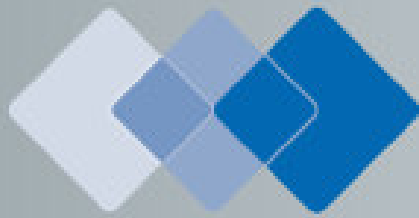




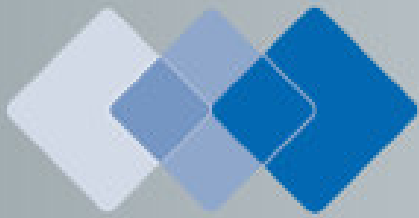
Performance Benchmarks for Passive UHF RFID Tags

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University of Kansas



- ◆ RFID – Introduction
- ◆ Need for Benchmarks
- ◆ Universe of RFID
- ◆ Passive RFID – Working
- ◆ What is Performance in RFID ?
- ◆ Benchmarks – Read Performance and Write Performance
- ◆ Interesting observation on tag-reader system
- ◆ Conclusion



What is RFID?

- ◆ Radio frequency identification (RFID) concept originated from World War II
- ◆ Has been used for animal tracking, toll-collection, access control and security
- ◆ Has found use in automatic identification (Auto-ID) of consumer products and goods since 2000
- ◆ Current Auto-ID technologies – **bar codes**, smart cards, voice recognition, biometric technologies, optical character recognition, **RFID** etc.

RFID vs. Barcode

- ◆ Non line of sight
- ◆ Simultaneous identification
- ◆ Data storage
- ◆ Read / write
- ◆ Durability
- ◆ Not easy to replicate





Potential of RFID in Supply Chain

How RFID is used ?

- ◆ Unique ID on each item
- ◆ Track and trace through supply chain
 - ◆ Pallets (current)
 - ◆ Cases (current)
 - ◆ Items

Potential to businesses

- ◆ Greater visibility through the supply chain
 - ◆ Real-time information
 - ◆ Fewer out-of-stocks
 - ◆ Lower inventory
- ◆ Reduced shrinkage
- ◆ Anti-counterfeiting
- ◆ Automatic faster checkouts





Mandates and Recommendations



METRO Group
Future Store Initiative

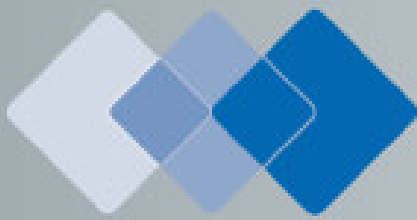


U.S. Food and Drug Administration



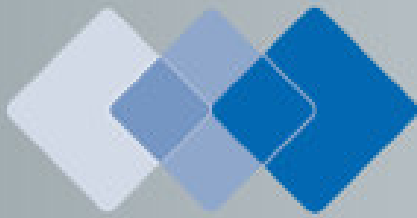
UNITED STATES DEPARTMENT OF
DEFENSE





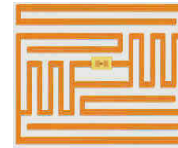
Need for Benchmarks

- ◆ Aggressive mandates
- ◆ Ignorant market
- ◆ Need to separate facts from hype
- ◆ No current established performance benchmarks for RFID
- ◆ RFID Alliance Lab created to serve as a useful, credible and unbiased source of information for RFID products
- ◆ Performance not conformance



Universe of RFID

- ◆ Chip / chipless tags
- ◆ Power



Chip tag



Chipless tag

Tag type	Battery	Transmitter
Active	Yes	Yes
Semi-passive	Yes	No
Passive	No	No

- ◆ Frequency of operation (generally at various ISM bands)

Frequency band	Maximum read range*	Tag type
LF – 125 kHz / 134 kHz	2 feet	Passive
HF – 13.56 MHz	5 feet	Passive
UHF – 915 MHz	20 feet > 100 feet	Passive Active
Microwave – 2.4 GHz, 5.8 GHz	Around 100 feet	Active

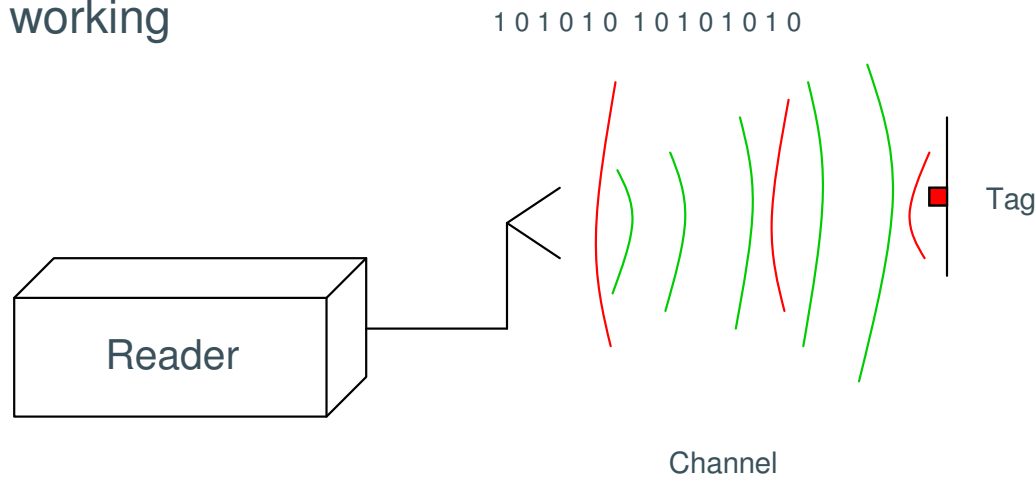
* Maximum read range increases with improvement in technology and changes in environment.



How Passive RFID works ?

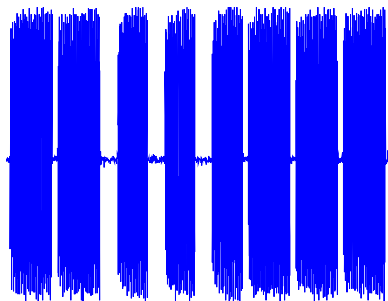
◆ Passive RFID working

1. Transmit carrier
2. Transmit command
3. Transmit carrier
4. Receive response



1. Power up
2. Receive command & Interpret command
3. Backscatter response

Reader to tag



Mismatched

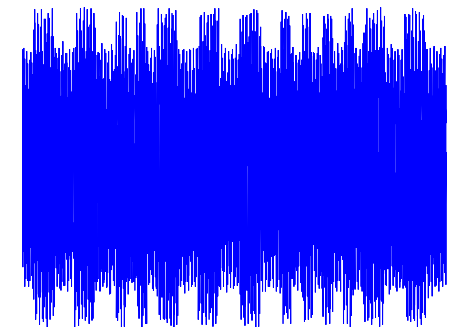


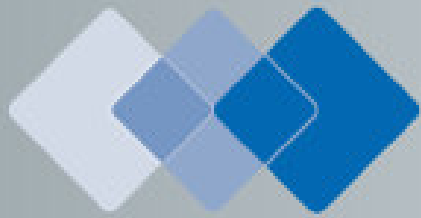
Matched



Tag to reader

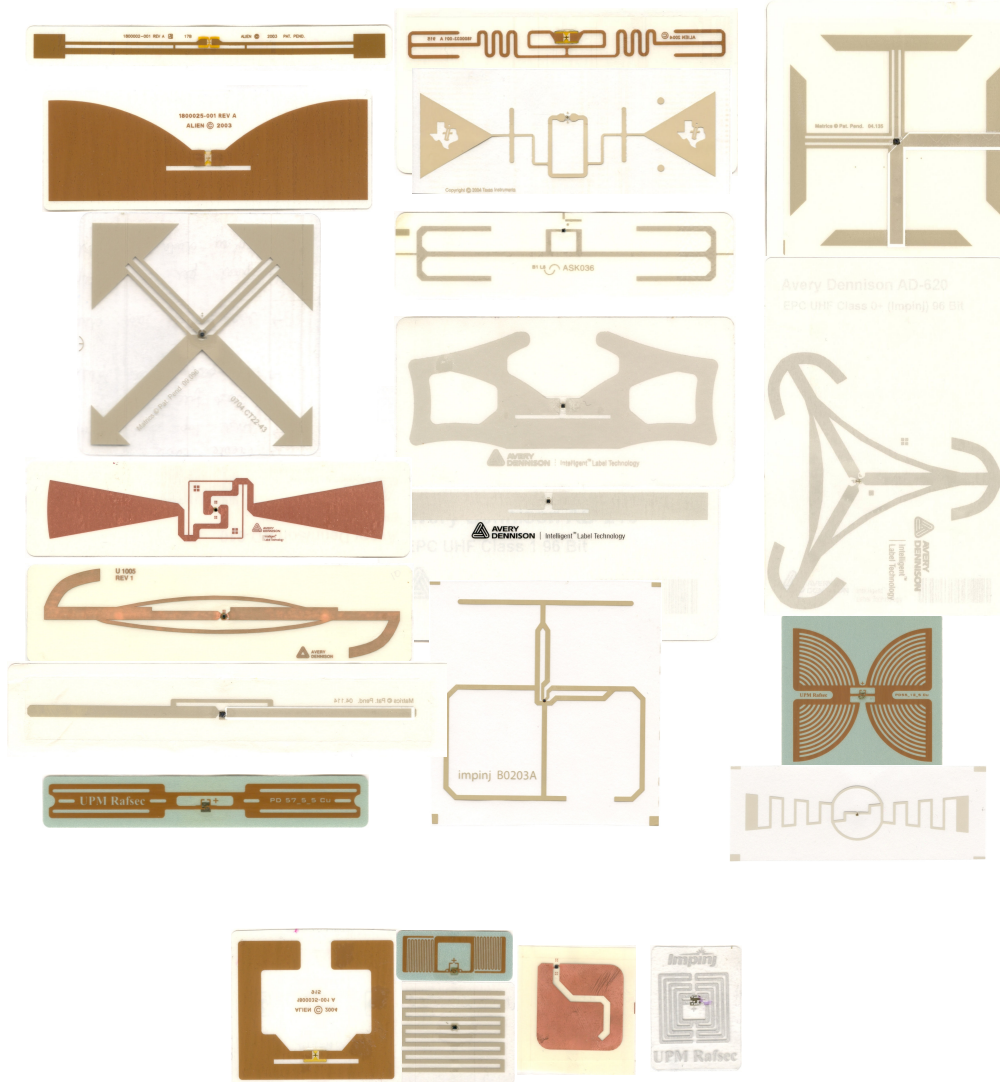
0 0 1 0 0 0 1 1 0 0





Sample UHF Tags and Readers

Sample tags in commercial market



Sample RFID readers





Challenges in UHF RFID

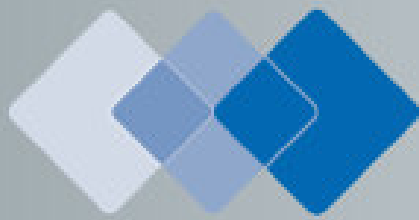
- ◆ Performance factors – tags, readers, and the environment (includes the channel)
- ◆ Effects of channel
 - ◆ Attenuation
 - ◆ Multi-path
 - ◆ Interference from readers and RF devices in ISM band
- ◆ Water / metal effects in UHF
- ◆ Interference from other tags in vicinity
- ◆ Standards



Standard	Capability	Communication	Collision Resolution
EPC Class 0	Read only	Full duplex, bit by bit	Binary tree approach
EPC Class 1	Read / write	Half duplex, packet based	Wake, read, sleep

- ◆ Common functions
 - ◆ Reading
 - ◆ Writing / programming

To overcome challenges and understand performance in RFID, we need benchmarks



Approach

- ◆ Identification of the characteristics of tags that need to be measured e.g. Distance, Read speed, Consistency etc.
- ◆ Benchmark for each characteristic defined as:
 - ◆ Objective to be measured
 - ◆ Test procedure that should be adopted. Also, contains the parameters / conditions under which measurement is made.

Test Parameter	Value
Environment	Anechoic Chamber
Reader Model	Factory Reader model
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Separation between reader and tag	3 feet

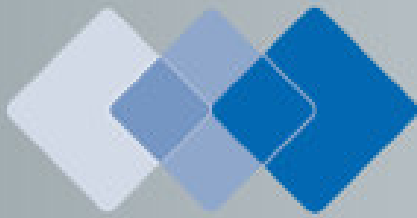
- ◆ Test metrics
- ◆ Our experiment
 - ◆ Sample result
 - ◆ Interpretation of result and lessons learned



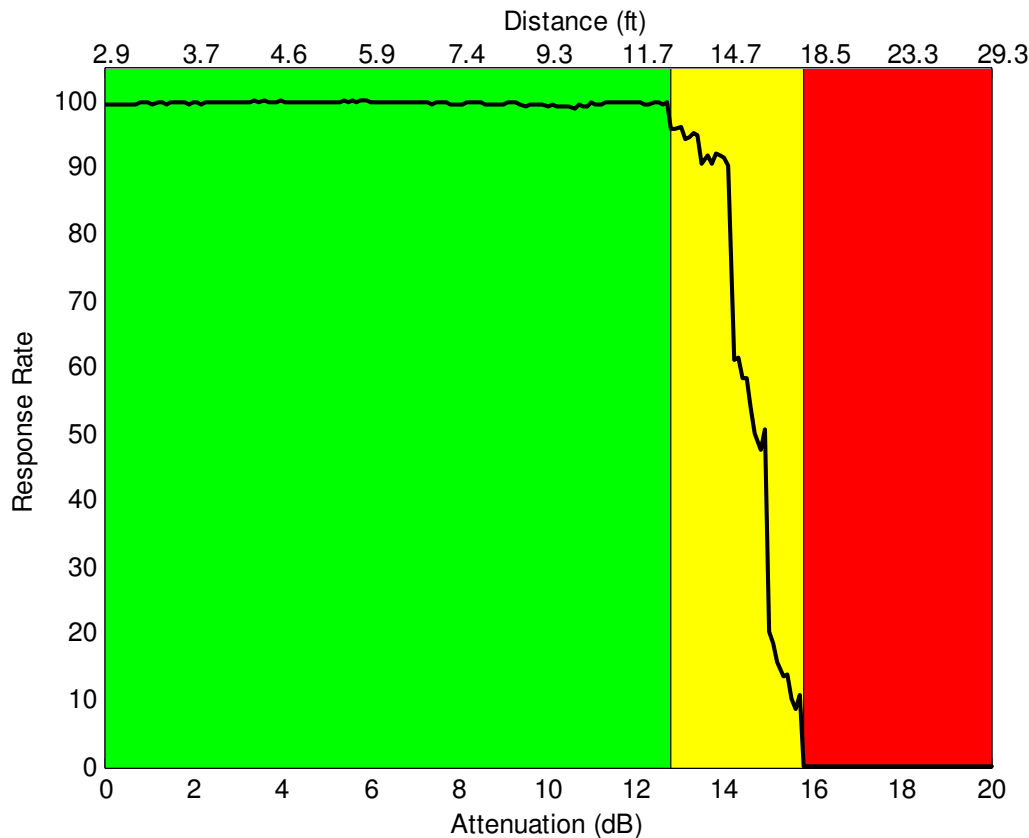
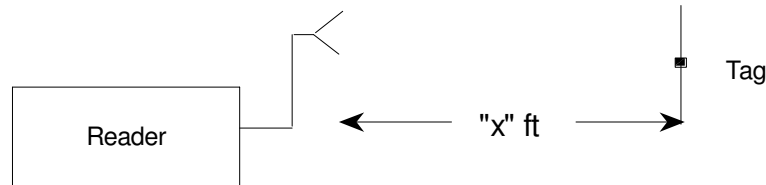
Benchmarks for Read Performance

- ◆ Tags can occur in a variety of scenarios
 - ◆ Static / Motion
 - ◆ Isolation / Population
 - ◆ Free-air / In front of materials

Benchmarks	Measured characteristic
Response rate vs. attenuation	Distance
Orientation sensitivity	Orientation
Variance of tags	Consistency
Read performance in front of metal / water	Material effects
Read rates in isolation	Speed
Read rates in population	Throughput



Tag Performance vs. Distance



Test procedure

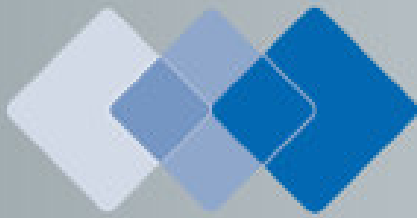
- ◆ x should be such that the tag is in far-field
- ◆ Response rate = $\frac{\text{Successful reads}}{\text{Attempted reads}}$
- ◆ Measure response rate as attenuation is increased in forward and back channel

Test metric

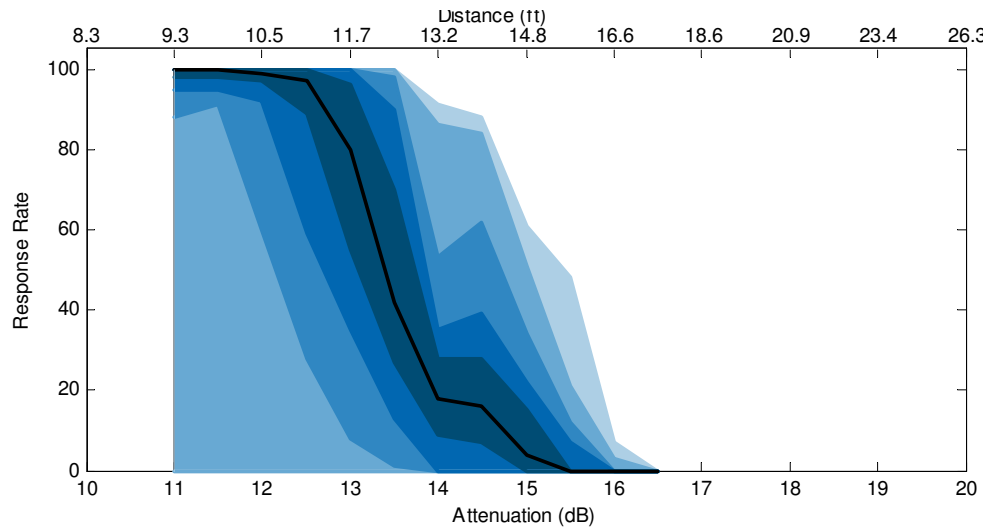
- ◆ Response rate vs. attenuation

Sample result for a commercial tag

- ◆ Three regions
 - ◆ Green – strong in-field
 - ◆ Yellow – weak in-field
 - ◆ Red – out of field
- ◆ For Class 0 tags, response rate in out of field > 0% “ghost reads” 0.1% of observed reads



Variance of Tag Performance



Range	Lower Bound	Upper Bound	% Included
Black	50%	50%	1 tag
Darkest	30%	70%	40%
	15%	85%	70%
	6.5%	93.5%	87%
Lightest	1%	99%	98%
	0%	100%	100%

- ◆ Variance in performance
 - ◆ Model to model
 - ◆ Tag to tag in the same model

Test procedure

- ◆ Measure response rate vs. attenuation for tags in a model at best orientation

Test metric

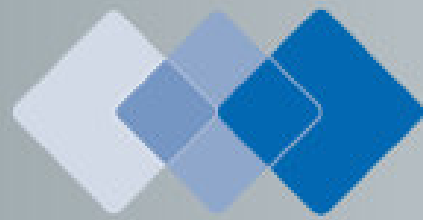
- ◆ Tags ranked from 0% (worst) to 100% (best) performing tag
- ◆ 1 Norm metric to compare and quantify two tags

$$\min_{\delta} \|f_1(x) - f_2(x + \delta)\|$$

f_1, f_2 – response rate vs. attenuation for tag 1, tag 2
 δ – shift to minimize the area
- ◆ Measure 1 norm metric for middle 98% tags

Sample results

- ◆ Typical variance from a commercial tag model = 6.2 dB
- ◆ % dead and quiet tags up to maximum of 20 %



Read Rates in Isolation

Test procedure

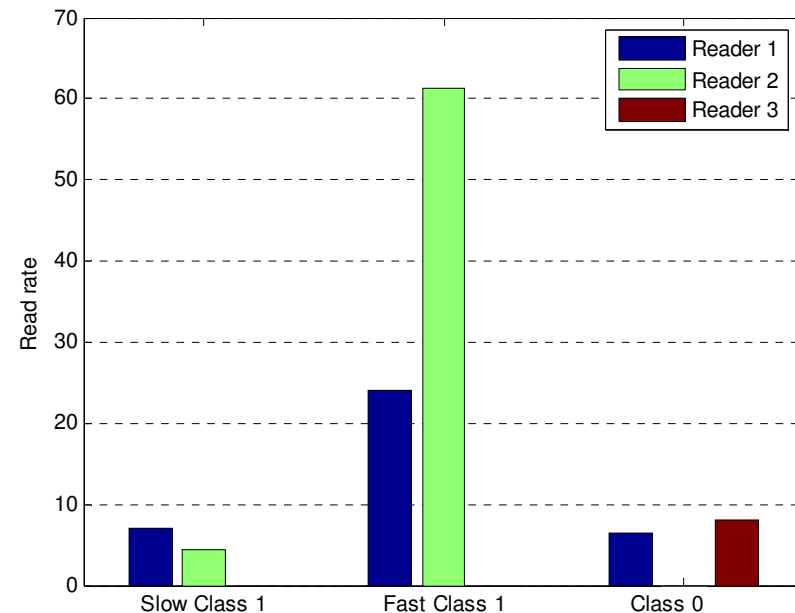
- ◆ Median tag, best orientation at a fixed distance
- ◆ Record the number of reads for a fixed duration of time

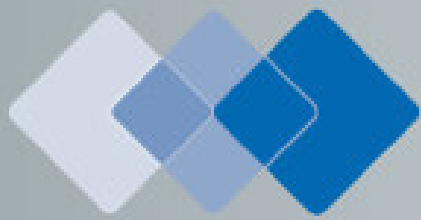
Test metric

- ◆ Read rate – number of reads per second

Sample results for three readers

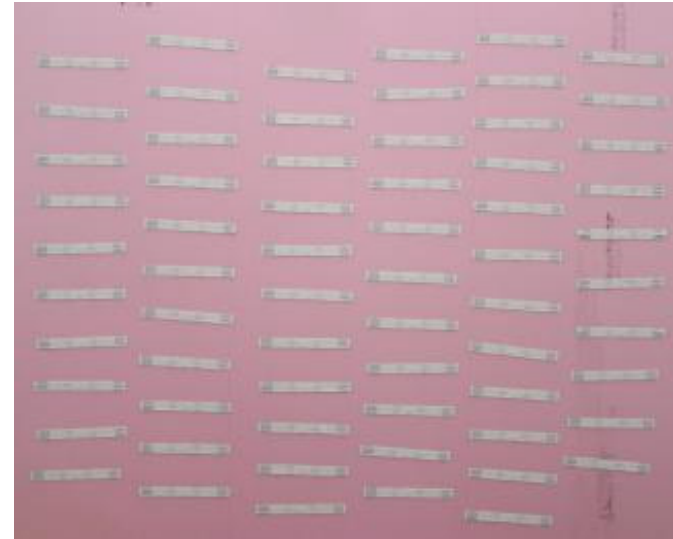
- ◆ Two groups of Class 1 tags
 - ◆ Slow and fast
- ◆ Isolation read rates dependent on tag-reader system
 - ◆ Similar trends across readers
 - ◆ Absolute values can vary to as much as 250 %
- ◆ Class 0 tags give consistent read rate

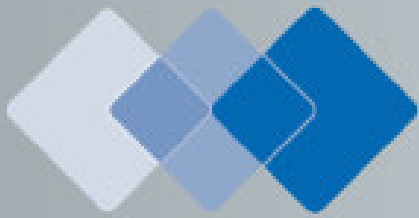




Read Rates in Population

- ◆ Common multiple tag scenarios
 - ◆ Items in a container
 - ◆ Cases in a pallet
- ◆ Population constraints
 - ◆ Variety of scenarios
 - ◆ Placement of tags
 - ◆ Tag size and interference
- ◆ Three experiments
 - ◆ Class 0 ~115 tags
 - ◆ Class 1 ~ 140 tags
 - ◆ Item-level Class 0, 48 tags





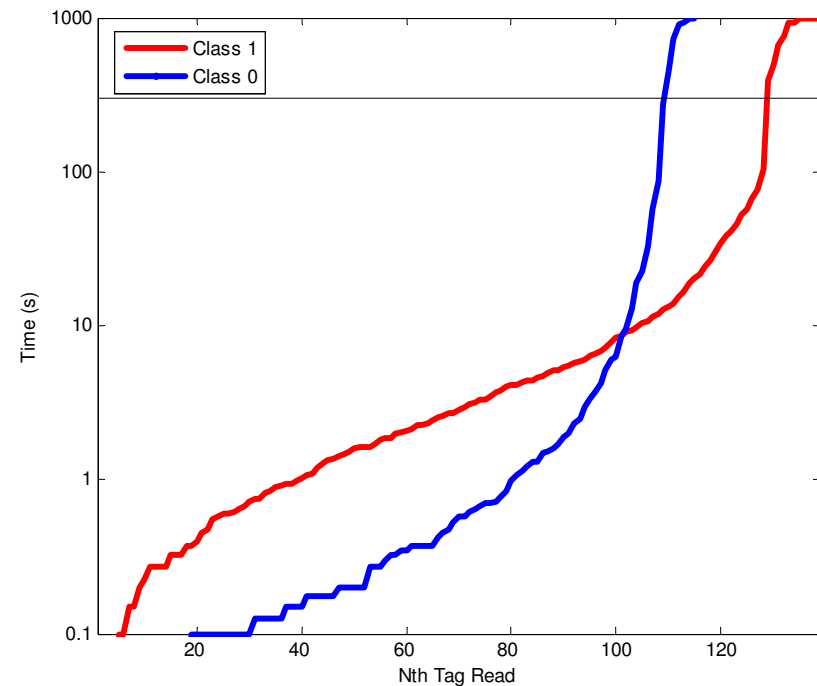
Read Rates in Population – TTFR

Population test metric 1

- ◆ Time to first read (TTFR) – time it takes for the reader to read the n^{th} new tag in population

Sample results

- ◆ Mean TTFR across 10 repetitions on the same setup
- ◆ Class 1
 - ◆ Linear TTFR until 90 tags then exponential
- ◆ Class 0
 - ◆ Exponential past 70 tags
 - ◆ Much faster than Class 1





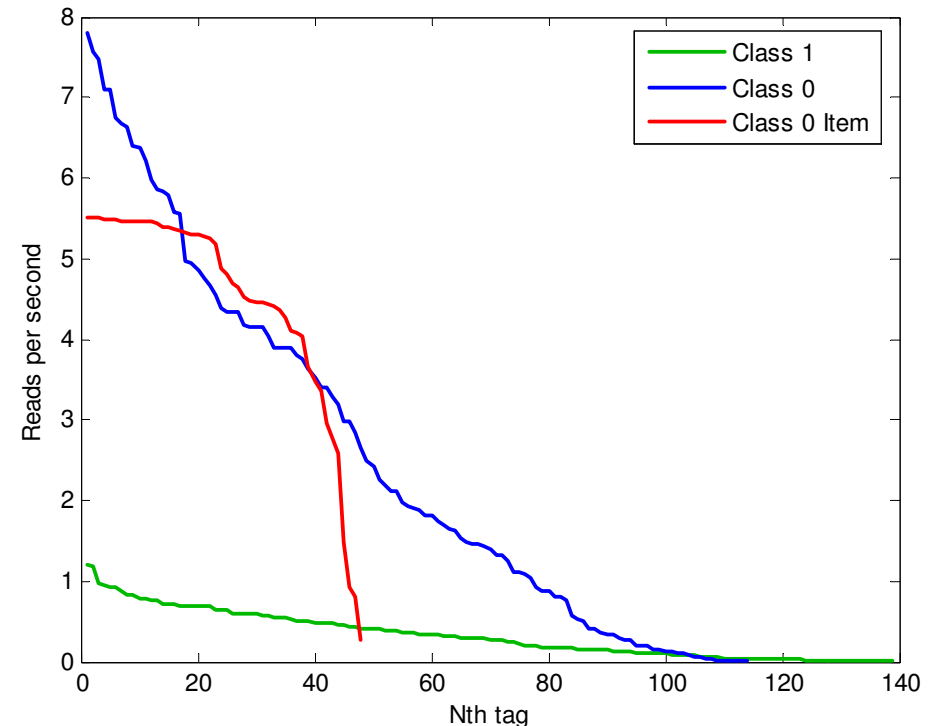
Read Rates in Population – Individual Tag Read rate

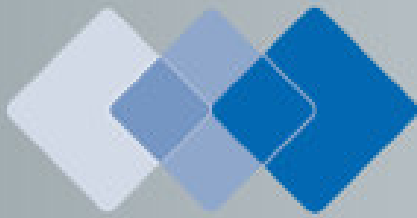
Population test metric 2

- ◆ Individual tag read rate – number of reads of each tag per second in population

Sample results

- ◆ Inferences
 - ◆ Class 0 item and Class 0 read rate remains close to isolation case
 - ◆ Class 1 read rates drops considerably
- ◆ Speculation on plot nature
 - ◆ Most Class 0 and Class 1 tags in the setup are in weak-field region
 - ◆ Class 0 item strong-in field region
- ◆ Class 0 scales better than Class 1 !!!





Performance In Front of Metal – Distance

Material effects in front of metal / water

- ◆ Performance in distance
- ◆ Frequency response

Test procedure

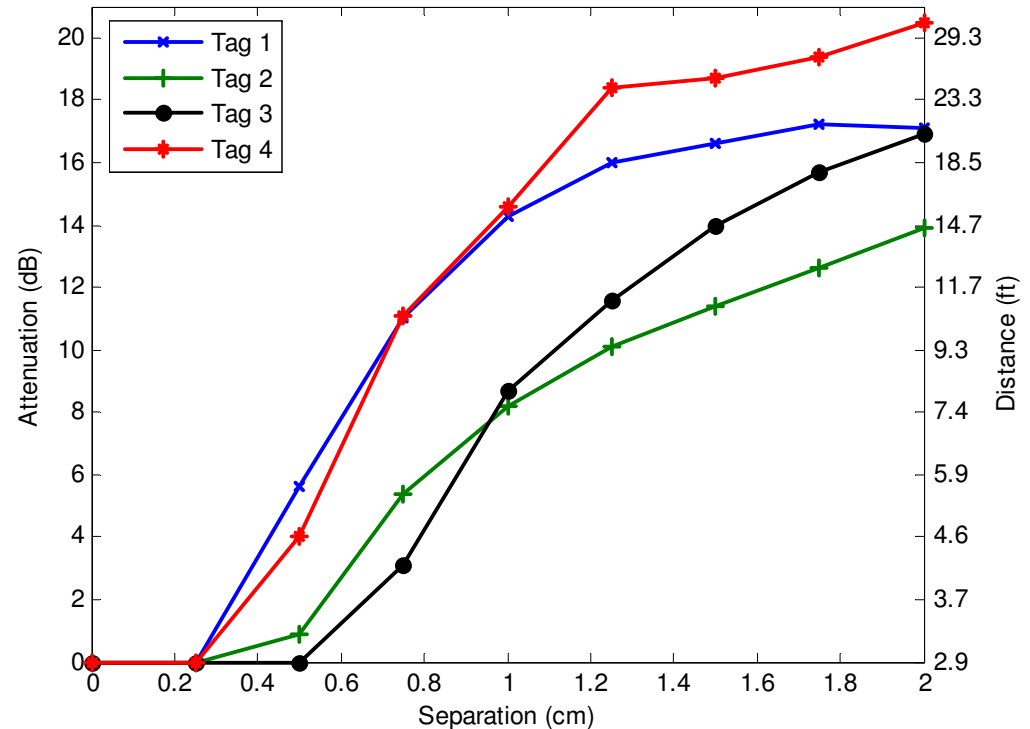
- ◆ Tag at fixed separations from big sheet of metal / big body of water
- ◆ Measure the attenuation at which tag becomes unreadable

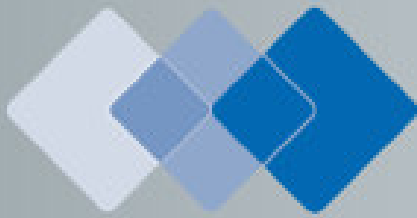
Test metric

- ◆ Separation in front of material vs. attenuation at which tag becomes unreadable

Sample results

- ◆ None of the tested tags worked in front of metal/water
- ◆ Apparent differences
 - ◆ Tag 1 performs much better than other tags at closer separation.
 - ◆ At greater separation, Tag 4 is the better tag





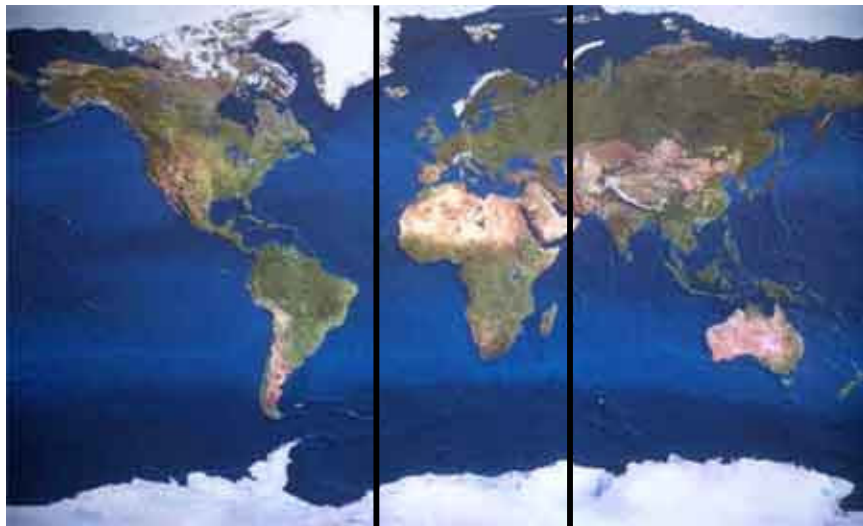
Performance In Front of Metal – Frequency Response

Test Metric

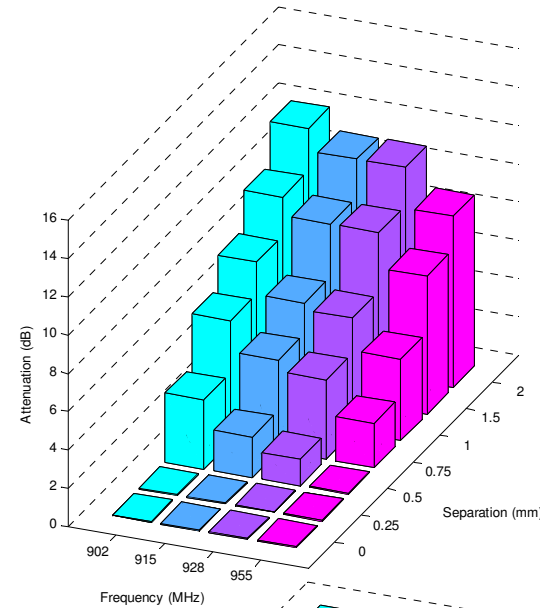
- ◆ For every frequency, measure the attenuation at which response rate goes down to 0%

Sample Results

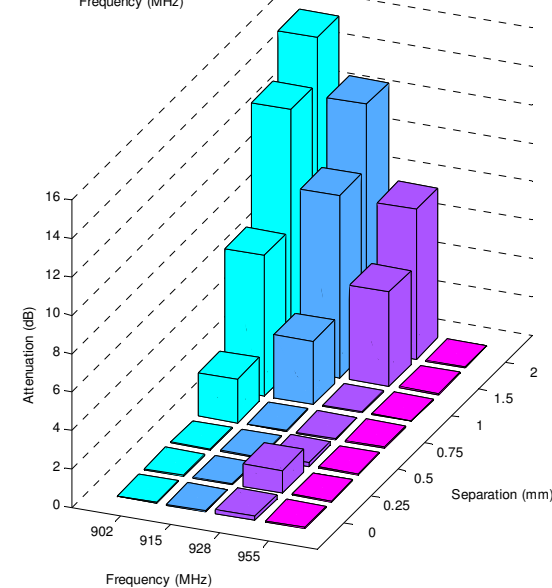
- ◆ Tag 1 and Tag 2 both work at all frequencies in free air
- ◆ Tag 1 works at ISM band in Japan whereas Tag 2 does not
- ◆ “Item level tags” have more frequency dependency compared to “Large tags”



North America	Europe	Japan
902-928 MHz	860 – 868 MHz	950 – 956 MHz



Tag 1



Tag 2

Interesting Observations – Channel Sensitivity

Objective

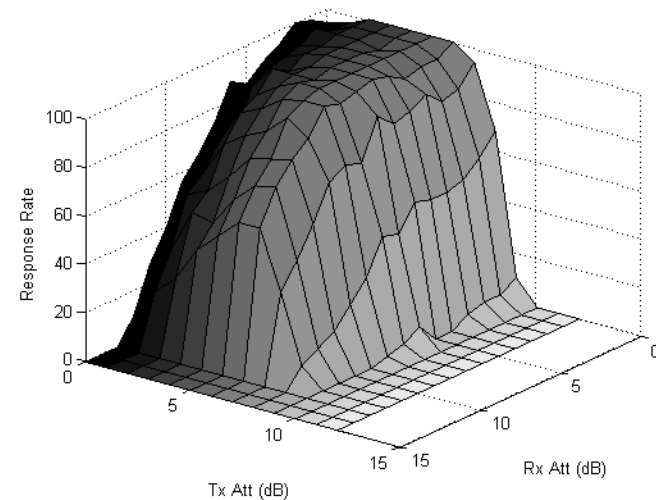
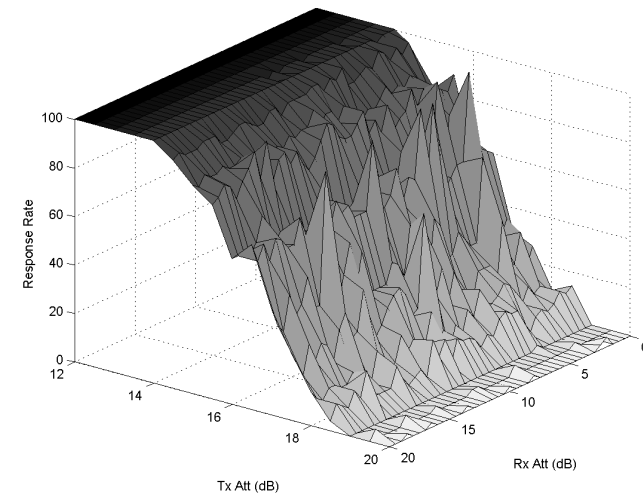
- ◆ To determine if forward channel attenuation can be used to simulate distance

Test procedure

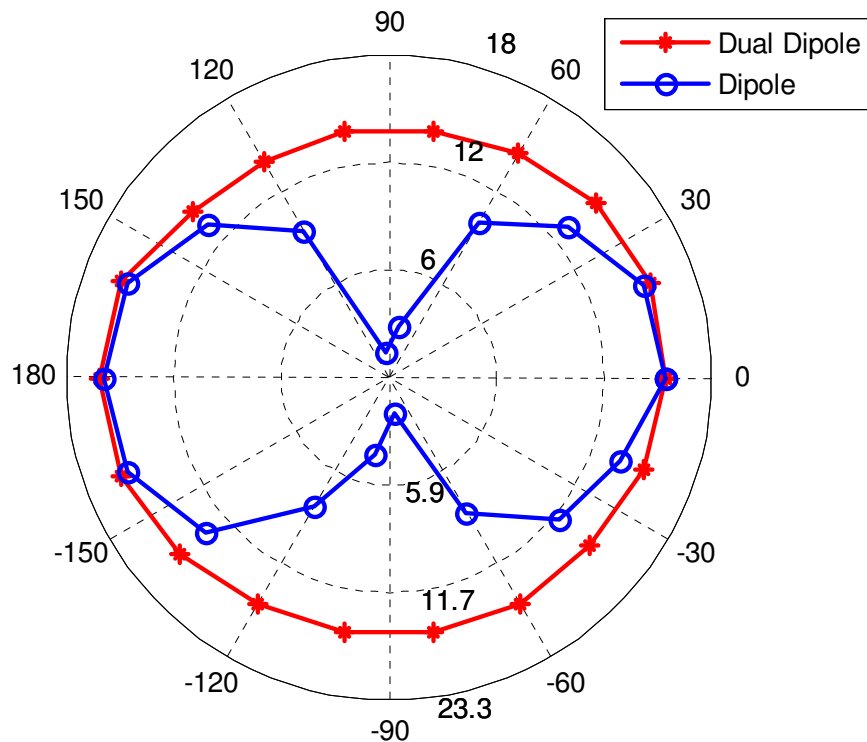
- ◆ Place the tag at its best orientation separated at a fixed distance from the reader antenna
- ◆ Attenuate both the transmit and receive lines for different values
- ◆ Measure the response rate of the tag at each value

Results

- ◆ Large tags
 - ◆ No sensitivity to receive channel attenuation
 - ◆ Forward channel power transfer is the dominating factor i.e. transfer of power to tag chip
 - ◆ Forward link-limited system at the tested distance
- ◆ Item level tags
 - ◆ Considerable sensitivity to receive channel attenuation
 - ◆ Reader sensitivity to detect the tag response plays a major role in determining performance



Orientation Sensitivity



Test procedure

- ◆ Rotate tags in two planes in fixed steps
 - ◆ E-plane and H-plane of dipole
- ◆ Measure the attenuation at which tag becomes unreadable

Test metric

- ◆ Attenuation at which response rate goes to 0% at each angle

Sample result for two Class 0 tags

- ◆ H-plane similar for all tags
- ◆ Two prevalent E-plane patterns
 - ◆ Long narrow tags – “Dipole”
 - ◆ Large square/triangular – “Dual Dipole”



Constraints in Writing to tags

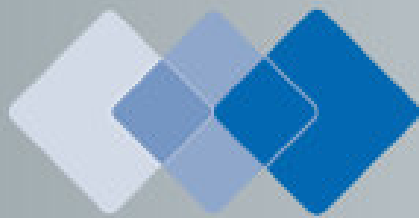
- ◆ Standards – only some tags are writable
- ◆ Power requirement – more power needed
- ◆ Only one tag should be present in the field
- ◆ More pronounced interference issues

Test procedure and metrics

- ◆ Try writing tag for a fixed number of times and record the time and the success of each of the writes

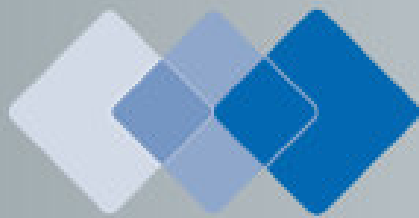
Lessons learned

- ◆ None of the tested tags were perfect
- ◆ Some tested tags were only 80% writable
- ◆ Write timings varied from 0.48 to 2.12 s



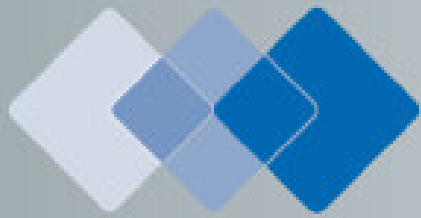
Open Questions

- ◆ Reason for Class 0 scaling better than Class 1 tags
- ◆ Analog measure for gain of tags in front of materials
- ◆ Changes in impedance bandwidth of tags in front of materials
- ◆ Custom reader to eliminate the unknowns with the commercial readers – pros and cons
- ◆ Common benchmark for dynamic testing



Conclusions

- ◆ First set of performance benchmarks for passive UHF RFID tags
 - ◆ Measures are relevant and intuitive to end-users
 - ◆ Scientific, repeatable way to compare performance of tags
- ◆ Observations often don't match hype
 - ◆ Today's RFID tags have read rates varying from as low as 20 tags/second to over 1,000 tags/second (quoted without reference)
 - ◆ We observed a range of 0 to 62
- ◆ Substantial differences between Class 0 and Class 1 tags
- ◆ Several interesting behavior with the tag-reader system
 - ◆ Variance of tag performance
 - ◆ Two sections in Class 1 tags – Fast and slow
 - ◆ Frequency dependence of tags
 - ◆ Characteristics of RFID tag-reader system for large and item-level tags
- ◆ Benchmarks does not answer all the questions but provide baseline information from where the end-users can start.



Thank you !!!