer.

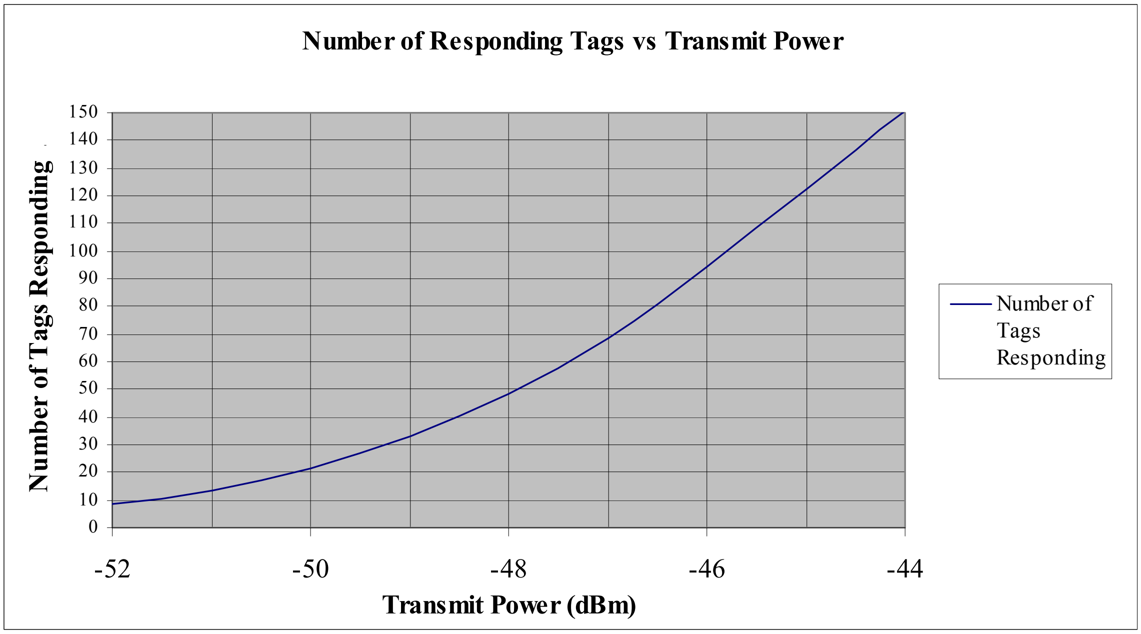

Figure 13: Number of Responding Tags vs Transmit Power

Note that for a transmit power of -47dBm, 70 tags shall respond to one collection command (e.g. one collection command for e-seals shall incur a response from 70 tags). The totalResolutionTime equation previously derived accounts for the best case windowing algorithm. That equation accounts for the total time to resolve a population and put them to sleep. The total population that responds as indicated in Figure 13 becomes the value for $numTags_0$ in the previously derived totalResolutionTime equation. Simply multiplying the values in the y-axis of Figure 13, by (e*tagResponseBurstDuration+sleepBurstDuration) shall give the totalResolutionTime (which has been plotted below versus transmit power):

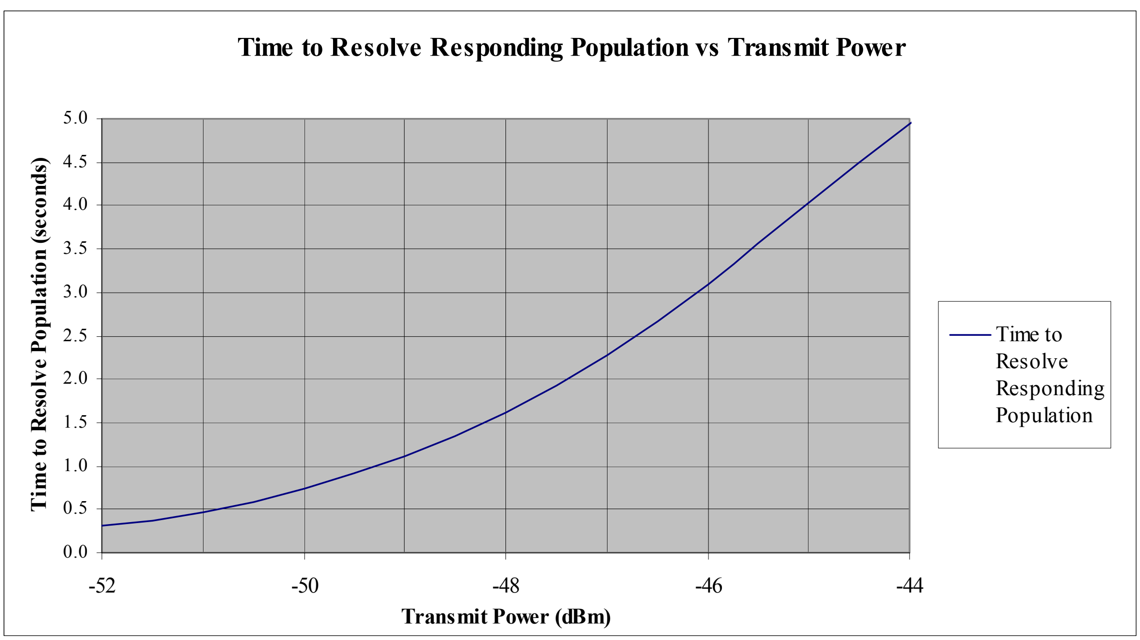

Figure 14: totalResolutionTime Required to Resolve Population as a Function of Transmit Power

Therefore the length of time to resolve a population of 70 tags with a transmit power of -47dBm is 2.3 seconds plus the 2.5 second wake-up tone which equals ~5 secs. If both the e-seal and license plate tag must be detected on a vehicle and two 2.5 second wake-up's are required, one for each type of tag, the total time expended to resolve one vehicle's tags is:

$$2.5 \text{ sec} + 2.3 \text{ sec} + 2.5 \text{ sec} + 2.3 \text{ sec} = 9.6 \text{ secs.}$$

Therefore it shall take 9.6 seconds to fully resolve the tags on one vehicle.

2..3 seconds to resolve one type of tag presents a serious issue. It's more than double the amount of time allowed due to FCC restrictions. The FCC has regulated that the tag upon first responding to a collection command, has only 1 additional second of time in which it may transmit subsequent responses. After the one second, the tag must cease transmissions for 30 seconds. If the entire population cannot be resolved within 1 second, there is a probability that the tag shall not be resolved by the interrogator for a period of 30 seconds or not at all. When referring to Figure 5, after 1 second, only (1/2.3) of the population shall be resolved, assuming the best case windowing algorithm (i.e. the 1 second allowed by the FCC divided by totalResolutionTime = 2.3 seconds means only 43% of the total time required to resolve the entire population will have elapsed in 1 second. This ratio means, according to Figure 5, only 43% of the population will have been resolved.) Therefore 100%-43%=57% of the time, the tag shall not be resolved in this scenario which is far below 99.99% reliability.

It is important to note that regardless of the position of the interrogator relative to the vehicle, the same results should be expected. This is primarily due to the transmit power required of the interrogator to overcome the approximate 20dB diffraction loss incurred by a container obscuring a tag and still maintain 99.99% detection reliability. Whether the interrogator is positioned in front, behind or the side of containers, if the tag doesn't have a line-of-site path with the interrogator, diffraction loss will occur.

This is the best case (minimum) time to resolve the tags on a stopped truck at the gate for reasons specified below:

1. It is assumed that the interrogator selects the perfect window size. This is impossible since the listening population shall be constantly varying and there is no way for the interrogator to know the population before issuing the collection command.
2. It is assumed that tag responses have a reliability of 100%. If the tag response reliability is any less, the time to resolve the population increases because each tag shall continue to try to transmit to the interrogator until successfully put to sleep.
3. It is assumed that there will be no CRC falsing which isn't true for the CRC specified in the standard. The CCITT CRC16 is only reliable 99.998% of the time. This is a well known liability of CRC16. A 20 bit CRC is minimally necessary for 99.9999% data accuracy for one transmission.
4. The noise figure (NF) chosen is on the high side. If the NF is chosen to be lower, this simply increases the number of responses on nearby stored containers for the same transmit power.
5. The burst size didn't include security overhead. If the burst size was larger, the totalResolutionTime would increase proportionately. For example, if the burst size increased by 20% because of security overhead the totalResolutionTime would increase by 20%.

5.2 Tags on Containers Carried by Trucks Moving Through Gates at 30kph

This scenario assumes that tags on containers moving at 30kph on trucks must be detected. Again as mentioned previously the two opposing factors must be balanced to system engineer this lane for successful reads i.e. the transmit power of the interrogator must be minimized to provide just enough coverage radius in the lane while minimizing the number of responding tags on nearby stored containers. This opposing behavior has been illustrated above.

However a new restriction is imposed on the system. Because the vehicle is moving, it shall pass through coverage areas of 99.99% coverage reliability. There is a finite duration of time that the vehicle shall be within the coverage area because the vehicle is moving. This coverage area is a function of transmit power. The two opposing behaviors illustrated above manifest in the following way:

1. A fixed transmit power from the interrogator must be selected in order to provide a specific 99.99% coverage region overcoming the link loss imposed by both free space loss and diffraction loss. This transmit power bounds the coverage area; this transmit power defines the maximum 0^0 (on axis) coverage distance from the interrogator (call this distance C).
2. The more power transmitted by the interrogator incurs more responses from tags on nearby stored containers, delaying the time to resolve the entire listening population which includes the one desired tag on the moving vehicle. The time to resolve the population multiplied by the speed of the vehicle becomes the coverage distance necessary to resolve the desired tag(s) (call this distance D).

In order to solve "C" and "D" above, first the events which must be system engineered are presented below.

In order to detect a license plate tag and an e-seal tag, the following sequence of Events must occur:

1. First a 2.5 second wake-up tone must be issued by the interrogator
2. Collection commands must be issued for the first type of tag (e.g. the license plate tag) and they must be eventually resolved by the interrogator
3. The interrogator must issue a second 2.5 second wake-up tone
4. A collection command must be issued for the second type of tag (e.g. the e-seal) and the second type of tags must be eventually resolved by the interrogator

In order to structure Event 2) and Event 4) as close as possible to the interrogator, the Events must be timed in sequence as the vehicle approaches the gate. The following depicts the Events as they would occur relative to the vehicle's and the interrogator's position:

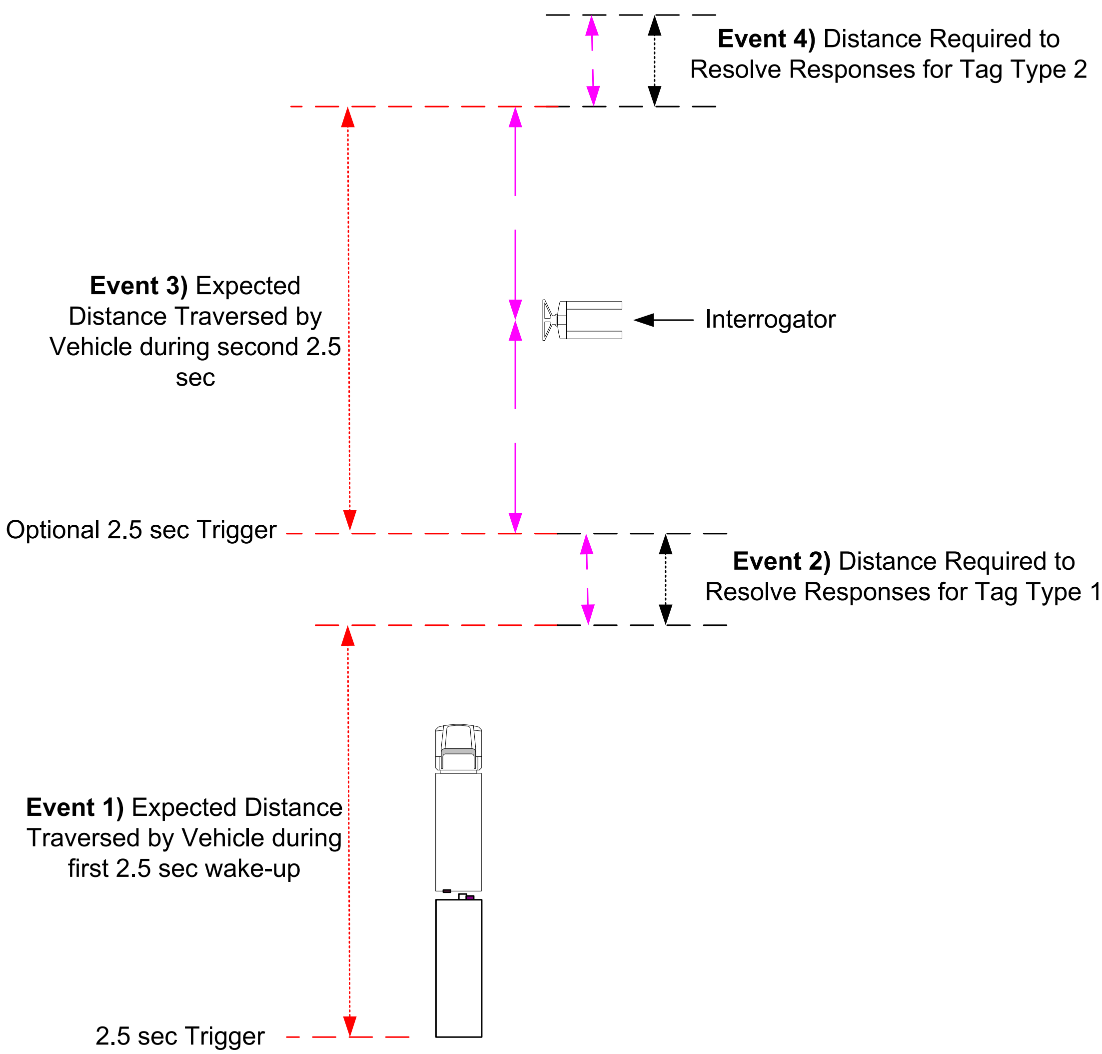

Figure 15: System Engineered for Optimum Detection of Moving Containers

In order to execute the Events above, assume the interrogator has two antenna's: one antenna positioned towards the area to execute Event 2, the other antenna positioned towards the area to execute Event 4 i.e. there is one antenna pointing down the front of the lane at the truck as it approaches the gate, another antenna pointing down the back of the lane towards the truck as it is driving away from the gate.

Note that having antenna's at the side would be impractical for at least two reasons:

1. The vehicle would move too quickly through the antenna's gain pattern to enable a full 2.5 second wake-up for the tag.
2. An antenna mounted on the side of a lane would inadvertently wake more tags on stored containers than an antenna pointing down the truck lane. An antenna pointing down the truck lane would avoid and point away from the area of stored containers; an antenna mounted on the side shall hit more tags on stored containers.

Events 2) and 4) are positioned as close to the interrogator as possible to maximize system performance. The less power necessary to maintain a 99.99% collection command coverage distance, the less responses unintentionally garnered from nearby containers. This is the only way to system engineer the problem while providing coverage for Events 2) and 4) with a hope for a solution for D.

Again, "D" is the distance traversed by the vehicle during the time it takes for the interrogator to resolve the population that responds to the collection command. The transmitter must transmit at a power level that ensures that at least the distance 34' plus D' is covered (distance C). This coverage distance (C) must upper bound the distance of 34' plus D' that is the following must be true:

C>= 34'+D

The distance 34' plus D' becomes the lower bound.

Both the upper bound and lower bound are plotted below. Curve 2 represents the 99.99% collection command reliability distance from the interrogator versus transmit power (distance C). Curve 1 represents the distance 34' plus D versus transmit power. In order for a solution set to occur, curve 2 must upper bound curve 1 somewhere in the plot. Nowhere in the plot does curve 2 upper bound curve 1. There is no solution to meet C>=34'+ D. It is impossible to system engineer this problem so that both Events 2) and 4) are covered by the interrogator. Therefore it is impossible to system engineer this problem. Unfortunately under all conditions, C < 34' + D.

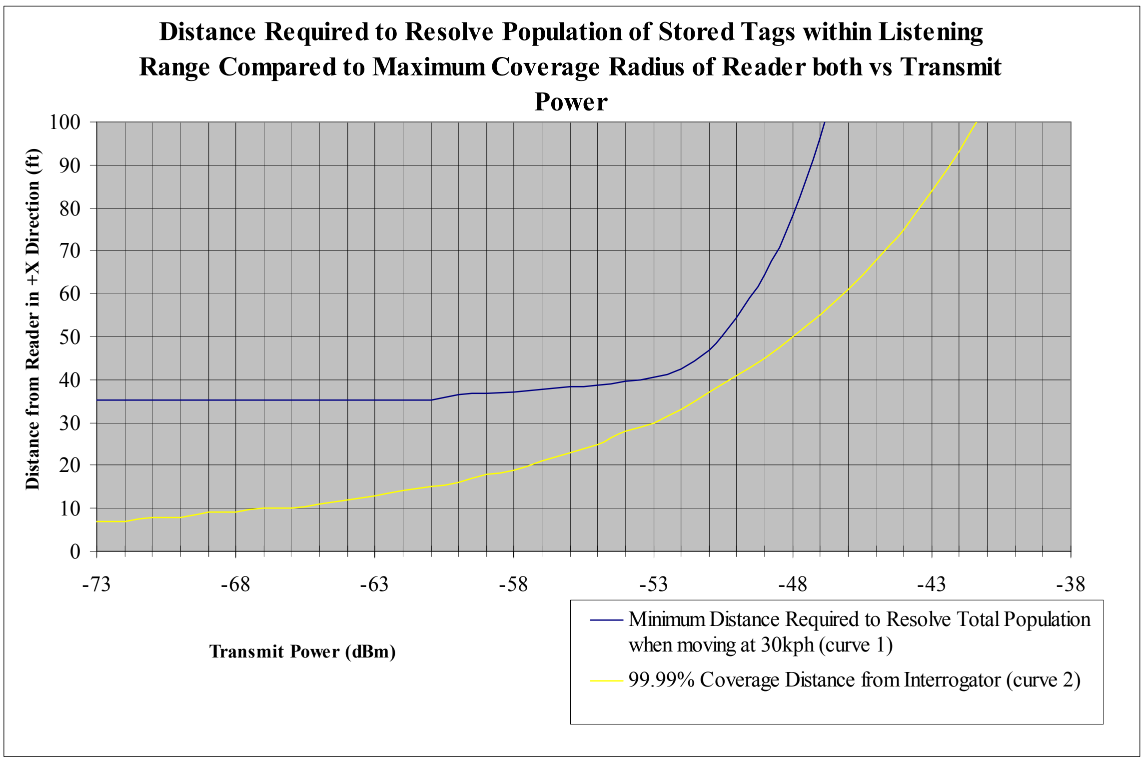

Figure 16: Solution Set for Moving Vehicle Problem

The main cause for this problem is the time it takes to resolve the tags unintentionally responding to the collection command making the value of D large as compared to C. If the time to resolve the population of responses is minimized, the value of D can be minimized which would make curve 1 go lower and intersect with curve 2.

5.3 Lift Location (Gantry Crane)

In this example it is assumed that the interrogator is in position on the bottom side of the boom, in place just above the hook. The interrogator has two antennas each with a 3dB beamwidth of 60^0 aimed at either side of where a tag would be. Note the following depiction:

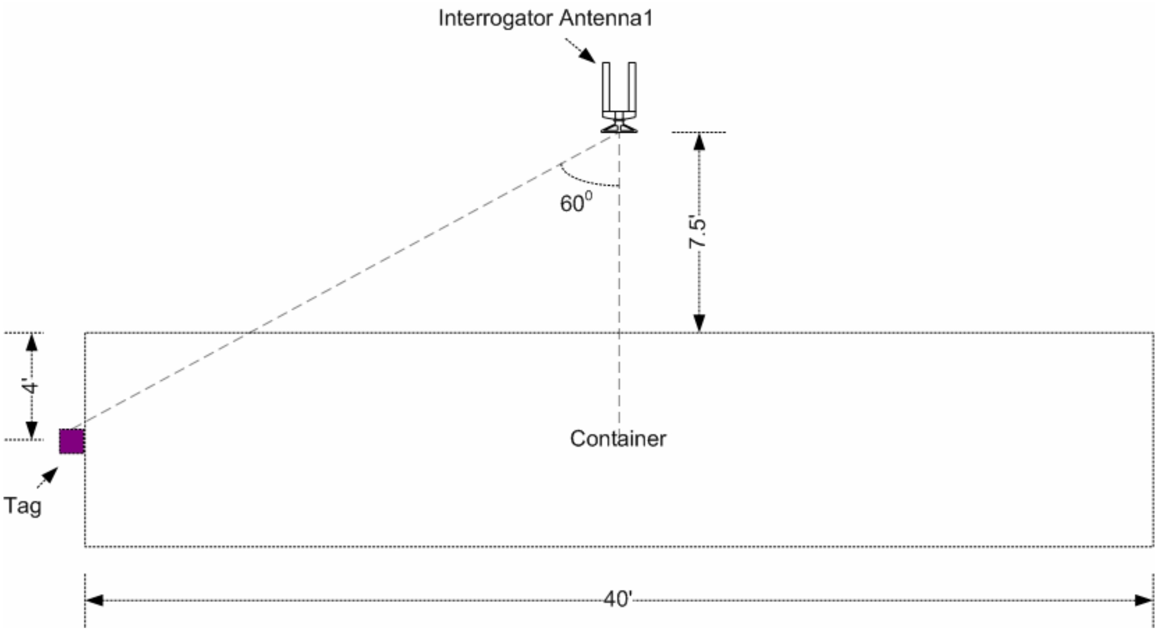

Figure 17: Interrogator Position Specifics for the Gantry Crane (Antenna Aimed at Left Side)

With the following positioning it is assumed that the antenna gain at the tag on a 40' container is 7.7dB – 3dB = 4.7dB.

As mentioned there is a second antenna aimed at the other side of the hook, with the exact same specifics as the first antenna (depicted below):

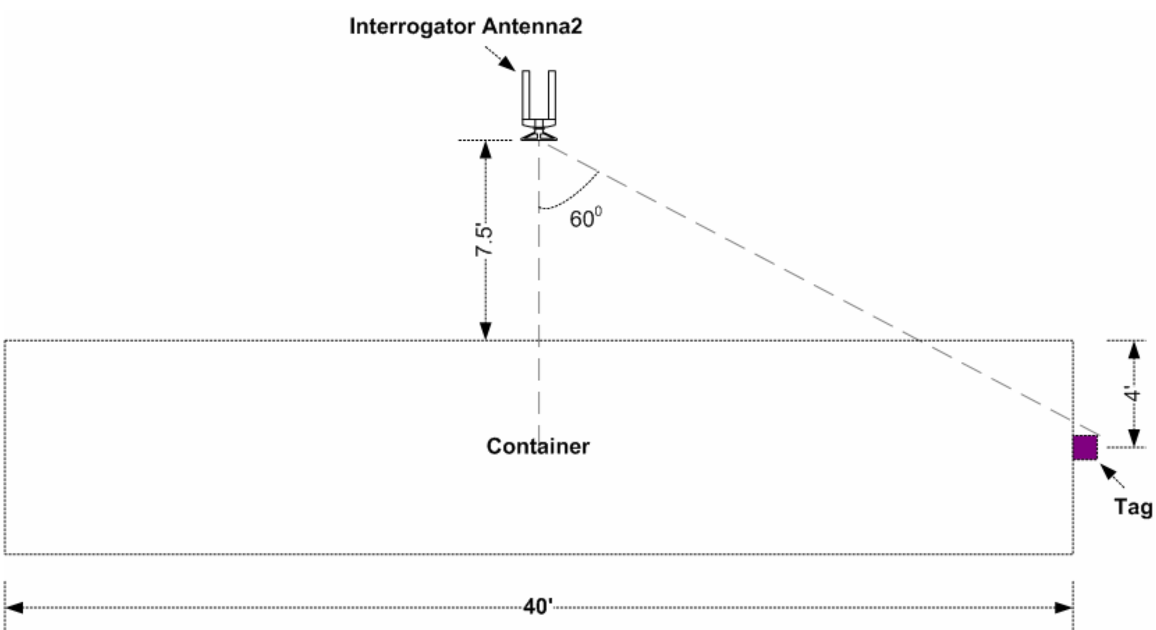

Figure 18: Interrogator Position Specifics for the Gantry Crane (Antenna Aimed at Right Side)

The tag on a 20' container shall have better antenna gain because it shall only be 11^0 off of center:

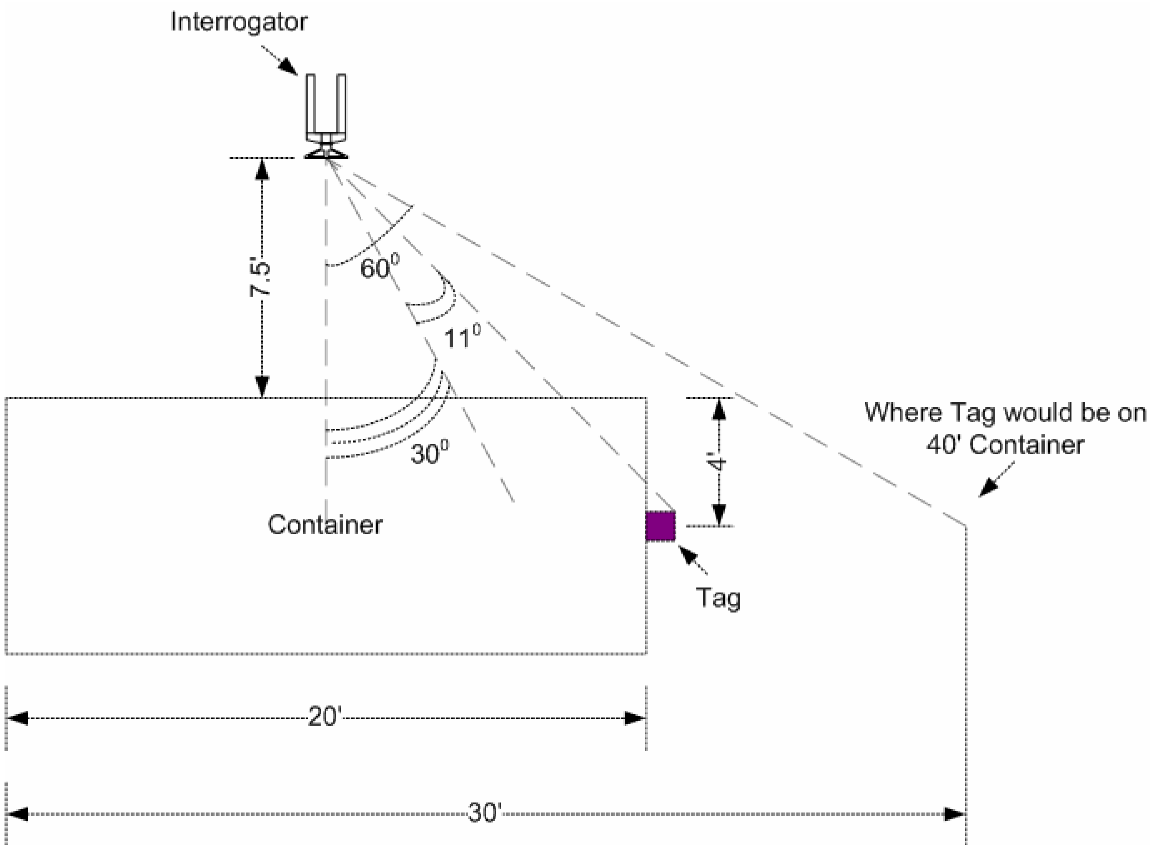

Figure 19: Interrogator Position Specifics for the Gantry Crane – 20' Container Example

Referring to Figure 11 to determine the transmit power:

- The sensitivity is taken to be -104dBm
- Both the freespace attenuation plus the diffraction loss shall be take to be -54dB at 20' (as indicated in Figure 11)
- The antenna gain shall be taken to be 7.7dB – 3.0dB = 4.4dB. This antenna gain is chosen because of the system configuration previously described. It is assumed the worst case situation where the tag is on one end of a 40' container. The worst case antenna gain seen shall be 4.4dB.

All of this indicates the transmit power should be -54.7dBm

Again, as stated in Section 5.1, there are two opposing forces:

1. A minimum power level must be transmitted by the interrogator in order to reach the immediate container just under the hook with a reliability of 99.99%
2. The more transmit power used, the more tags on neighboring containers shall respond and unintentionally interfere and delay resolution of the intended (desired) tags.

The amount of responses on containers that are currently in place on the ship can be plotted with the following assumptions:

- Assume that ~1500 containers are on the ship and the hook with the reader is over the center of the ship.
- Assume that the containers are stored 8 high, 20 columns wide, 10 columns deep.

- Take the freespace attenuation and the diffraction as a function of position relative to the interrogator (as indicated in Figure 11)

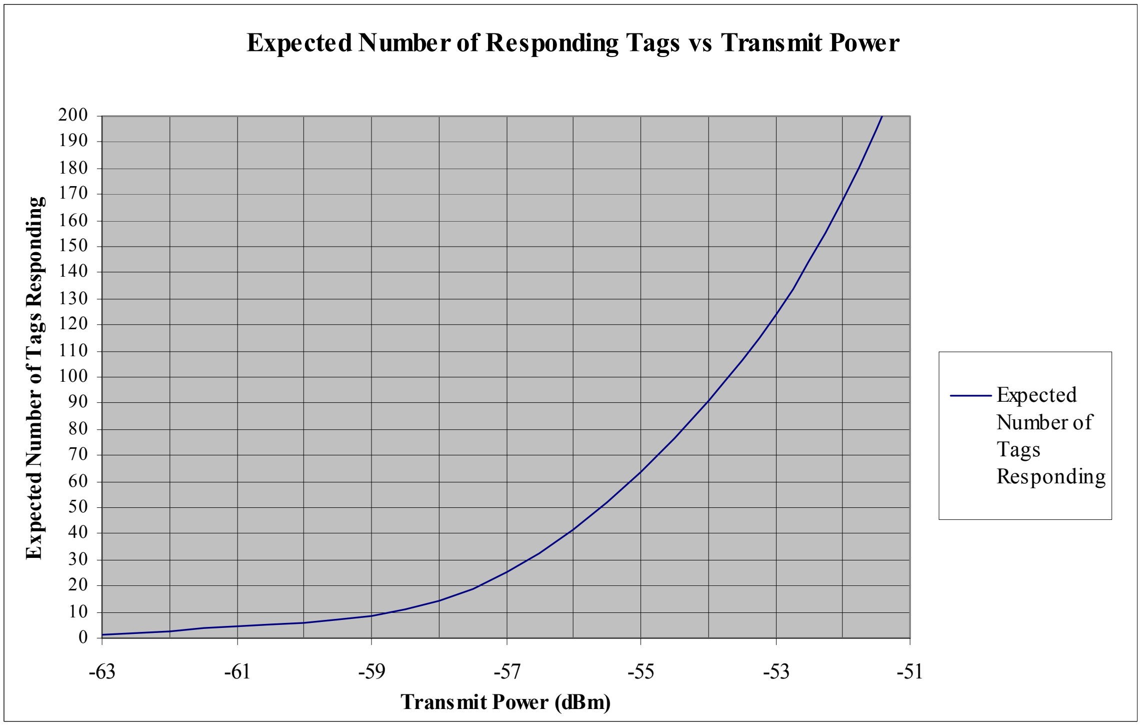

Figure 20: Expected Number of Responding Tags vs Transmit Power for Lift Scenario

Therefore it can be expected that there shall be 70 respondents.

Assuming the total amount of data payload in the responses is 20 bytes (as given in *Table 1*), the plot above can be scaled to indicate the total amount of time that shall elapse to resolve the responding population:

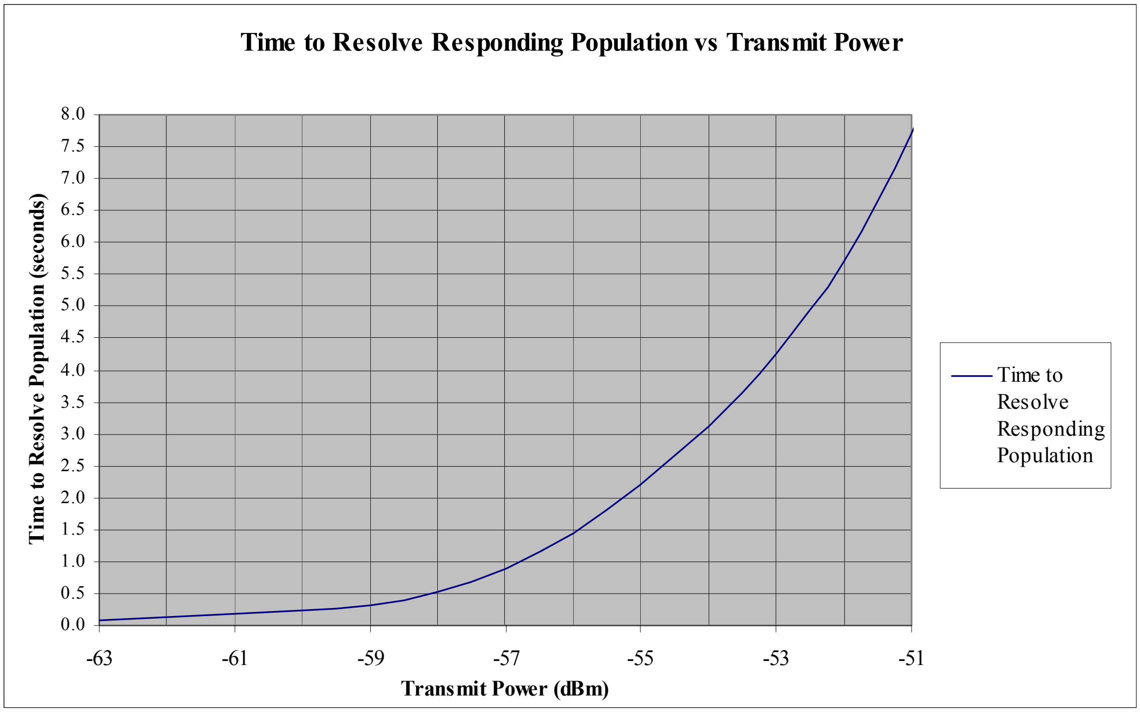

Figure 21: Time to Resolve Responding Population vs Transmit Power for Lift Scenario

From the plot above, it can be seen that it shall take 2.5 seconds to resolve the population with a transmit power of -54.7dBm.

2.5 seconds presents a serious issue just as indicated in section 5.1. It's more than double the amount of time allowed due to FCC restrictions. The FCC has regulated that the tag upon first responding to a collection command, has only 1 additional second of time in which it may transmit subsequent responses. After the one second, the tag must cease transmissions for 30 seconds. If the entire population cannot be resolved within 1 second, there is a probability that the tag shall not be resolved by the interrogator for a period of 30 seconds or not at all. When referring to Figure 5, after 1 second, only (1/2.5) of the population shall be resolved, assuming the best case windowing algorithm (i.e. the 1 second allowed by the FCC divided by totalResolutionTime = 2.5 seconds means only 40% of the total time required to resolve the entire population of 70 tags will have elapsed in 1 second. This means, according to Figure 5, only 40% of the population of 70 tags will have been resolved.) Therefore 100%-40%=60% of the time, the tag shall not be resolved in this scenario which is far below 99.99% reliability.

If both the e-seal and license plate tag must be detected on a container and two 2.5 second wake-up's are required, one for each type of tag, the total time expended to resolve one vehicle's tags is:

(2.5 second wake-up tone) + (time to resolve license plate tag tags) + (2.5 second wake-up tone) + (time to resolve e-seals)

Or:

2.5 sec + 2.5 sec + 2.5 sec + 2.5 sec = 10 secs.

Therefore it shall take 10 seconds to fully resolve the tags on one container.

5.4 Interrogation of Grounded Storage

In this scenario an interrogator is moving at 10kph through an aisle of containers. The interrogator is using a 0dBi omni-directional antenna. On each side of the aisle are 20' containers, stacked 5 high. There are two tags (eseal and shipment) on the face of each container, both exposed to the aisle. This scenario has been depicted below (and drawn to scale):

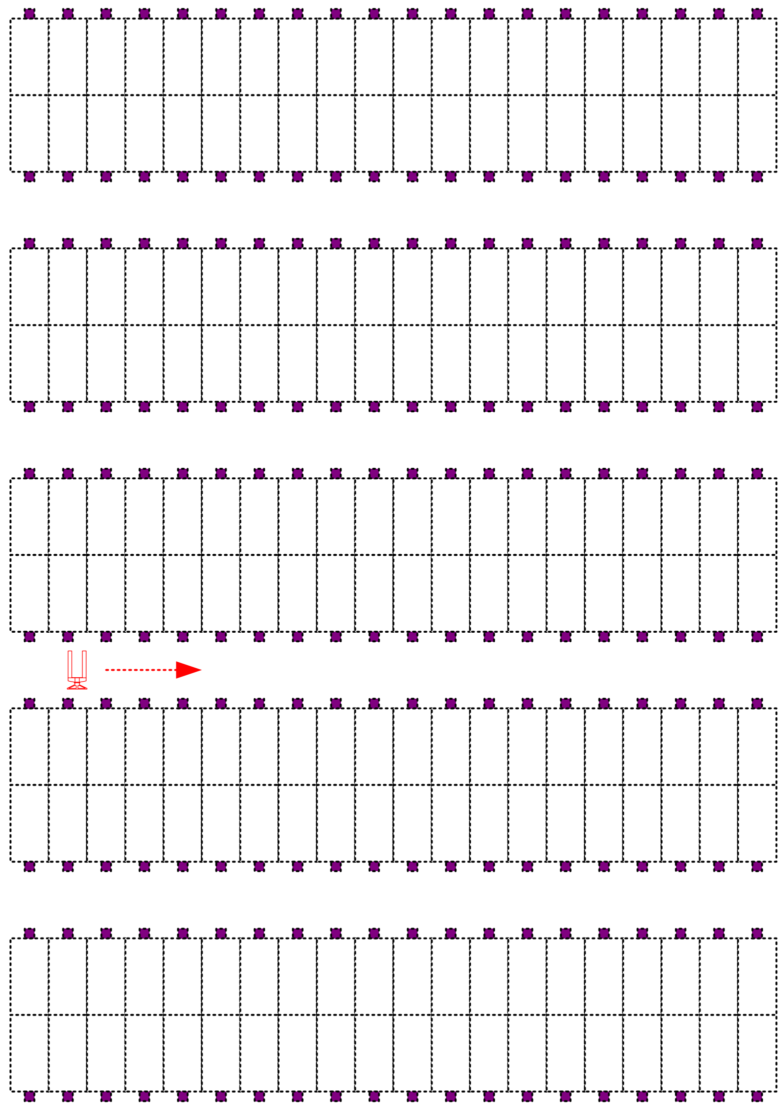

Figure 22: Bird's Eye View of Interrogator Moving Through an Aisle between Stacked Containers

Again, as stated in Section 5.1, there are two opposing forces:

1. A minimum power level must be transmitted by the interrogator in order to reach the highest container (the 5th container on the stack) with a reliability of 99.99%
2. The more transmit power used, the more tags on neighboring containers shall respond and unintentionally interfere and delay resolution of the intended (desired) tags. Because the interrogator is moving at 10kph, it's possible that this resolution delay may prevent the intended tag from hearing subsequent collection commands. The interrogator may simply drive out of range before the intended tag was ever resolved.

If the aisle is 20' wide, the interrogator is in the middle of the aisle and the furthest tags is 44' high (5 containers * 8'/container + 4'), the distance between the tags and the interrogator is 45'. Therefore the interrogator must transmit at a power level that enables the tags on the top container to receive the collection command with 99.99% reliability.

Assuming the only loss is due to free-space loss at 433MHz (assume there is no diffraction loss because the containers were arranged in such a way to expose the tags to the aisles for easier reception), the 99.99% coverage (detection) distance is plotted below versus transmit power. This is the maximum distance from the mobile interrogator the collection command can be detected with 99.99% reliability for the given transmit power :

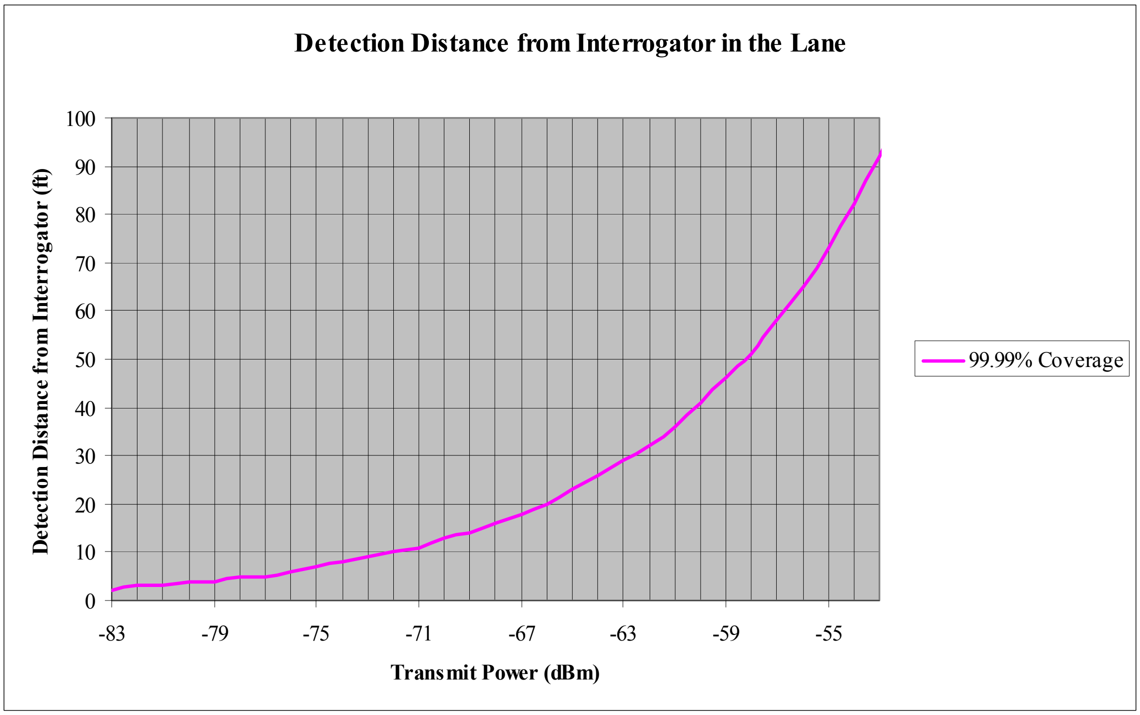

Figure 23: Detection Distance vs Transmit Power for Stored Container Scenario

One can see from this plot that the optimum transmit power is -59dBm (the free space loss is -45dB). However again, there is an expected number of nearby tags that shall also respond to the collection command.

The number of nearby tags responding to the collection command transmitted by the mobile interrogator has been plotted below. This assumes:

- A diffraction loss of 40dB for tags not in the same aisle as the interrogator.
- For tags in the same aisle, there is no diffraction loss.
- Only the containers in an approximate 500' radius from the reader are considered

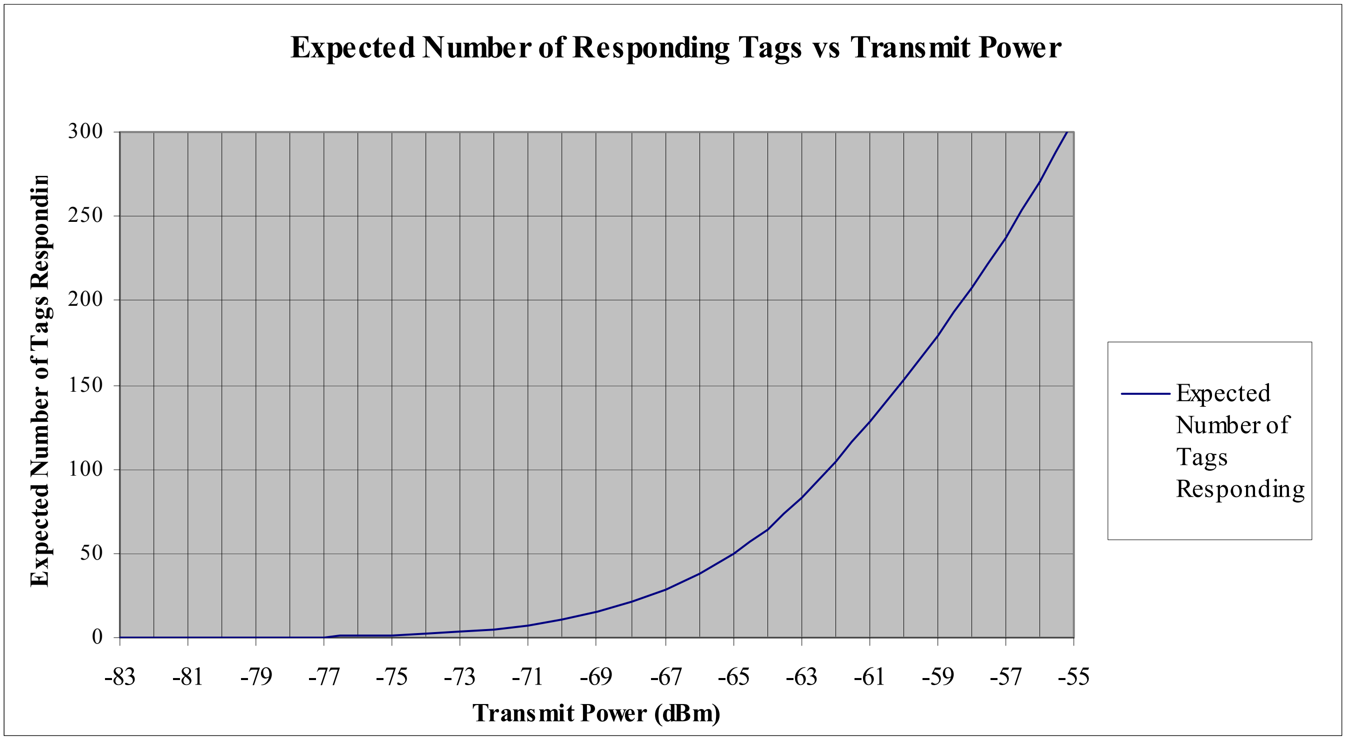

Figure 24: Expected Number of Tags Responding vs Interrogator Transmit Power for Stored Container Scenario

One can see that if the interrogator transmits at -59dBm, a large of number of responses are expected (i.e. 175 responses)

Referring to the totalResolutionTime equation given previously, the totalResolutionTime can be plotted versus interrogator transmit power. This assumes that all tags shall respond with a burst that contains no more than 45 bytes of data. The plot is depicted below:

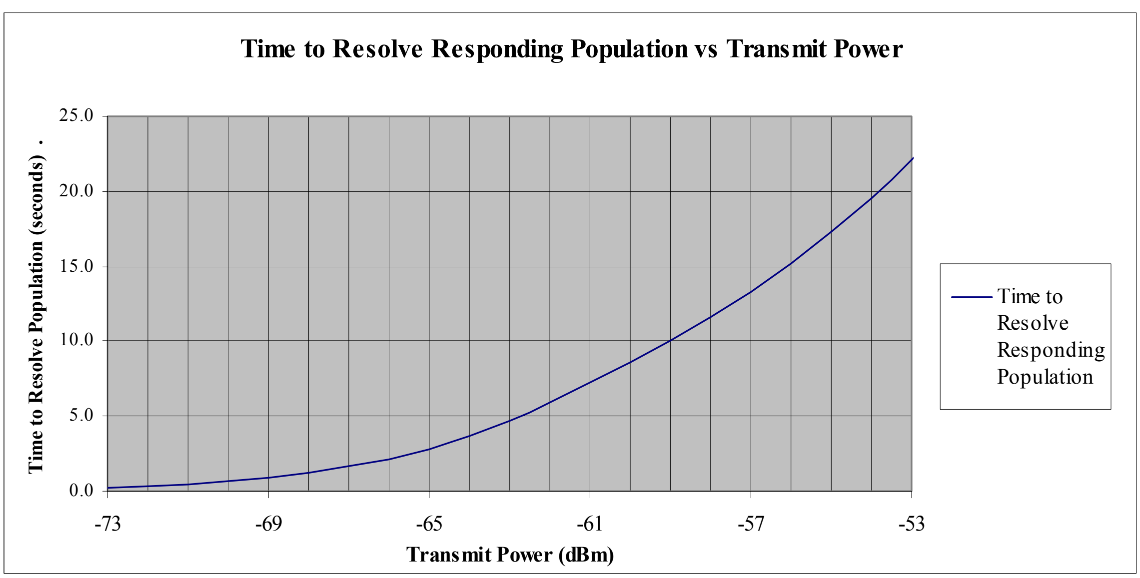

Figure 25: Expected Time to Resolve Responding Population vs Transmit Power for Stored Container Scenario

Referring to the above figure, it can be seen that the time to resolve the entire population will take 10 seconds (the transmitter is transmitting at -59dBm)

Note that there is a finite probability that the desired (intended) tags won't be resolved until the final iterations. For example, the desired tags may be in the last 10% of the total population left to resolve. If every tag has an equal probability of being in this set, that will occur 10% of the time. If one were to refer to Figure 4, one can then see that it shall take (2.45/e) to reach 90% resolution. In this example, if transmitting at -59dBm, the amount of time it would take for the desired tags to be resolved would be (2.45/e) * 10 seconds = 9 seconds.

If the vehicle upon which the interrogator responds is moving at 9ft/sec (10kph), the vehicle will have traveled 81' in 9 seconds.

Below is depicted the probabilities of collection command detection (by a tag) versus distance (the tag is from the interrogator) for various interrogators transmit powers:

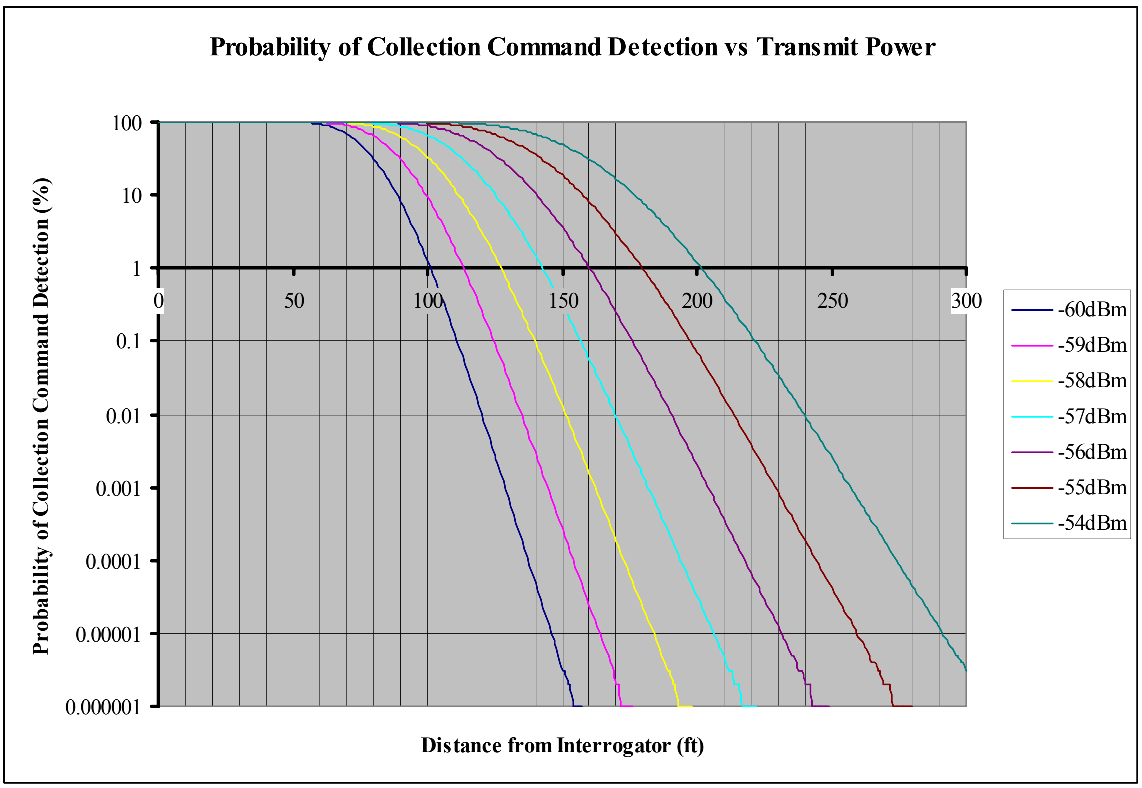

Figure 26: Probability of Collection Command Detection vs Transmit Power (logarithmic), Stored Container Scenario

The above plot is also represented linearly below:

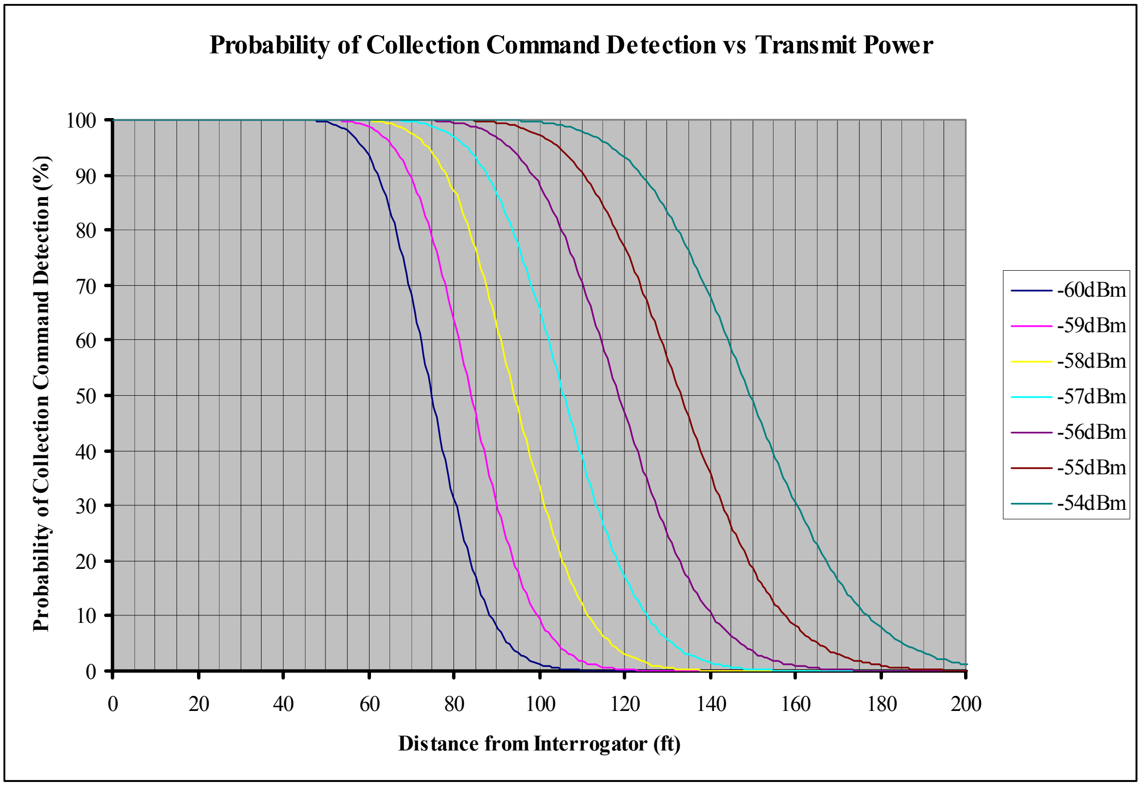

Figure 27: Probability of Collection Command Detection vs Transmit Power (linear), Stored Container Scenario

Note that if the interrogator moves 81' from the original location from which the 1st collection was initiated, there is 80% chance of collection command detection by the tag if the interrogator issues subsequent collection commands 81' away. 10% of the time, the interrogator will have moved this distance (10kph multiplied by 9 seconds) before the tag was ever resolved by the interrogator. The tag will need to hear a collection command in order to be eventually resolved by the interrogator.

Actually this problem can be worked backwards. The 99.99% detection command probability is at ~56'. At 9'/sec, it takes 7 seconds to traverse 56'. As stated earlier, it would take 10 seconds to resolve the population that heard the first collection command. Therefore this system has 7seconds/10seconds =70% system reliability of detecting the tags to which the interrogator intended.

6. Summary

As shown in the above analysis, ISO 18185 and ISO 18000-7-based products will perform in environments where small populations need to be read or when a system reliability of substantially less than 99.99% is acceptable. However, the analysis also clearly shows that in environments with realistic tag and seal populations, several issues arise including the real probability of missing reads and transmitting in violation of US FCC regulatory rules. System engineering efforts and time consuming fine tuning in the field will solve some, but not the vast majority, of these issues.

Increasing the available bandwidth through the use of a more sophisticated modulation and utilizing more efficient communication coordination schemes will ensure tags, seals, and readers to perform at the 99.99% reliability level in the challenging RF environments faced in locations containers are used. The higher number of tags resolved per time slot would enable the system to resolve the entire responding population in a timely fashion and within the constraints imposed by regulatory agencies like the United States FCC.

Appendix A Scenario Parameter Information

Appendix A lists the compilation of parameter information collected from the original SWG document created by Dick Schnacke and appended using inputs from SWG member emails.

A.1 General parameter information:

1) The analysis needs to take into account that readers are not operated at maximum power levels all the times.
2) Omni-directional antennas are assumed unless the communication zone overlaps a problematic number of devices. In this case, directional antennas with 60-degree beam width are assumed. Antenna gain is allowed, but over-ridden if needed by transmit power reduction.
3) Amount of information transmitted depends on application/scenario. Exact data quantities for the purposes of this analysis are provided for each scenario outlined below.
4) The specified data quantities do not include security overhead messages. The impact of security related overhead on system performance should be included within the analysis."
5) Per the ocean carrier community request, analysis should assume a target read reliability of 99.99% and a read accuracy of 99.999%.

A.2 Individual scenario parameter information:

Scenario #1: Gate/railhead location (Consider that these two locations are geometrically similar)

1) An 8-lane (each direction) gate in a perimeter fence. (This number was discussed in length to be as little as 3 gates and as large as 10-12. We use 8 as a logical compromise, given the number of facilities with multiple gates.)
2) Containers on chassis simultaneously resident in all eight lanes, but interrogations do not occur simultaneously in all lanes. Containers on chassis are in queue, 3 deep, in each of the 16 lanes. 25% of the chassis are loaded with two 20-foot containers. The other 75% have 1 40-foot container on the chassis.
3) Stored containers within the yard are arranged in 5-high stacks starting 50 feet from the gate.
4) Speed of passage is 30 KPH.
5) 20 bytes of data collected during interrogation of seals and container tags; 40 bytes of data collected during interrogation of shipment tags. Numbers do not include security overhead.

Scenario #2: Lift location (Consider a gantry crane, lifting container from chassis to ship stowage)

1) Tags & seals must be read at some point during lift (but not continuously).
2) Other containers in vicinity are on chassis in single file ahead of and behind container undergoing lift and on the vessel being loaded or unloaded.
3) Speed of passage is 10 KPH.
4) 20 bytes of data collected during interrogation of seals and container tags; 40 bytes of data collected during interrogation of shipment tags. Numbers do not include security overhead.

Scenario #3: Storage location: (Consider grounded storage in a dense arrangement)

1) Storage is 5-high, 20-wide, 2-deep blocks with access lanes between blocks.
2) Speed of passage is 10 KPH. (This number was discussed in length to be as little as 0 and as large as 25 KPH. We use 10 KPH as a compromise, as it is assumed that the reader is moving, yet slowly.)
3) 45 bytes of data collected during interrogation of seals and container tags; 60 bytes of data collected during interrogation of shipment tags. Numbers do not include security overhead.

A.3 Radio regulations parameter information:

All system simulations and tests must account for and conform to the relevant radio frequency regulations around the world, including those of the United States Federal Communications Commission (FCC) and similar organizations in various countries.

A.4 Tag & seal parameter information:

1) All containers in scenario equipped with two tags and one seal.

2) All chassis equipped with one tag.
3) Two conditions to consider:
    a. All tags & seals are active 433.92 MHz
    b. Chassis tag + one container tag are passive 860-960 MHz. Other container tag + seal are active 433.92 MHz.