How RFID Works, Now and Future

9 May 2017, IEEE RFID 2017

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- Space Solar Power Institute
- Georgia Tech Research Institute

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Goals of Today's Tutorial

- Walk through RFID technology to understand
  - Where it has been (a little history of electronics)
  - Where it is now (how it works, current capability)
  - What it will become (innovation in the pipeline)
- Enjoy discussing RFID technology

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Who is This Tutorial Meant for

- General engineers who want to gain familiarity with RFID and Low-Energy Sensors
- Technologists interested in RFID
- Businessmen interested in evaluating RFID Technologies
- Advanced engineers who want to learn a new area to apply their craft

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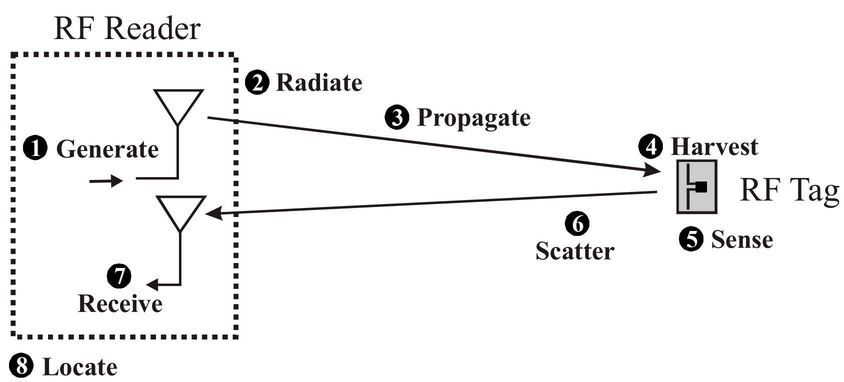
Visual Outline of Our Tutorial



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Terminology Used in this Talk

- VLF 30 kHz − 300 kHz (1 km < λ < 10 km)
- LF 300 kHz − 3 MHz (100 m < λ < 1 km)
- HF 3 MHz – 30 MHz (10 m < λ < 100 m)
- VHF 30 MHz – 300 MHz (1 m < λ < 10 m)
- UHF 300 MHz – 3 GHz (10 cm < λ < 1 m)
- Microwaves 3 GHz – 30 GHz (1 cm < λ < 10 cm)
- mm-Wave 30-300 GHz (1 mm < λ < 1 cm)

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Examples of RFID at Different Frequencies

- VLF RFID: Electronic Article Surveillance, Animal Tracking, Misc Sensing.
- HF/Inductive UHF RFID: Smart Cards, Farecards, Near-Field Communications, etc.
- UHF/ISO 18000-6C/Gen 2: Inventory, Logistics, Retail, Highway Tolling, etc.

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The EPC Gen 2 RFID Standard

- Spun out of AutoID Center (formerly AutoID Labs, headed by MIT)
- Published "The One Standard to Rule Them All" in 2005
- Concurrently ratified as International Standard Organization ISO 18000-6C Standard
- Extremely Flexible

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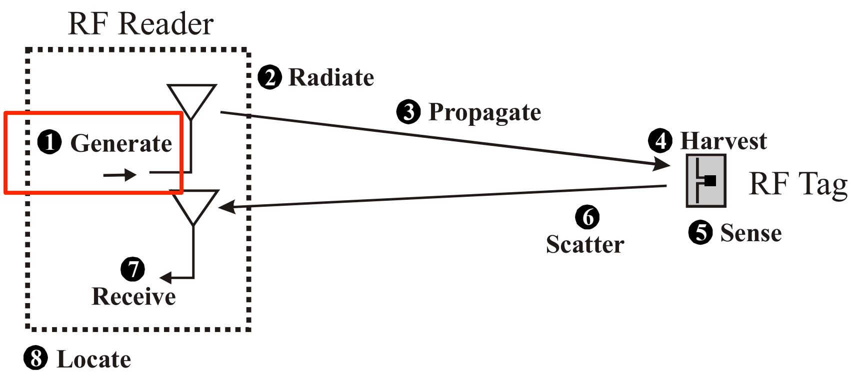
Section 1: Generate



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Part 15 Rules – Frequency Specifications

- Unlicensed band rules (including 915 MHz, 2.45 GHz, and 5.8 GHz)
- No more than 1 Watt into an Antenna
- No more than 6 dBi peak gain (a factor of 4) for transmit antenna
- Direct Sequence Spread Spectrum (DSSS) or Frequency-Hopped Spread Spectrum (FSSS)

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Digital or DSSS Systems

- A digital/DSSS system is any system modulating a carrier with digital symbols at a rate >= 500 kbps
- Allowed to "park" transmission on any channel within unlicensed band
- Examples: WiFi, ZigBee

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Frequency-Hopped Spread Spectrum (FHSS)

- Transmitted signal is "narrowband" – total RF bandwidth less than 1 MHz
- Must be an agile/hopping signal
  - Jump around 75 or more non-overlapping channels in 30 seconds or less
  - Examples: Bluetooth, UHF RFID

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International Regulations for ISM Bands

Europe	North America	Japan	Worldwide Tag Q	Bottleneck Bandwidth
863-868 GHz	902-928 MHz	950-956 MHz*	9.8	5 MHz
2.400-2.48 GHz	2.400-2.483 GHz	2.400-2.500 GHz	24.5	83 MHz
5.725-5.825 GHz	5.725-5.825 GHz	5.725-5.825 GHz	46.3	100 MHz

*changing to 917-923 MHz

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The Future…

- Higher Frequencies for RFID
- Multi-band Operation
- Lower-Power Oscillators
- Energy-Harvesting *Readers*

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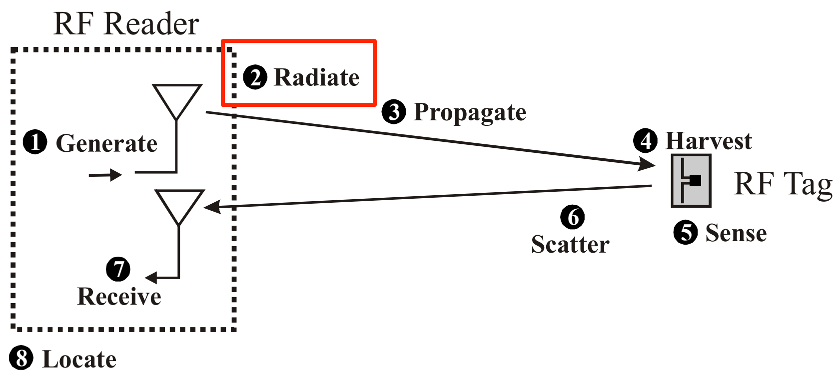
Section 2: Radiate



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Reader-to-Tag Communications

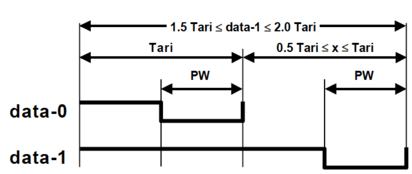

Figure 6.1: PIE symbols

- Reader to Tag communications uses Amplitude Shift Keying (ASK)
- Gen2 Uses Pulse Interval Encoding (PIE)
- High and Low transmission levels

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Antenna Shape vs. Pattern

- Beamwidth varies inversely to antenna dimensions
- Peak gain scales with wavelength

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Conventional RF Link Budget

$$P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2}$$

- P_t: Power Received by the Tag Antenna (Watts)
- P_T: Power Transmitted by the RFID Reader (Watts)
- G_T: Reader TX Antenna Gain
- G_t: Tag Antenna Gain
- λ: Wavelength (m)
- r: Reader-Tag separation distance (m)

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Broadcast to Broadcast Link Budget

- No a priori orientation, pointing knowledge
- Reader & Tag antennas transmit to/receive from any direction
- Therefore, these antennas *must* be low-gain
- Result: link loss will **increase** with the square of the carrier frequency (higher is worse)

$$P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2}$$

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Point-to-Broadcast/Broadcast-to-Point Link

- One antenna – either reader or tag – has a priori spatial knowledge
- The radio link may contain an aperture antenna that points
- For a fixed area, peak gain increases as frequency increases
- Result: **no net benefit** in changing frequencies for these links

$$G_{peak} = \eta \frac{4\pi A_{eff}}{\lambda^2} \qquad P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2}$$

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Point-to-Point Link

- Tag and reader antenna have a priori spatial knowledge
- Both tag and reader employ aperture antennas that point
- For a fixed area, peak gain increases as frequency increases
- Result: link loss **decreases** to the square of increasing carrier frequency (higher is better)

$$G_{peak} = \eta \frac{4\pi A_{eff}}{\lambda^2} \qquad P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2}$$

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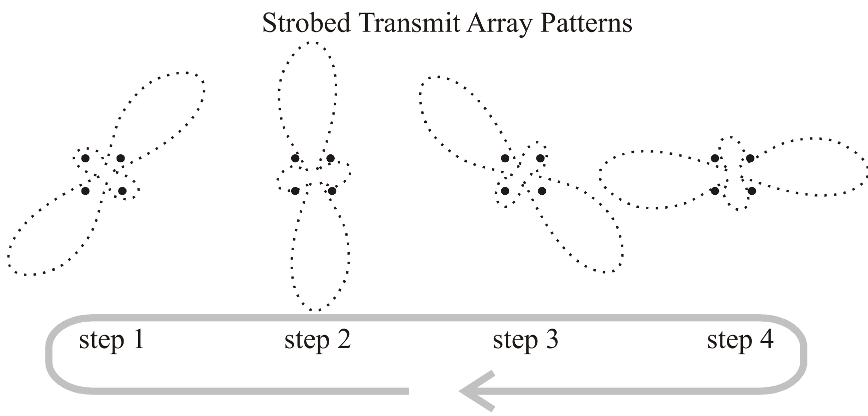
FCC Part 15 Rules, § 15.247

- (4)(ii) Systems operating in the 5725–5850 MHz band that are used exclusively for fixed, point-to-point operations may employ transmitting antennas with directional gain greater than 6 dBi without any corresponding reduction in transmitter peak output power.

Pattern Strobing



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Why Strobing is Better

- Is it better for an RFID or Sensor to get…
  – A steady stream of received power
  – 4 times the power only 1/4th of the time
- Answer: the latter
  – RF harvesting more efficient at high power levels
  – Pattern strobing results in more harvested power without actually transmitting more power

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The Future …

- Pattern Strobing/Beam-forming
- Higher frequencies
- On-object reader antenna operation

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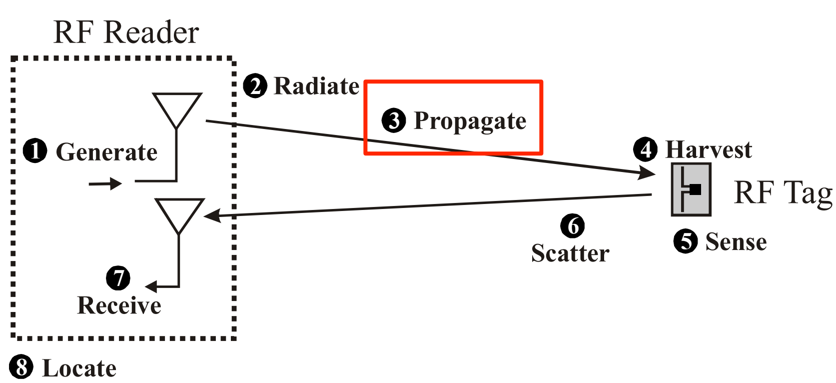
Section 3: Propagate



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On-Object Tag Degradation at 915 MHz

- Pattern distortion
- Terminal mismatches
- Change in radiation efficiency

	Cardboard Sheet	Acrylic Slab	Pine Plywood	De-ionized Water	Ethylene Glycol[†]	Ground Beef[††]	Aluminum Slab
Average Gain Penalty, AGP (dB)	0.9	1.1	4.7	5.8	7.6	10.2	10.4
Relative Permittivity[*], ϵ_r	≈ 1[**]	2.6	1.7	77.3	33	50	-
Loss Tangent[*], $\tan\delta$	≈ 0[**]	0.0061	0.036	0.048	0.4	0.7	-
L x W x H[***] (cm)	31 x 65 x 4	15 x 61 x 3	30 x 57 x 3	22 x 10 x 10	22 x 10 x 10	11 x 22 x 1.0	46 x 58

[†]Undiluted antifreeze containing at least 90% ethylene glycol
[**]Assumed to be approximately equal to free space.
[††]At approximately room temperature.
[***]L x W are the surface dimensions and H is the height/depth of the material
[*]These values were interpolated to 915 MHz from data of similar materials given by Von Hippel [8]

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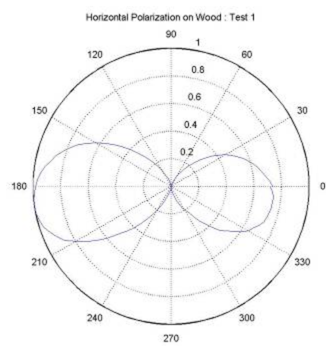
Tag Pattern on a Wooden Slab

Back Side → ← Front Side



The plot is linear and is normalized to-43.55 dBm.

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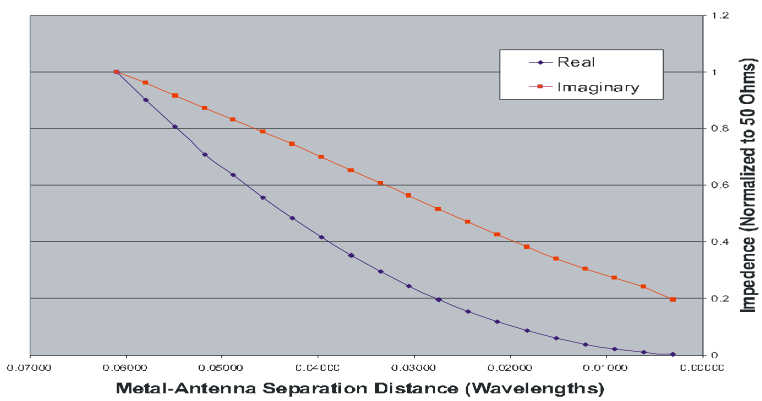
On-Metal Degradation of Dipole



J.T. Prothro, G.D. Durgin, J.D. Griffin. "The Effects of a Metal Ground Plane on RFID Tag Antennas." *APS '06 Antennas and Propagation Symposium.* Albuquerque, NM, July 2006. 4 pages.

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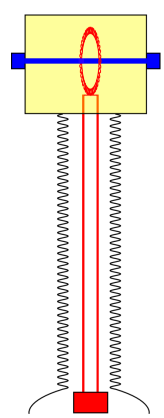
Traditional High-Voltage Sensing

- Current Transformers
  - Used in current monitoring
  - Oil used for insulation
- Advantages
  - Reliable communication link
  - Widely tested, well understood
- Disadvantages
  - Costly
  - Bulky
  - Limited location



Courtesy http://www.abb.com/ProductGuide/

Marcin Morys, GT Dissertation 2015

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Wireless High-Voltage Sensing

- Wireless Sensing
  - Air gap insulation
- Advantages
  - Inexpensive
  - Small
  - Versatile
- Disadvantages
  - Complex communication channel
  - Need to power sensor

Marcin Morys, GT Dissertation 2015

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The Future …

- Extreme Environments
- Object-Resistant Tags
- Fading and Blockage for Longer-Range Links

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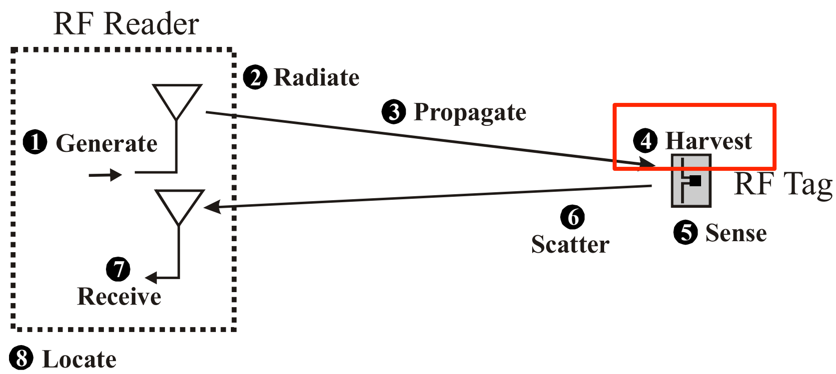
Section 4: Harvest



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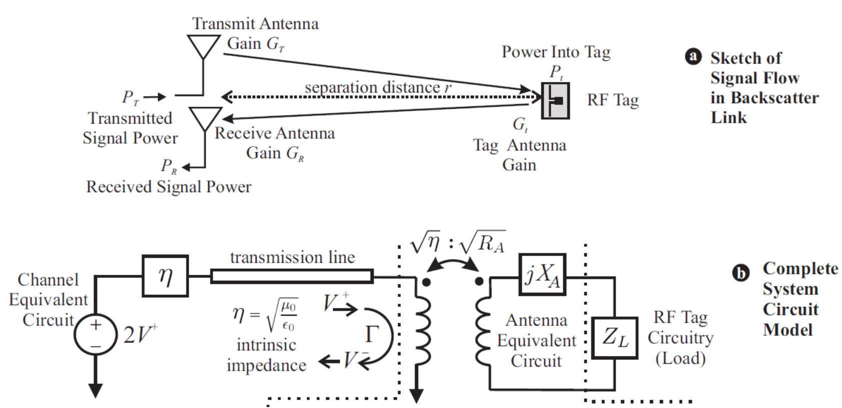
Physical Circuit Model for RFID Link



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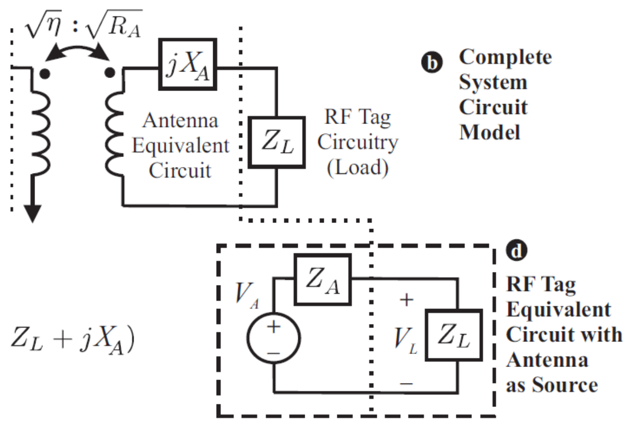
Physical Circuit Model for Reception



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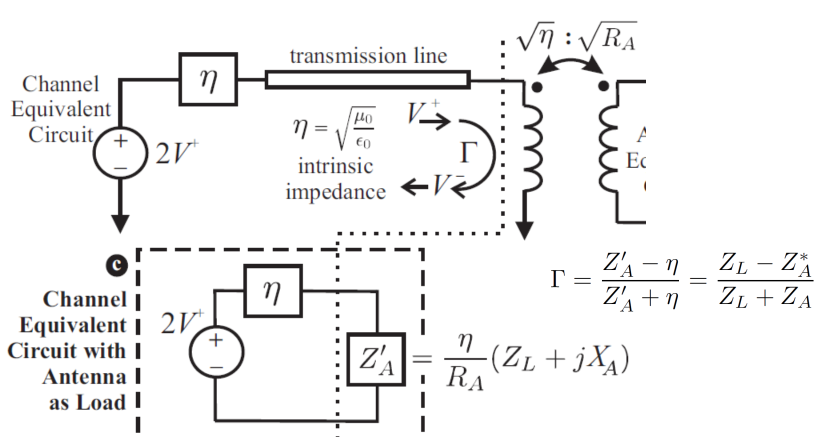
Physical Circuit Model for Reflection



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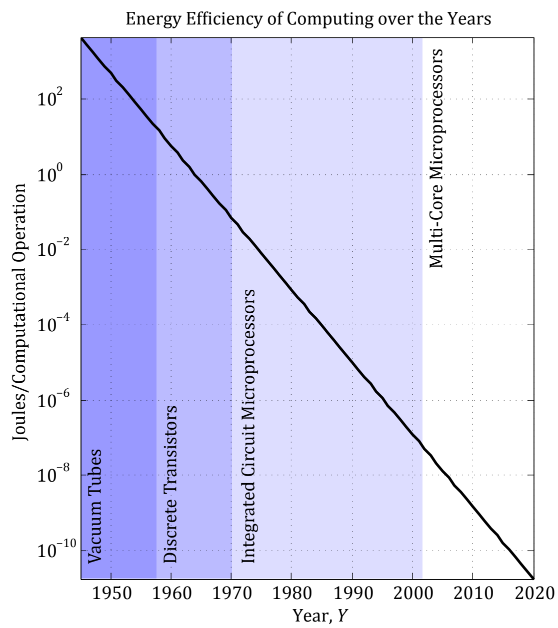
Trends in Electronics: Computation

The energy-efficiency of computation doubles every 19 months, a consistent trend for over 70 years!

The trend is independent of technological epoch (vacuum tubes, transistors, ICs, etc.)

The trend will continue well beyond 2020.



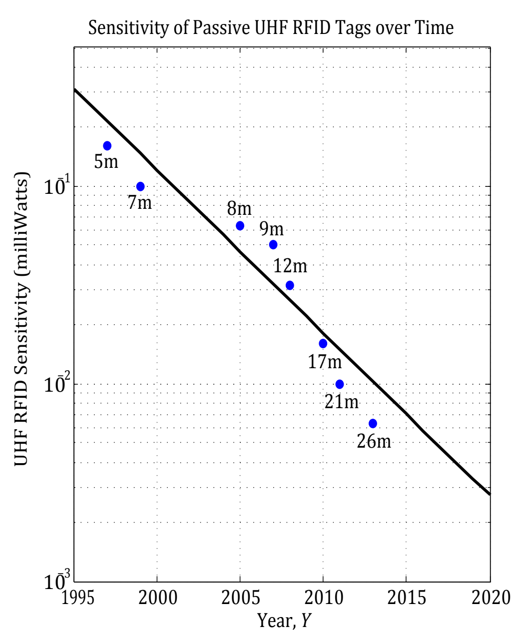
*J.G. Koomey, *IEEE Spectrum*, March 2010

Trends in Electronics: UHF RFID

This trend is driving the current buzz around the Internet of Things (IoT) and Internet of Everything (IoE).

This energy efficiency doubles every 46 months.

The 100m tag will likely occur around 2020. Or will it?...



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G.D. Durgin. "RF Thermoelectric Generation for Passive RFID," *IEEE RFID 2016*, Orlando, FL. 5 May 2016.

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Energy-Harvesting Circuitry

- Rectifier: simple circuit (diode+capacitor) that converts AC to DC
- Rectenna: antenna+rectifier circuit that harvests RF energy
- Charge Pump: RF energy harvester circuit consisting of stages of rectification to convert AC to a boosted DC signal
- Boost/Buck Circuit: Circuit that converts DC voltage to higher/lower DC output (a "DC" transformer)

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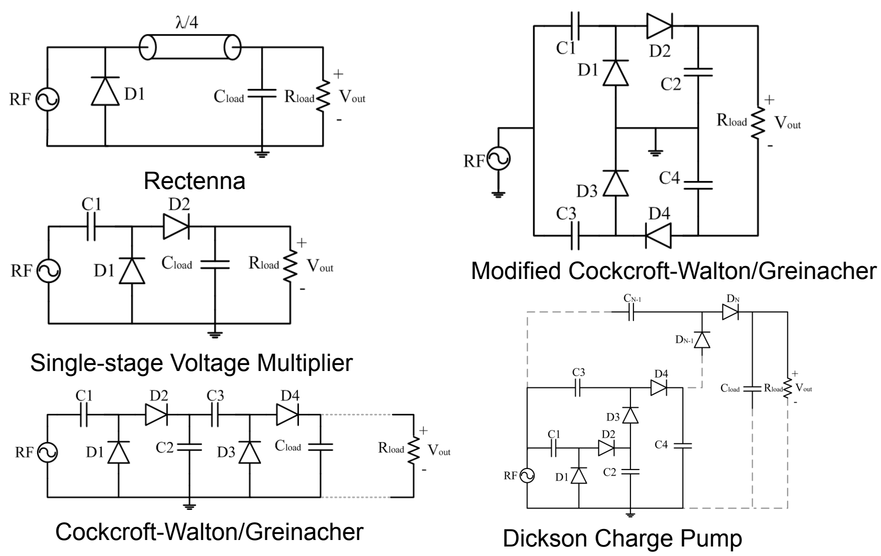
RF Energy Harvesting Circuits



C.R. Valenta, G.D. Durgin, "Rectenna Performance Under Power-optimized Waveform Excitation," IEEE RFID 2013

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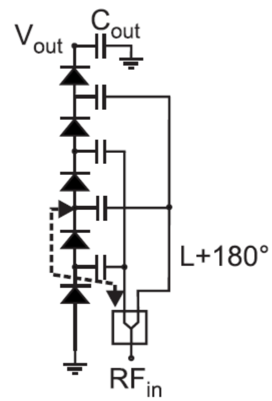
Low-Voltage Problem

- Pre-biasing diodes
- Impedance transformations
- Dual-phase clock
- Power Optimized Waveforms (POWs)



G.A. Koo, "Signal Constellations of a Retrodirective Array Phase Modulator (RAPM)", Georgia Tech MS Thesis 2011

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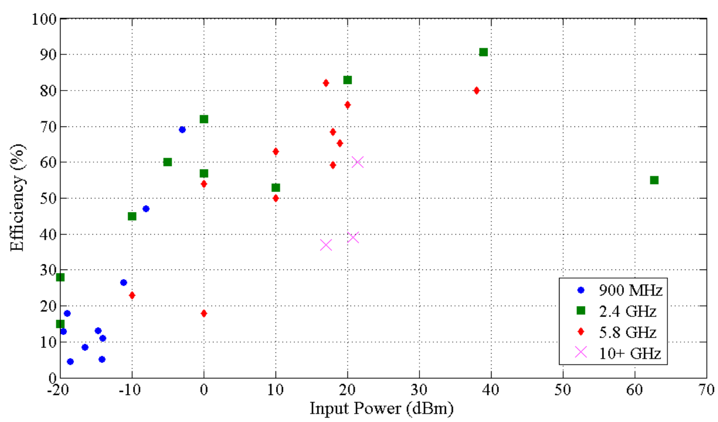
State-of-the-art Energy Harvesters



C.R. Valenta, G.D. Durgin, "Rectenna Performance Under Power-optimized Waveform Excitation," IEEE RFID 2013

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Exotic Devices for Harvesting

- Schottky Diode (currently used)
- Metal-Insulation-Metal (MIM) Diode
- Tunnel Diode Harvester
- Spin Diode Harvester
- RF Thermoelectric Generation

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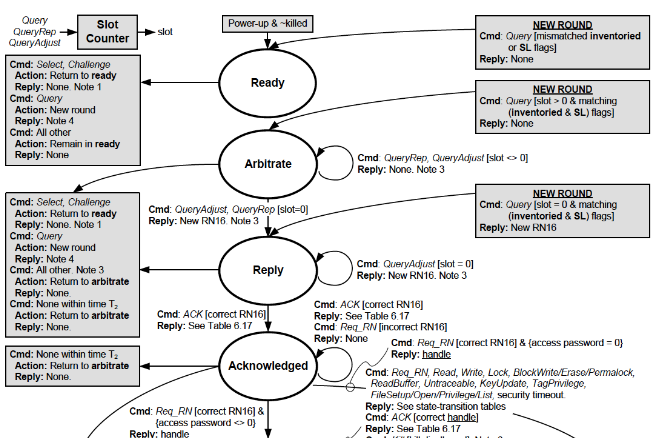
Singulation Algorithm for Gen 2



EPC™ Radio-Frequency Identity Protocols Generation-2 UHF RFID Specification for RFID Air Interface Protocol for Communications at 860 MHz – 960 MHz Version 2.0.0 Ratified

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Singulation Algorithm

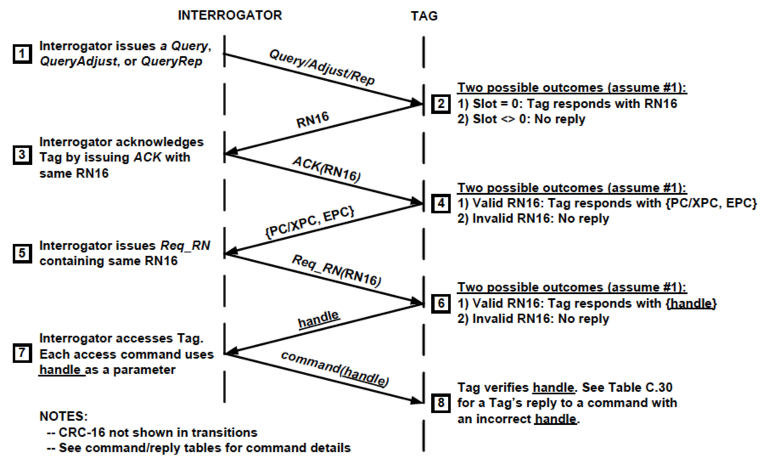
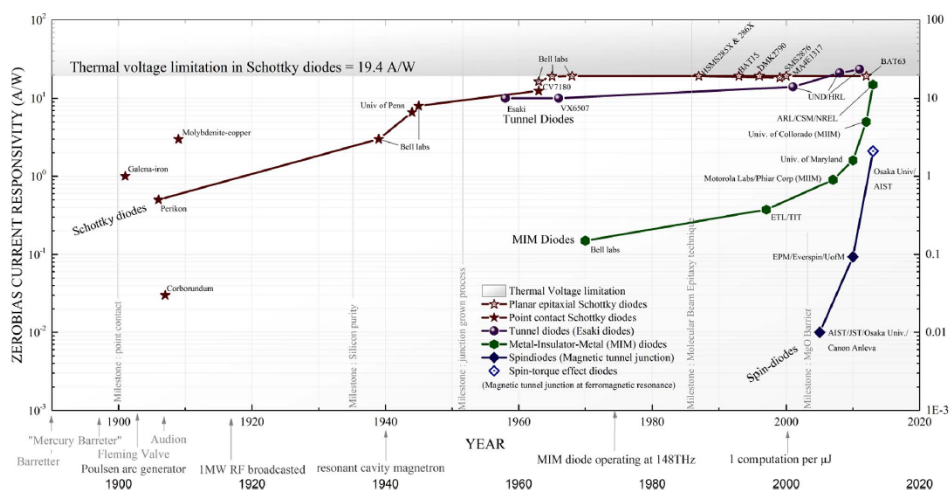


Figure E.1: Example of Tag inventory and access

EPC™ Radio-Frequency Identity Protocols Generation-2 UHF RFID Specification for RFID Air Interface Protocol for Communications at 860 MHz – 960 MHz Version 2.0.0 Ratified

Exotic Devices for RF Harvesting



S. Hemour and K. Wu, "Radio-Frequency Rectifier for Electromagnetic Energy Harvesting: Development Path and Future Outlook," *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1667–1691, Nov 2014.

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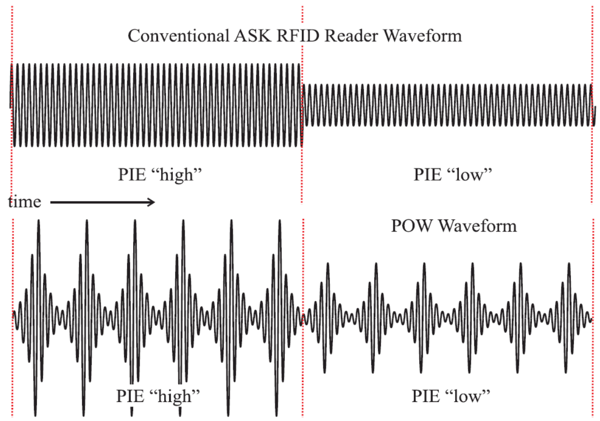
Power-Optimized Waveform (POW)



M.S. Trotter, J.D. Griffin, and G.D. Durgin. "Power-Optimized Waveforms for Improving the Range and Reliability of RFID Systems." *IEEE RFID 09 Conference*, Orlando, FL. April 2009. 8 pages.

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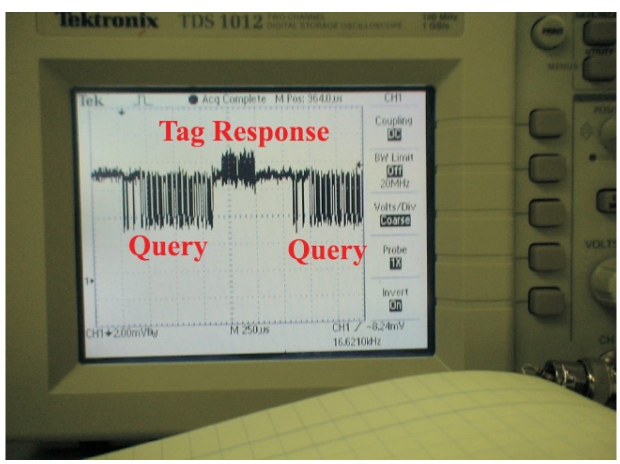
Gen 2 tag responding to POW reader



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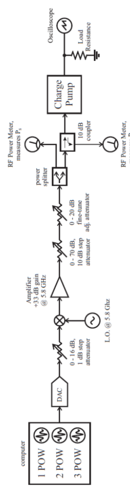
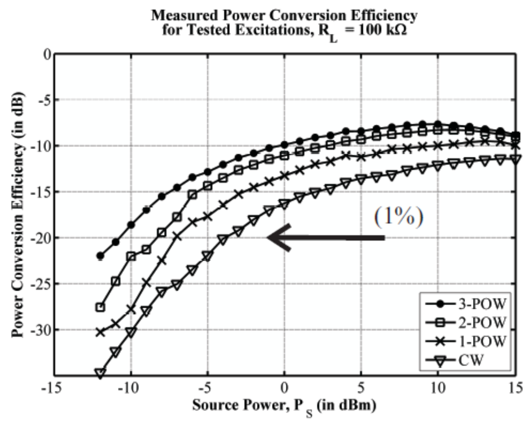
Test 5.8 GHz Charge Pump with POWs





M.S. Trotter, *Range Finding in Passive Wireless Sensor Networks Using Power-Optimized Waveform.* Georgia Tech PhD Dissertation, Nov 2011.

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Harvesting with Multiple Tag Antennas

- Smaller antennas allow multiple harvesters
- Issues with coverage vs. gain
- Unique microwave structures possible

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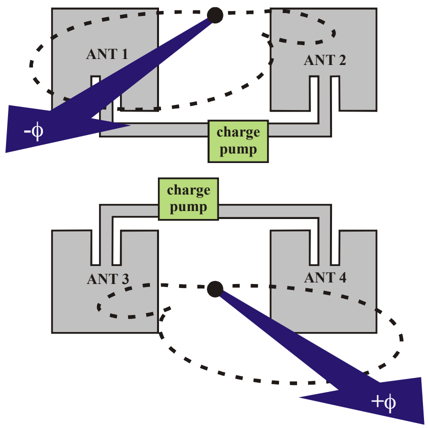
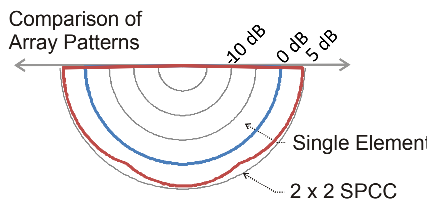
Staggered-Pattern Charge Collector





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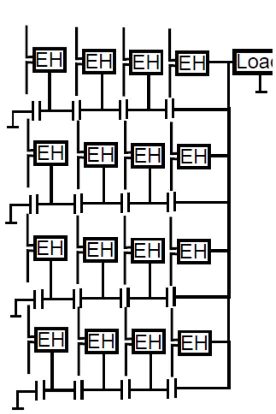
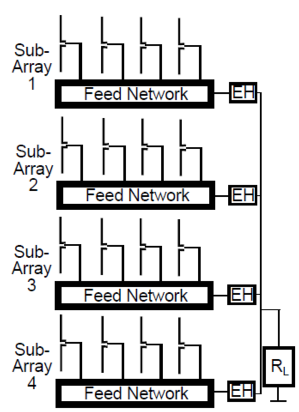
Comparison of Rectenna Arrays





B.R. Marshall, C.R. Valenta, G.D. Durgin, "DC Power Pattern Analysis of N-by-N Staggered Pattern Charge Collector and N^2 Rectenna Array," IEEE WPCT 2013

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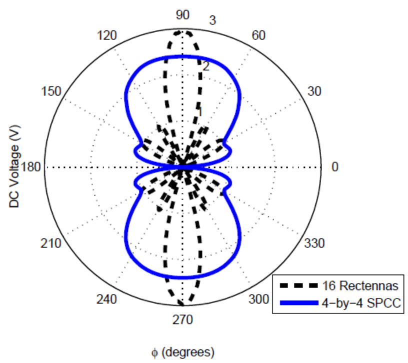
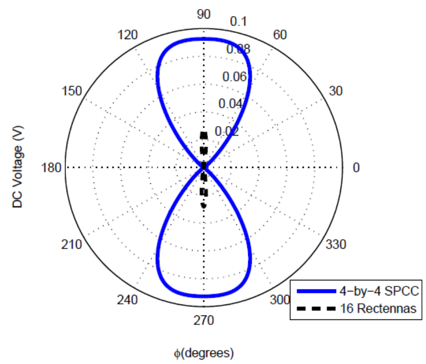
Comparison of 4 x 4 Arrays

B.R. Marshall, C.R. Valenta, G.D. Durgin, "DC Power Pattern Analysis of N-by-N Staggered Pattern Charge Collector and N^2 Rectenna Array," IEEE WPCT 2013



Comparison at .1m



Comparison at 1m

Projected Range of a 5.8 GHz RFID tag

x **0.16** move from 915 MHz to 5.8 GHz

x **0.71** lossier electronics at 5.8 GHz (-3 dB)

x **2.0** 4-element beam strobing at transmitter

x **1.8** 4-element tag array for power collection

x **2.0** improve tag resonance, isolation

x **2.2** increased bandwidth, POW gains

= x **1.8** net increase in range

The Future …

- Exotic Electronics for Harvesting
- Multi-Sine Transmission (different locations)
- Power Optimized Waveforms (POW)
- Hybrid Harvesting Technology

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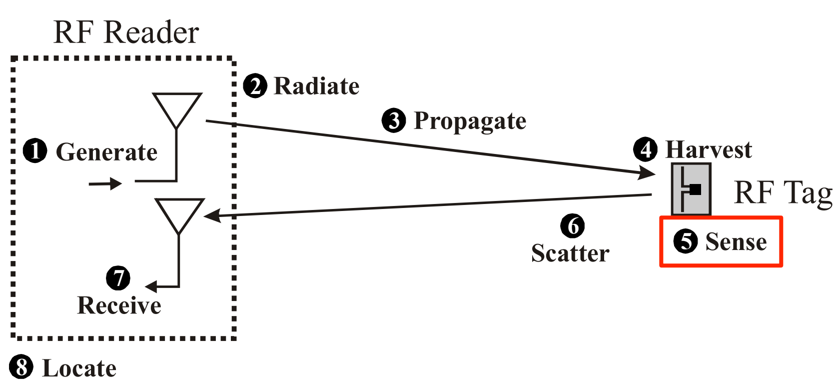
Section 5: Sense



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Sensor Technology …

- IEEE 1451.7-2010 Smart Transducer Standard
- Wireless Sensing Platform (WISP)
- Custom Discrete RF Tags

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Detection of Skimming Devices

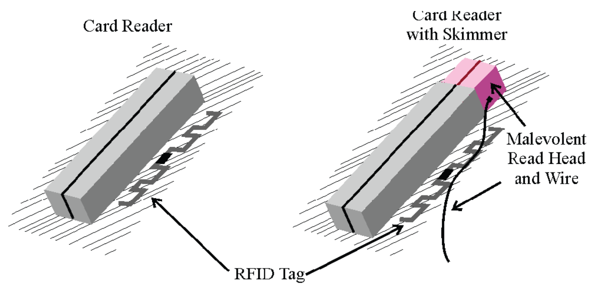

Fig. 1. Illustration of a magnetic card "swipe" reader equipped with a UHF or microwave RFID tag. An electronic skimming device alters the electrical properties of the tag, which can then be detected by a nearby coherent reader.

M.Morys, M. Akbar, G.D. Durgin, "Malevolent Object Detection Using Microwave RFID Tags," IEEE RFID 2013

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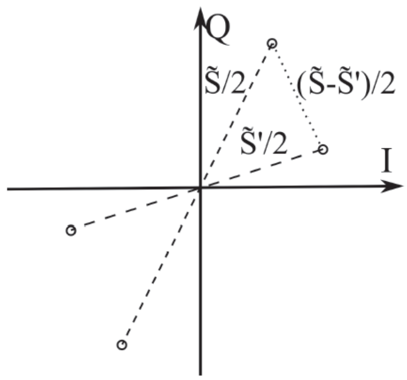
Complex Phase/Amplitude Distortion



- Alarms sounded if persistent change in modulated return
- Works at any frequency, although
- 5.8 GHz wavelength…
  - Sensitizes to small wires
  - Desensitized to droplets

M.Morys, M. Akbar, G.D. Durgin, "Malevolent Object Detection Using Microwave RFID Tags," IEEE RFID 2013

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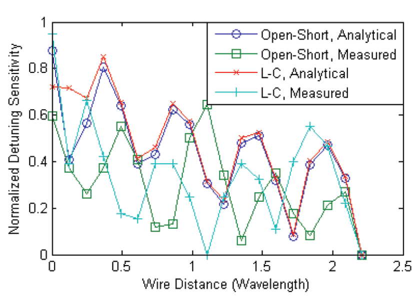
Design of Anti-skimming Sensor



- For this application, short-open is not the best
- L-C shown to maximize sensitivity

M.Morys, M. Akbar, G.D. Durgin, "Malevolent Object Detection Using Microwave RFID Tags," IEEE RFID 2013

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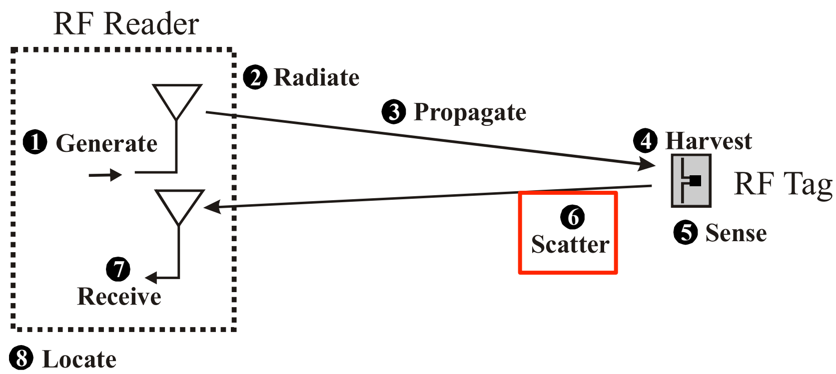
Section 6: Scatter



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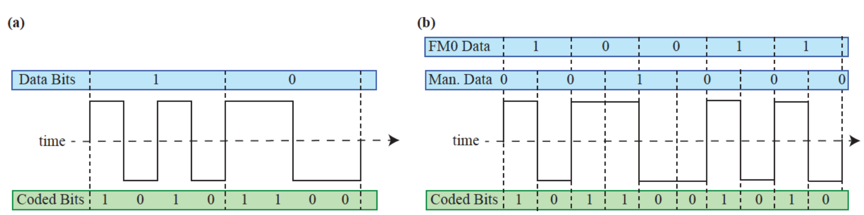
How to Send Data Back



- Gen 1 F2F – Frequency/Double Frequency (a)
- Gen 2 FM0 – Frequency Modulation 0 (b)
- Gen 2 MMS – Miller Modulated Subcarrier

Multi-Antenna Modulation

- **Stockman Modulator** – classical single-antenna backscatter
- **Griffin Modulator** – simultaneous modulation of multiple tag antennas (simple, extra power, resistant to multipath)
- **Koo-Lu Modulator** – retrodirective array modulator (near optimum backscatter)

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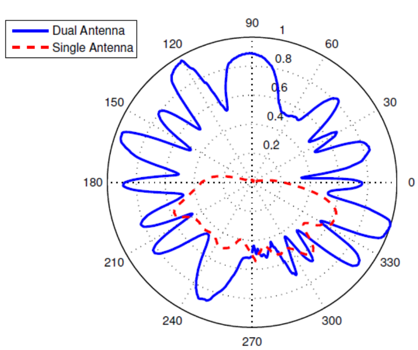
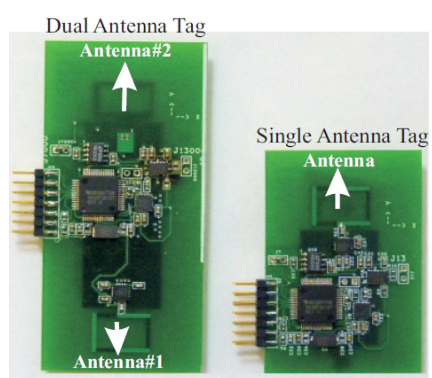
Comparison of Dual vs. Single Ant. Tags





M. B. Akbar, M. M. Morys, C. R. Valenta, G. D. Durgin, "Range Improvement of Backscatter Radio Systems at 5.8GHz using Tags with Multiple Antennas", IEEE APS Symposium, 2012

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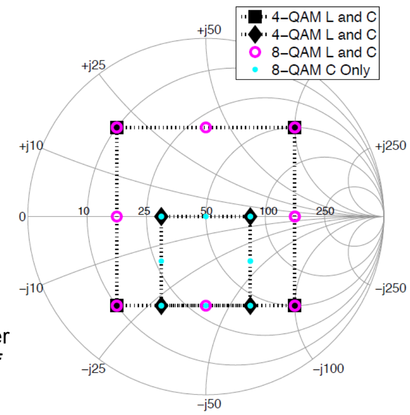
Higher Order Modulation

- Possible to load modulate with higher-order constellation
- Sends more bits per cycle – energy efficient!



S.J. Thomas, M.S. Reynolds, "QAM Backscatter for Passive UHF RFID Tags", *in Proceedings of IEEE RFID 2010*, April 2010.

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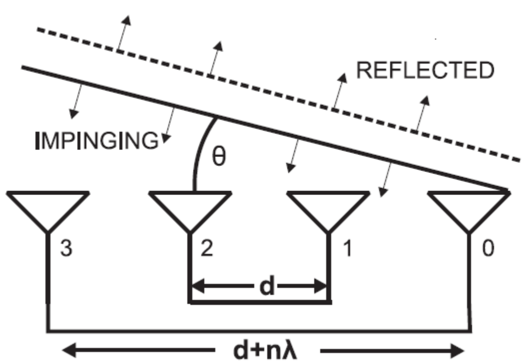
Operation of a Van Atta Array



L.C. Van Atta, "Electromagnetic Reflector", US Patent 2908002, Issued in 1959.

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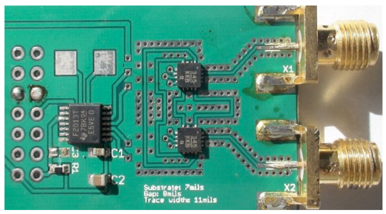
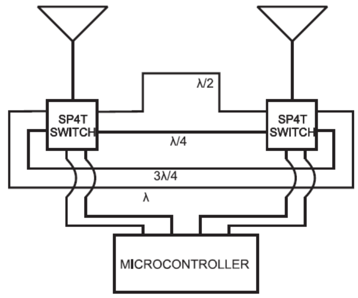
Koo-Lu Modulator





- Switch 2-element RA between 4 **li**ne lengths
- Only requires 2 switches and microcontroller

M.S. Trotter, C.R. Valenta, G.A. Koo, B.R. Marshall, G.D. Durgin, "Multi-Antenna Techniques for Enabling Passive RFID Tags and Sensors at Microwave Frequencies", *in Proceedings of IEEE RFID 2012*, May 2012.

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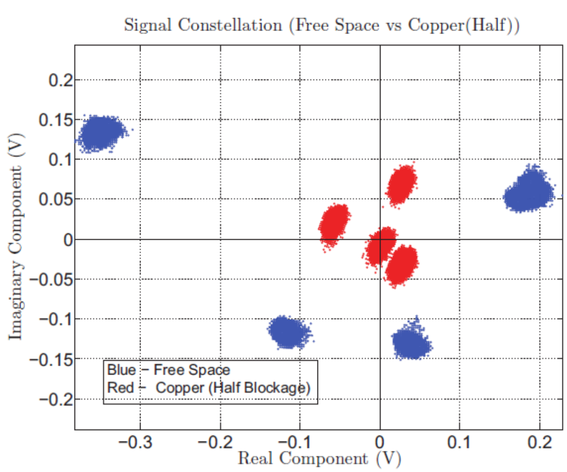
On-Object Degradations



G.A. Koo, "Signal Constellations of a Retrodirective Array Phase Modulator (RAPM)", Georgia Tech MS Thesis, http://www.propagation.gatech.edu/Archive/Collection_TR/Collection_TR.htm, May 2011.

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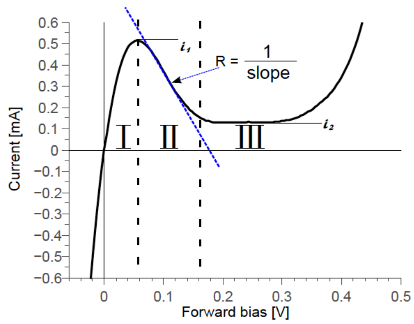
Quantum Tunnel Reflectors



- Tunnel diode at end of antenna
- Bias in neg-resistance region makes amplifier
- Very low power consumption (10s of microWatts)

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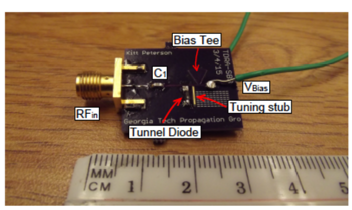
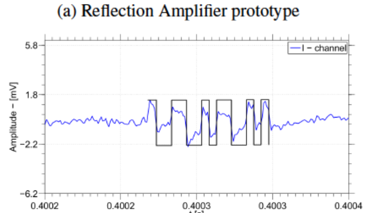
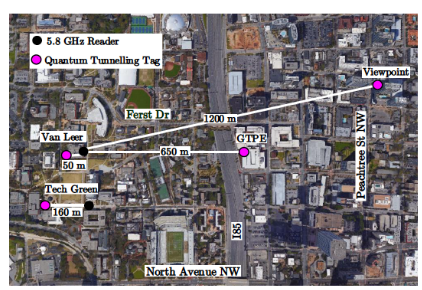
Quantum Tunnel Reflectors



(a) Reflection Amplifier prototype





1200m Range Through Midtown Atlanta at 5.8 GHz

F. Amato, C.W. Peterson, B.P. Degnan, M.B. Akbar, G.D. Durgin. “Long Range and Low-Powered RFID tags with Tunnel Diode”. *IEEE RFID-TA 2015*. Tokyo, Japan. 16-18 September 2015.

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The Future …

- Multi-antenna signaling
- Retrodirectivity
- Quantum Tunnel Reflectors
- Higher-Order Modulation
- Ambient Radio Scatter
- Physical Sensing Applications

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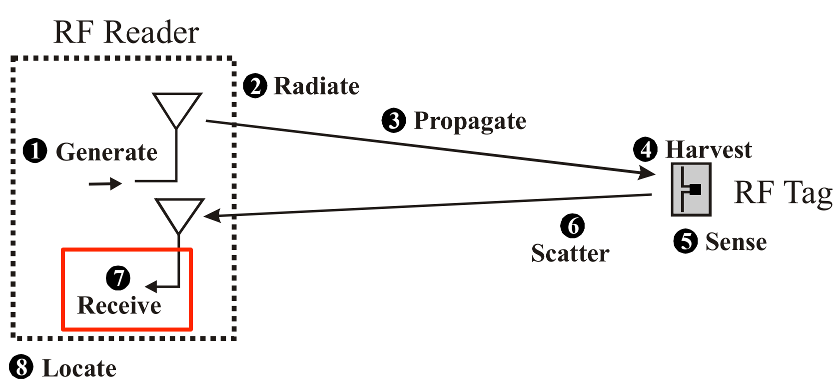
Section 7: Receive



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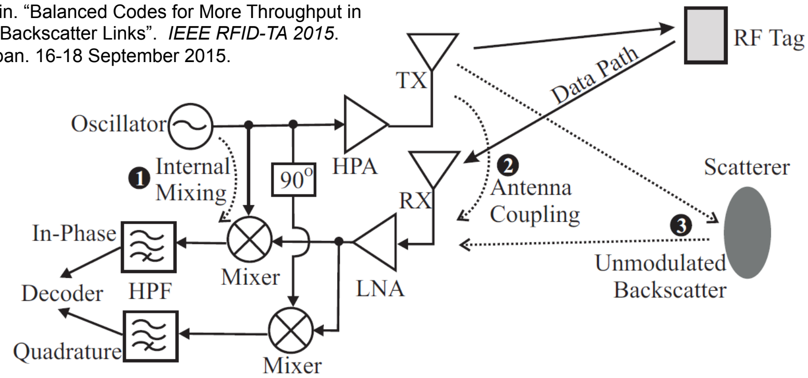
Homodyne Transceiver Architecture

G.D. Durgin. “Balanced Codes for More Throughput in RFID and Backscatter Links”. *IEEE RFID-TA 2015*. Tokyo, Japan. 16-18 September 2015.



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The Future …

- Array Reception
- Cleaner RF Chains
- Interference Cancellation
- Subspace Detection
- Better Channel Coding Techniques
- Link Encryption

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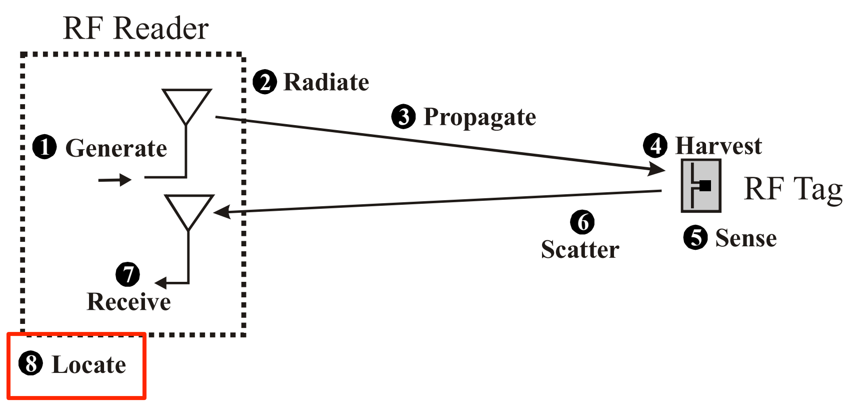
Section 8: Locate



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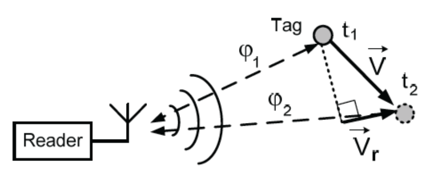
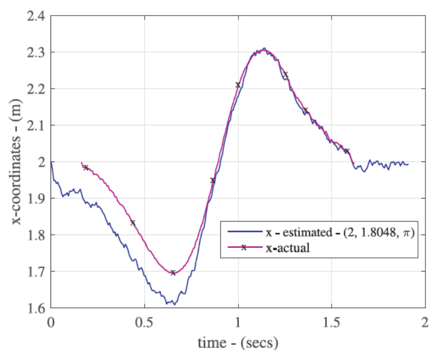
Localization Techniques

- Portals
- RX Signal Strength
- Time-of-Flight
- Coherent Phase
- Hybrid Techniques



Pavel V. Nikitin, Rene Martinez, Shashi Ramamurthy, Hunter Leland, Gary Spiess, and K. V. S. Rao. "Phase Based Spatial Identification of UHF RFID Tags", IEEE RFID 2010

Hybrid Inertial Microwave Reflectometry (HIMR)



- Inertial measurements + phase tracking
- Motion-capture grade localization

M. Bashir Akbar GT Dissertation 2016

[Questions]