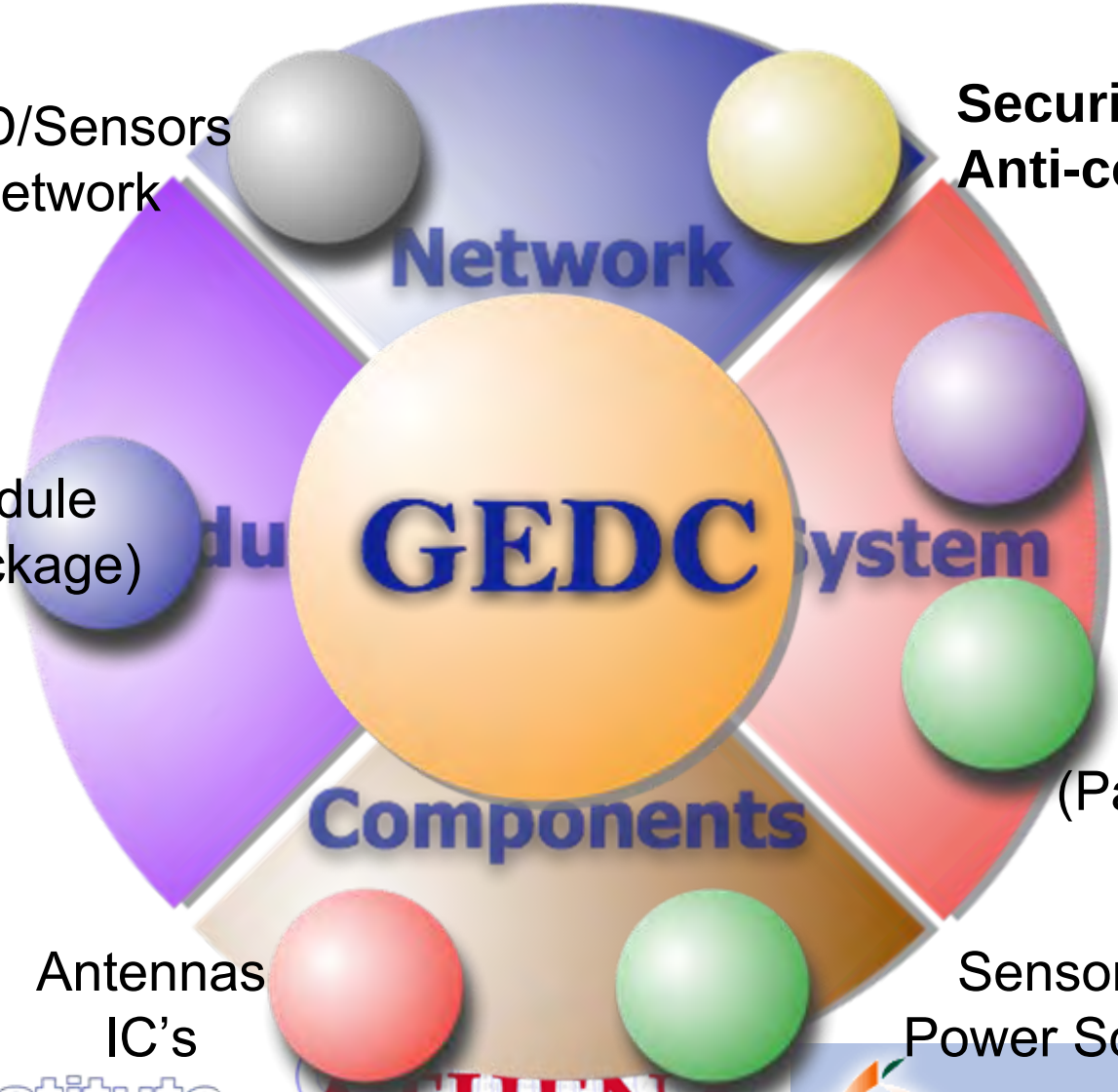
Inkjet-printed Paper-based RF Electronics: the Solution for Ubiquitous Sensing and Pervasive Computing??

GEDC/Georgia Tech

Manos M. Tentzeris

(etentze@ece.gatech.edu)

GEDC *P.I.R.E.A.S. Testbed*
(Prototypes of Integrated RFID-Enabled Agile Systems)



RFID/Sensors
Network

Security
Anti-counterfeiting

Multistandard
HF, VHF, RF

Integrated Module
(System-on-Package)

Low-cost
Materials
(Paper, Organics)

Antennas
IC's

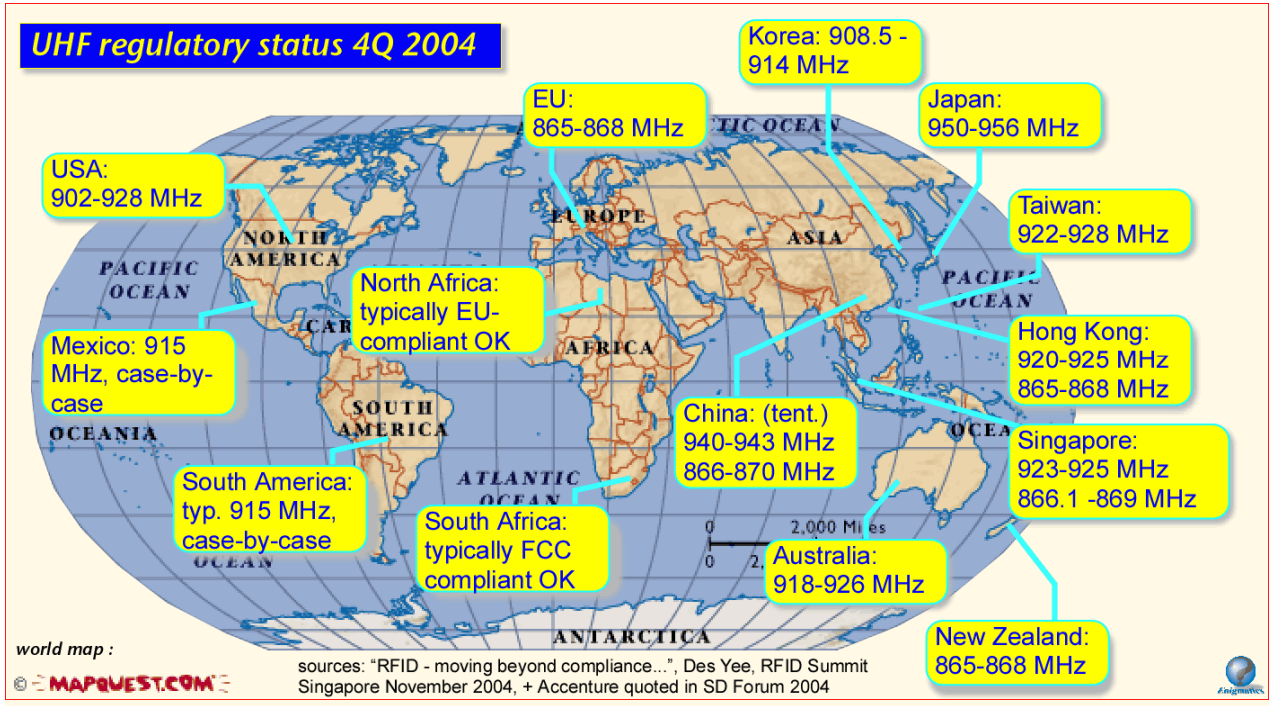
Sensors
Power Sources

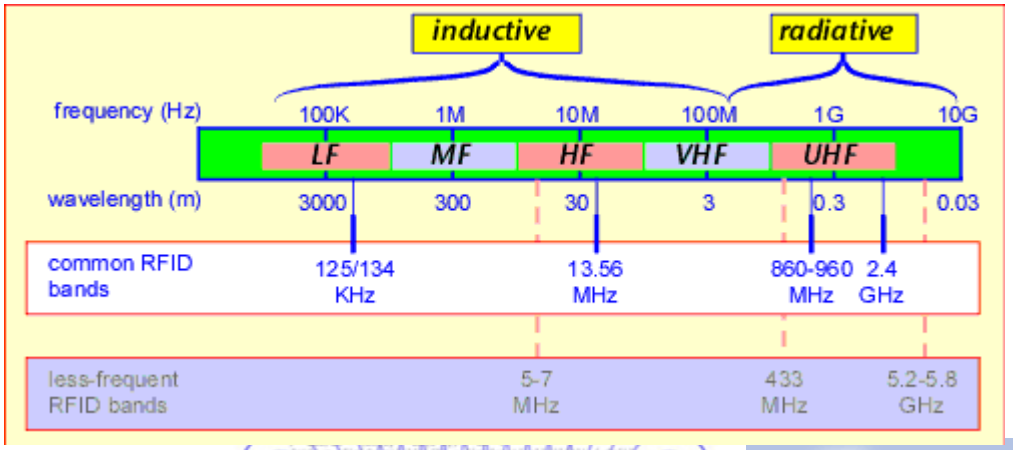
PIREAS RFID/Sensors Lab

- **Building designs using ink-jet metal printing on/embedded in low-cost paper for various thicknesses and sizes (hydrophobic paper)**

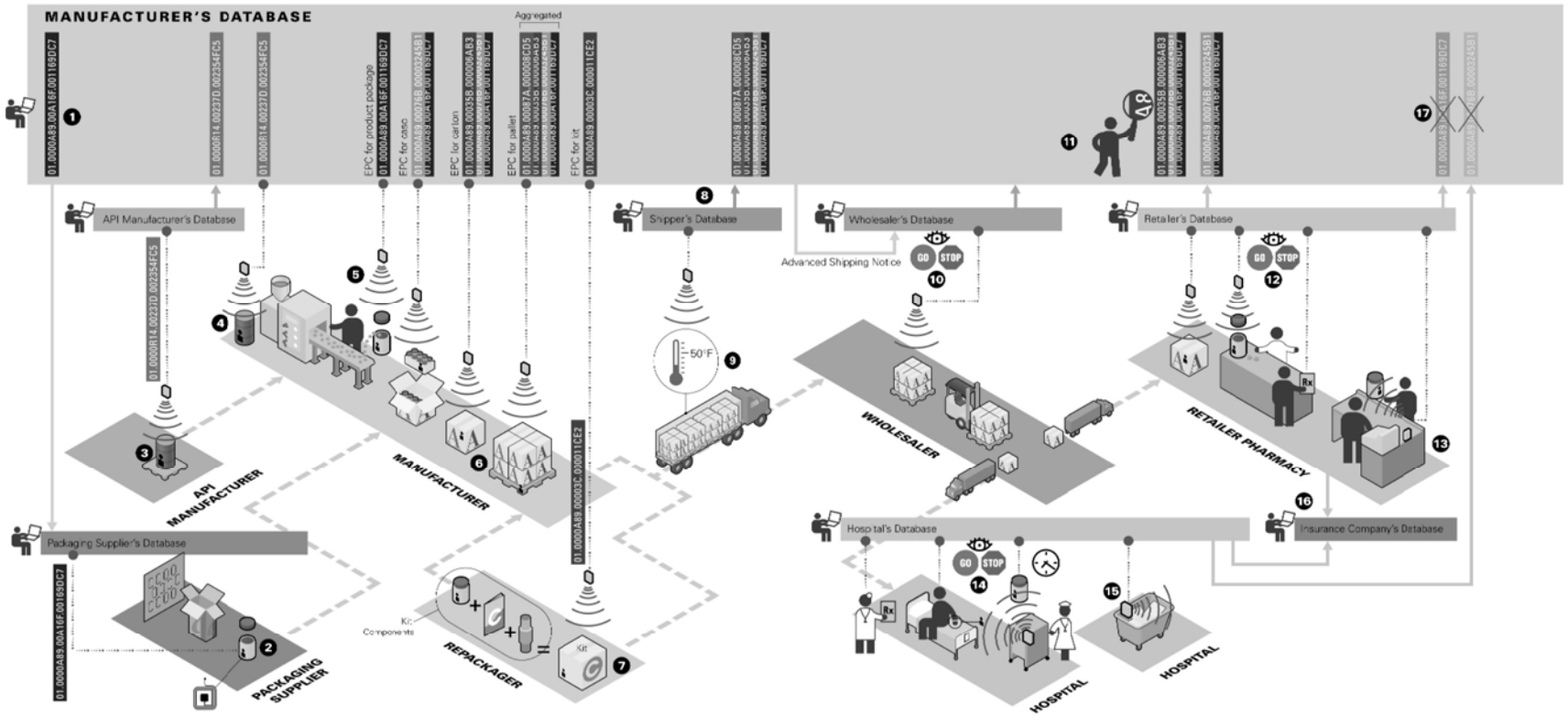
- Test Bed facility for various RFID applications:
  - Aeronautical industry
  - Pharmaceutical industry
  - Port security
  - Airport security and baggage tracking
  - Automotive industry (tire pressure monitoring sensor system)
  - Inventory control
  - Wearable electronics

RFID Frequency Bands





How RFID Technology Protects Pharmaceutical Supply Chain



1
Manufacturer assigns a unique EPC number to each product to allow track and trace throughout the supply chain.

2
Packaging supplier "writes" to the tag the EPC number assigned by the manufacturer and embeds the tag in empty packaging materials.

3
Raw materials are tagged to allow the product's pedigree to extend back as far as needed.

4
Manufacturer receives raw materials and records their EPC numbers in the manufacturer's database, linking raw material data to final product EPC and building pedigree.

5
EPC number and product information are recorded in the manufacturer's database at the end of the manufacturing process. Only products with valid EPC numbers can move through the supply chain.

6
Additional EPC numbers are assigned to cases, cartons, and pallets as products are aggregated. The aggregation information is recorded in the manufacturer's database.

7
Kits can be assembled with both tagged and untagged products. If needed, a kit can have its own unique EPC number.

8
Sharing data among trading partners removes the burden of collecting and storing every detail. The EPC number serves as a key to ensure a perfect match between products and their data. Security rules prevent unauthorized parties from accessing sensitive data.

9
Sensors can record conditions throughout the supply chain and add this information to the product's history.

10
Advance Shipping Notices (ASN) give the wholesaler detailed EPC data about shipments before products arrive. Radio frequency scans of incoming shipments can reveal mismatches before products come off the truck.

11
Virtual agents continually monitor EPC numbers throughout the supply chain and instantly highlight any EPC numbers that are odd, duplicated, or out of place.

12
Prescription errors can be reduced by automatically comparing the data associated with a product's EPC number to customer's records.

13
POS system detects when a product is purchased at a pharmacy and leaves the supply chain.

14
Administering errors can be reduced by scanning patient ID and drug EPC number and automatically comparing the associated information to check for expiration date and pedigree and to ensure a match to the physician's prescription.

15
RFID readers on recycling bins can detect the tags of discarded products and deduce that they have reached the end of the supply chain.

16
Insurance companies can collect a wealth of accurate and useful information when the EPC number of a drug is linked to a specific patient at the point when a drug is actually administered.

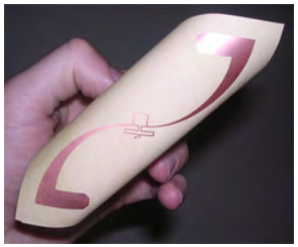
17
EPC numbers become inactive when the product reaches the end of the supply chain, but product information remains in the database.

BearingPoint

RFID tag/sensor on organic Material

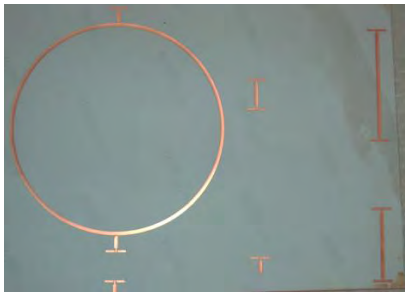
Why consider LCP as a substrate?

- Liquid Crystal Polymer (LCP) can be used as a high performance multilayer substrate
- Excellent electrical properties ($\varepsilon_r \sim 3.10$ and $\tan\delta=0.002$)
- Flexible (Sensors can be rolled or molded into desired shape)
- Good performance: mechanical integration compatibility and economic viability



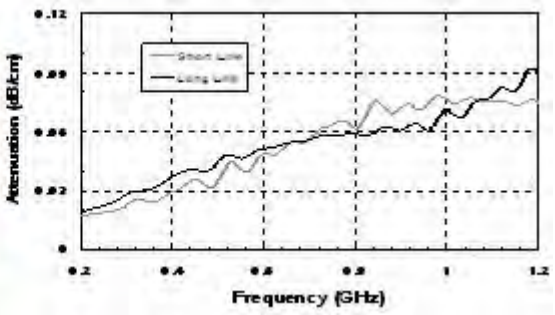
High-bandwidth S-Antenna

Antennas fabricated on 12”x12” in LCP Film



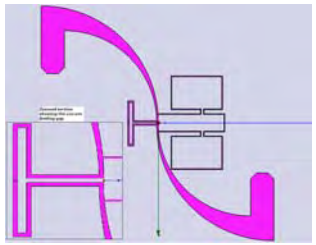
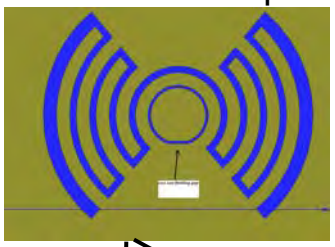
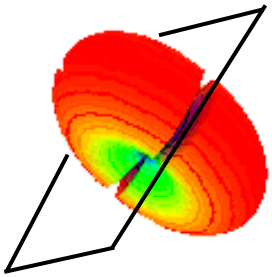
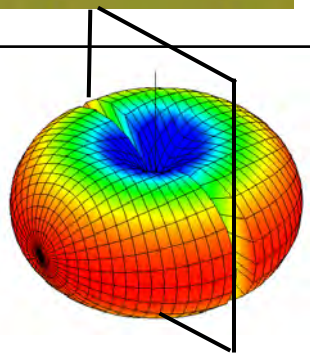
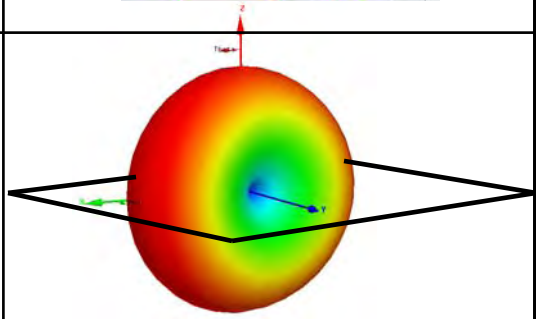
Ring Resonator Method

Cavity Resonator Method



Transmission Line Method

Radiation patterns

	• Wide-band dipole	• Circular coupled	• Dual polarized
			
Rad. Pattern (simulated)			
Directivity (simulated)	2.18 dBi	1.99 dBi	1.67 dBi
Efficiency (simulated)	95%	90%	93%

RFID on paper: paper

Paper types:

- **Regular photocopy paper: 60 μm thick**
- **Artistic paper – hot pressed, 140 μm thick**
- **Photograph paper, 260 μm thick**

Process:

- **Paper nano-restructuring**
- **Printing with silver conductive ink:**
- **Curing and testing**

	Paper-based Substrate	Plastic Substrate
Thickness	Limited	Average to High
Security	High	Low
Cold lamination	Average	Average
High temperature treatment	Excellent	Very low
Reliability / life time	Very high	Average to low

Results:

- **Paper protected against water and mud**

Sheet resistivity of 75 mΩ/□ @ 0.4 μm thickness

Why Consider Paper as a Substrate

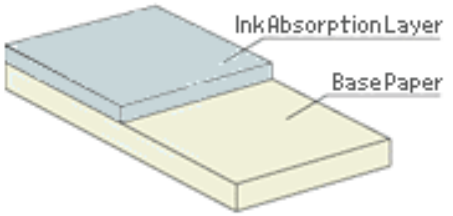
- Environmental Friendly and low cost **(LOWEST COST MATERIAL MADE BY HUMANKIND)**
- Large Reel to Reel Processing
- Low surface profile with appropriate coating
- Compatible for printing circuitry by direct write methodologies
- Host nano-scale additives (e.g. fire retardant textiles)
- Can be made hydrophobic
- Dielectric constant ε_r (~3) close to air's, allowing EM waves to penetrate substrate easily with minimum (5-6%) power reflection

Reel paper board

Drop of water on hydrophobic paper

Ideal RFID paper: characteristics

- **Thickness ~= 260** µm
- **Possible inks (pigment or dye based):**
  Dye inks show less scatter than pigment ones
- **Long grain paper** (better withstands high T^a)
- **Holdout: High**
- **Smoothness < 20SU (mL/min)**
  (lower Sheffield Units indicate a smoother surface, thus higher ink density and abrasion resistance)
- **A glossy surface finish indicates smoothness**
- **pH = 7** (neutral pH for better preserving)
- **Hydrophobic:** Done trough surface nano-restructuring with a bio-alcohol treatment
- **Adhesion: Minimum rating = 3~4** (in ASTM D3359-02 tape test)



Coated paper


Drop of water on hydrophobic paper

RFID printed on paper: conductive ink

PAPER:

• Environmental Friendly and low cost

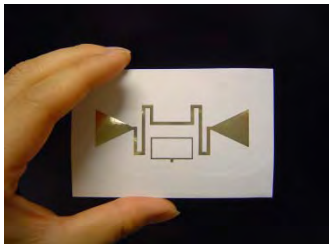
(LOWEST COST MATERIAL MADE BY HUMANKIND)

• Large Reel to Reel Processing

• Compatible for printing circuitry by direct write methodologies

• Can be made hydrophobic and can host nano-scale additives (e.g. fire retardant textiles)

• Dielectric constant εr (~2) close to air's

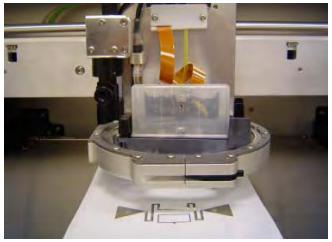


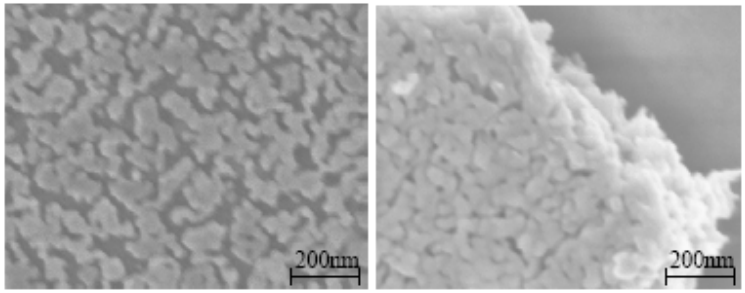
INK:

• Consisting of nano-spheres melting and sintering at low temperatures (100 °C)

• After melting a good percolation channel is created for electrons flow.

• Provides a better result than traditional polymer thick film material approach.



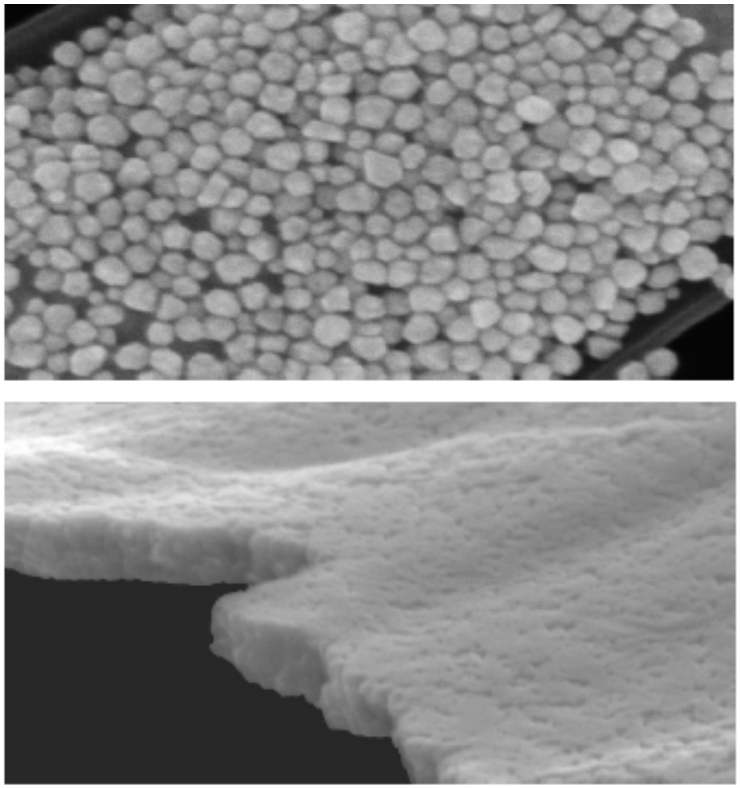


SEM images of printed silver nano-particle ink, after 15 minutes of curing at 100°C and 150°C

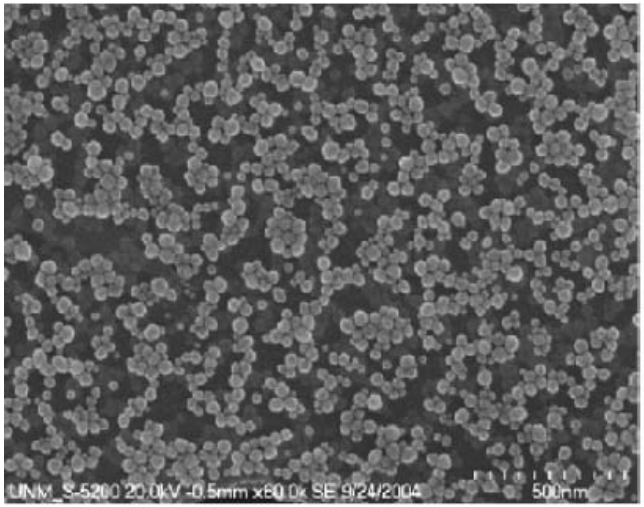
RFID printed on paper: conductive ink

Ink:

- **Consisting of nano-spheres melting and sintering at low temperatures (100 °C)**
- **After melting a good percolation channel is created for electrons flow.**
- **Provides a better result than traditional polymer thick film material approach.**



SEM Images of a Layer of Printed Ink, Before and After a 10 Minute Cure at 180 °C

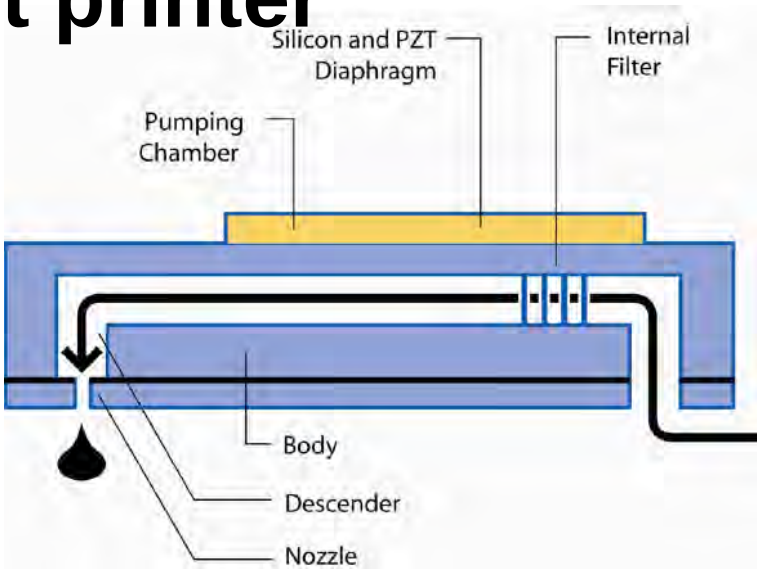


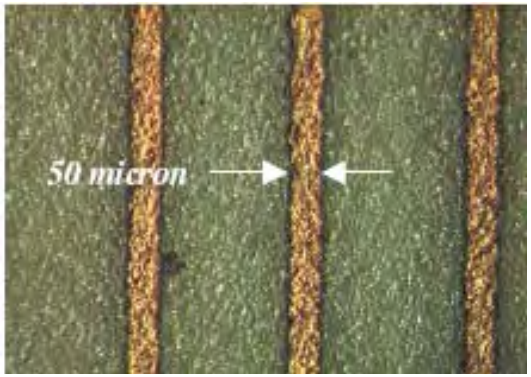
Particle size = 30 nm

RFID on paper: Inkjet printer

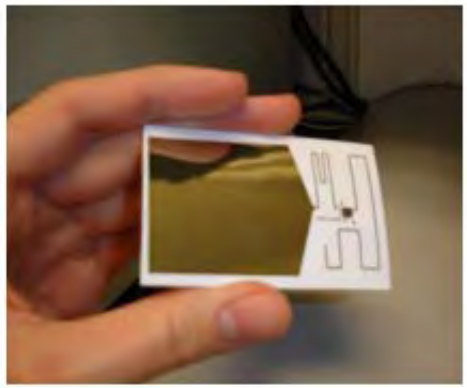
Characteristics:

- **Piezo-driven jetting device to preserve polymeric properties of ink**
- **10 pL drops give ~ 21** μm
- **Drop placement accuracy ±10** μm **gives a resolution of 5080 dpi**
- **Drop repeatability about 0.5%**
- **Applications: flexible circuits, RFID tags and displays, wearable electronics, DNA arrays**





High resolution inkjet printed copper (50 μm)

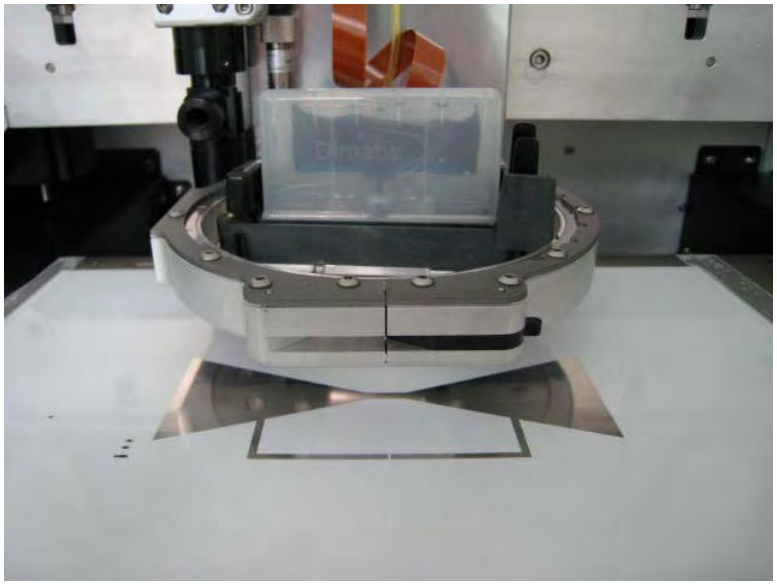


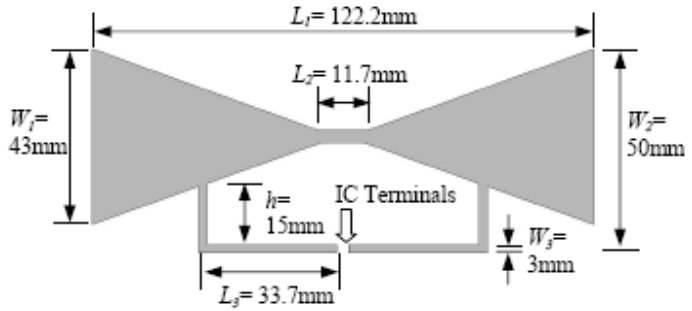
Ink jet printed RFID tag

UHF RFID Antenna- Global Operability

Tracking boxes, pallets, and containers imported imposes a challenge namely frequency of operation and bandwidth.

- In order to tackle this challenge a universal RFID tag needs to be designed (frequency 860MHz → 960 MHz) with a certain added tolerance.

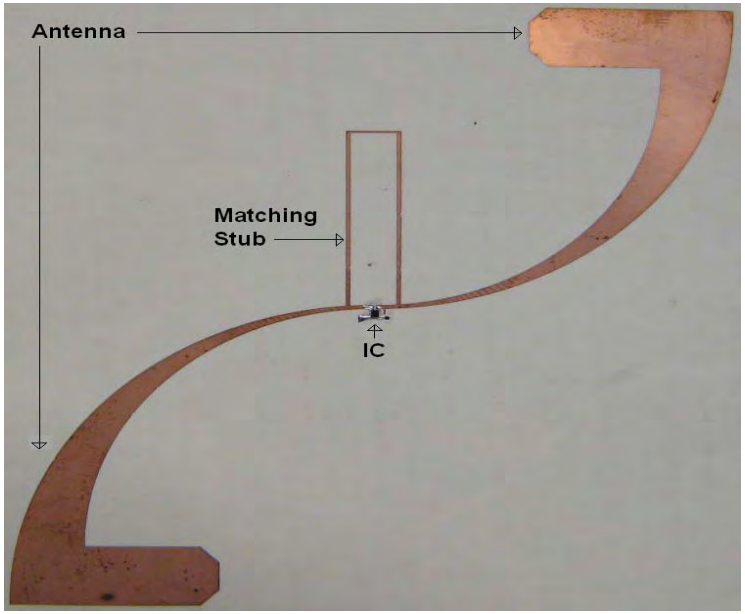




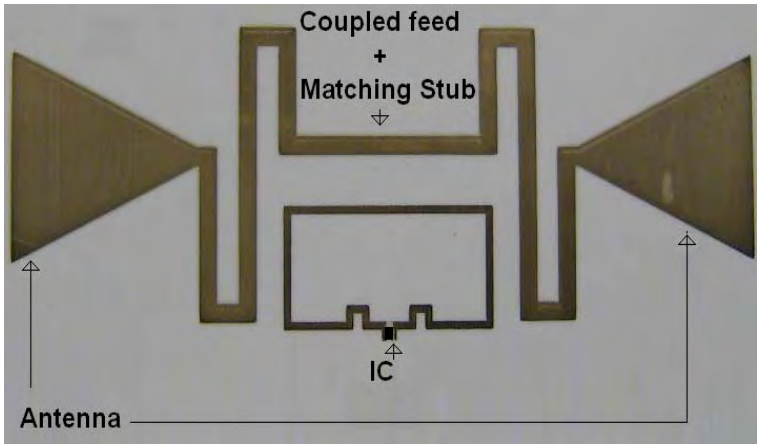
T-match folded bow-tie RFID tag module

More RFID Tag Prototypes

- S-Shaped Dipole
  - IC Assembly: solder bump flip chip
  - Omni directional radiation pattern

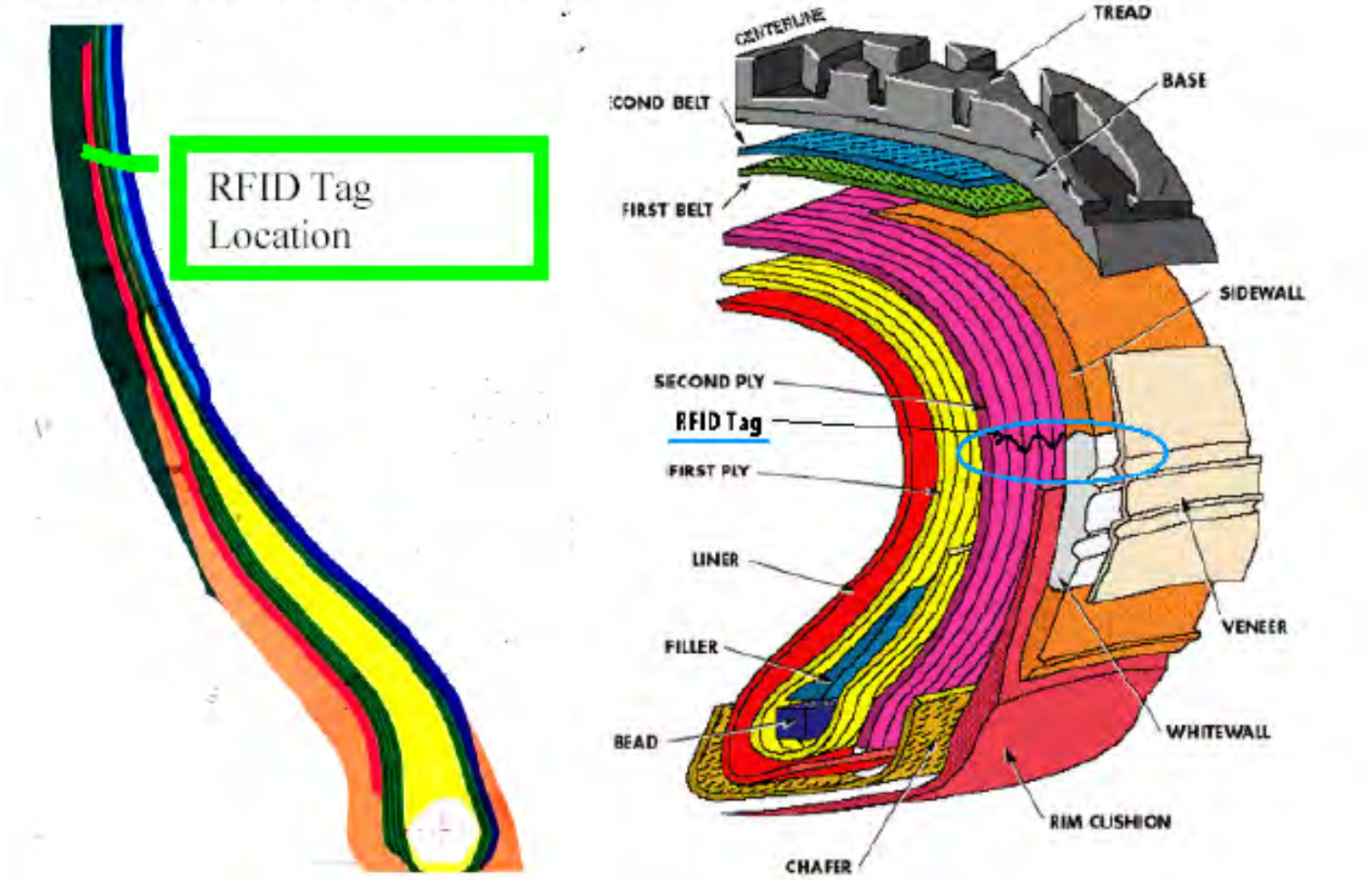


- Coupled Feed Dipole
  - IC Assembly: Surface mount soldering technique
  - IC Package: TSSOP

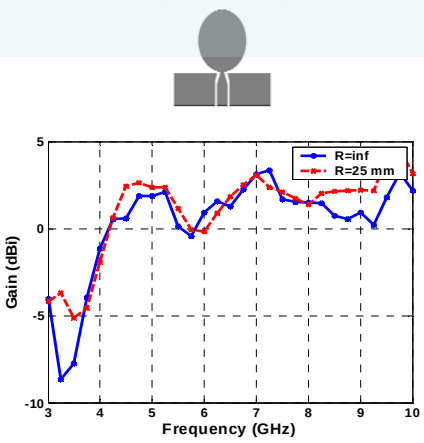


RF Tag for Tire

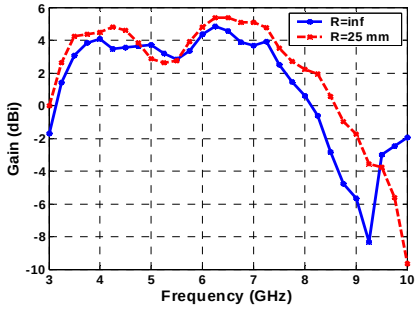
Placement of the transponder in the tire:



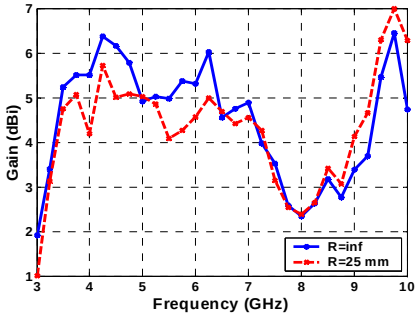
High Gain Performance and Consistent Pulse Fidelity with Folding



(a)

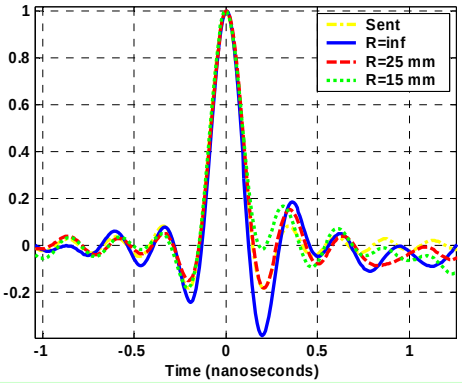


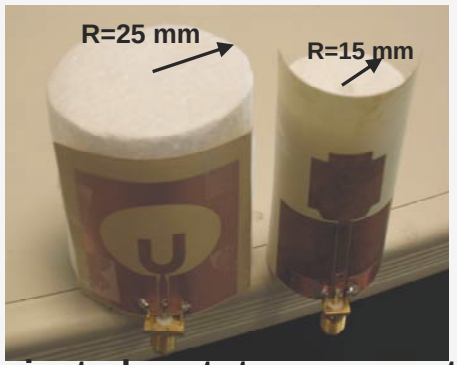
(b)



(c)

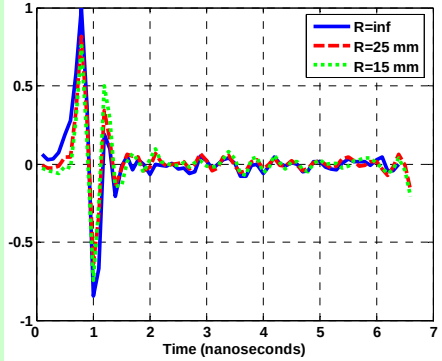
Raised Cosine Pulse



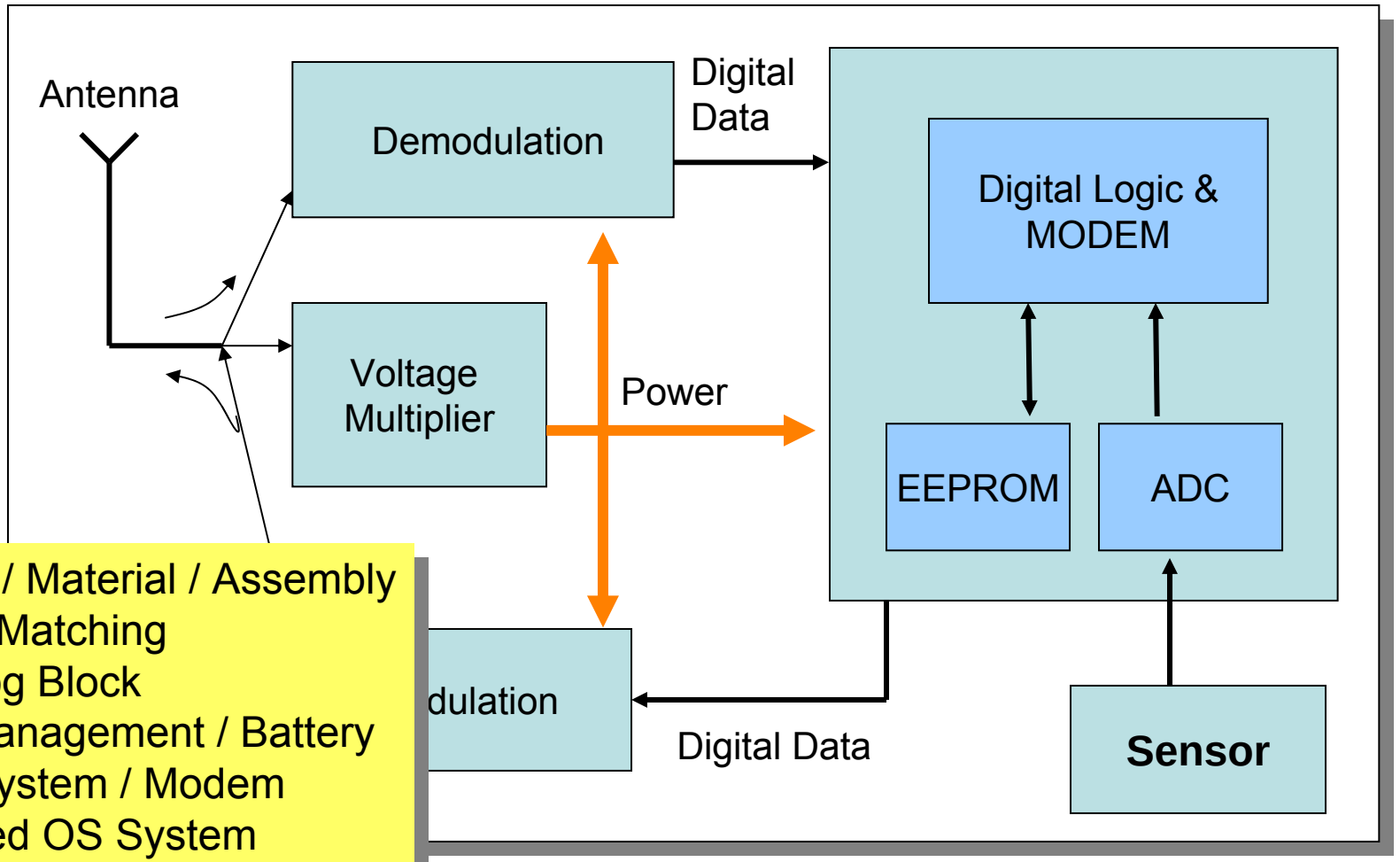


Fabricated prototypes mounted on Styrofoam cylinders

Impulse Response



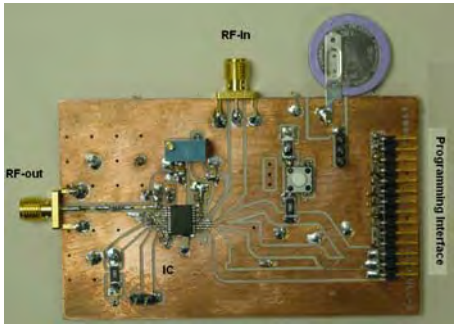
Wireless Sensor Architecture



- Package / Material / Assembly
- Antenna/Matching
- RF/Analog Block
- Power management / Battery
- Comm. system / Modem
- Embedded OS System
- Ad-Hoc Network Management

Wireless Sensor Module: 433.9 MHz

- Circuit on Duroid & Antenna on paper based substrate
- Integrated microcontroller and wireless transmitter operating @ 433.9 MHz
- Module can be custom programmed to suit to any kind of commercial sensor and environment
- Rechargeable Li-ion battery for remote operation



Circuit on Duroid

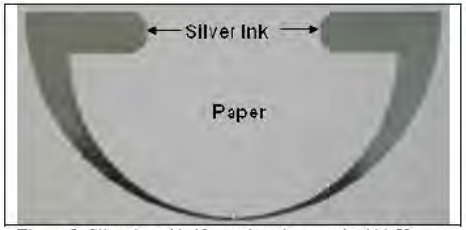
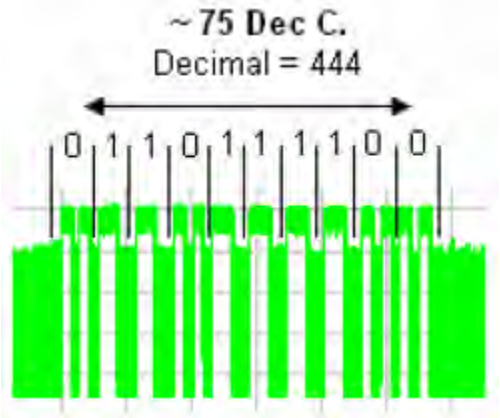
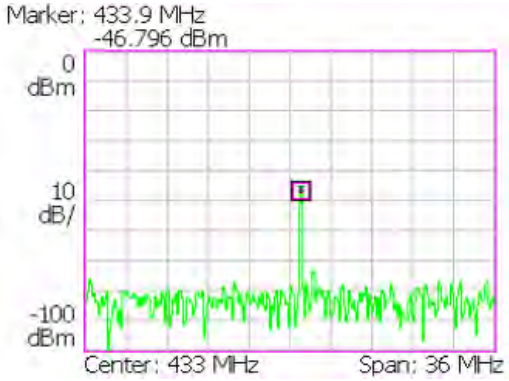


Figure 1. Silver based half-wavelength tapered-width U-shaped antenna

Antenna on Paper



Wireless ASK modulated Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer



Wireless Signal Strength sent out by module, measured by Spectrum Analyzer

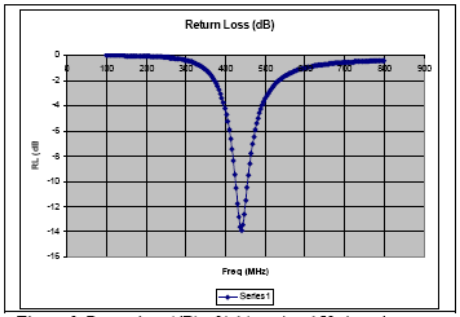
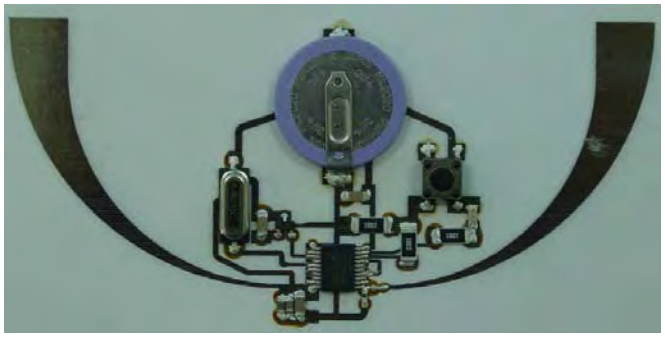


Figure 2. Return loss (dB) of inkjet printed U-shaped antenna on paper.

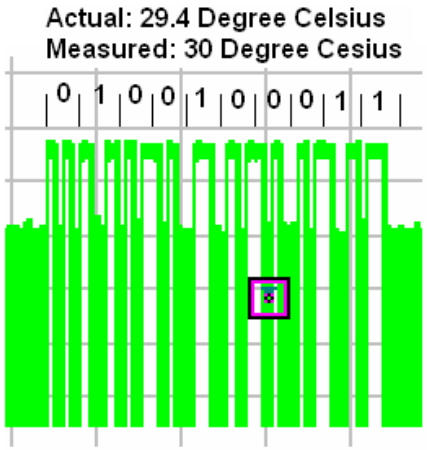
Antenna return loss showing good power transfer (>90%) from circuit to antenna.

Wireless Sensor Module: 904.2 MHz

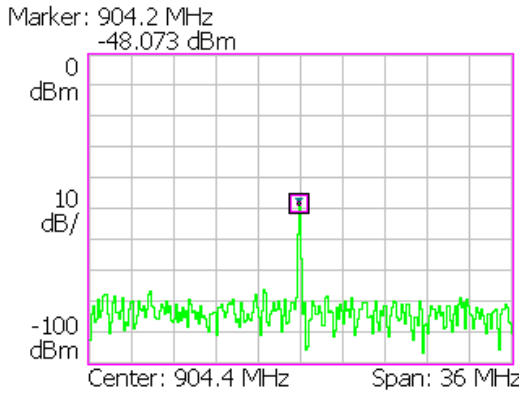
- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation



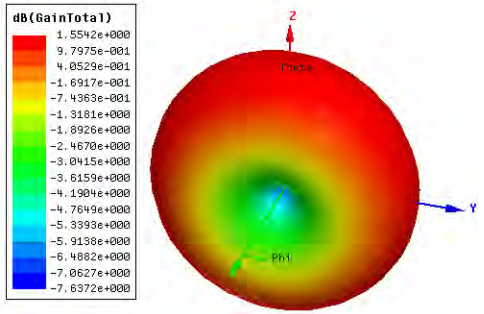
Circuit + Antenna on Paper



Wireless ASK modulated Temperature Sensor Signal sent out



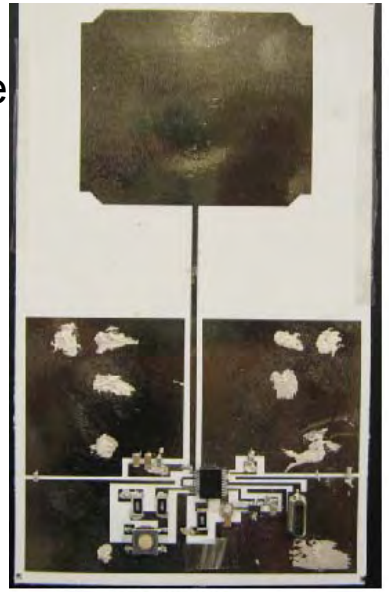
Wireless Signal Strength sent out by module,



Antenna Radiation Pattern showing high gain

Wireless Sensor Module: 904.5 MHz

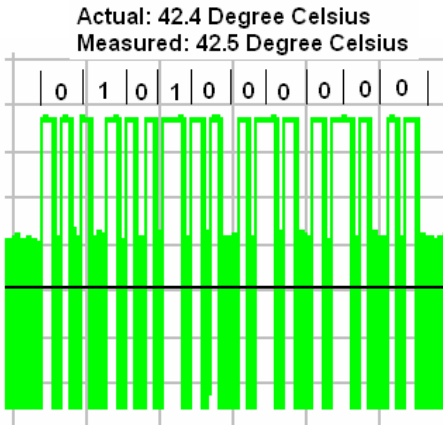
- Double Layer Module Circuit printed on Pape using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation



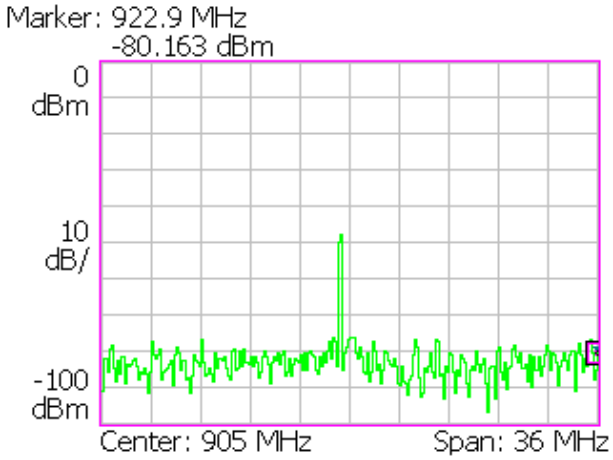
TOP VIEW

BOTTOM VIEW

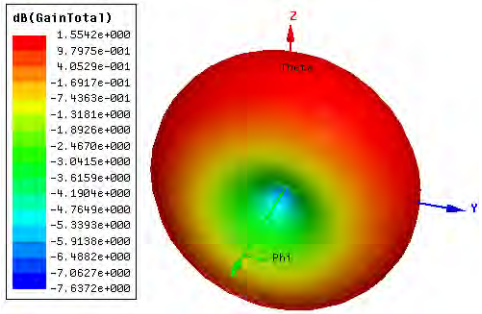
Circuit + Antenna on Paper



Wireless ASK modulated Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer



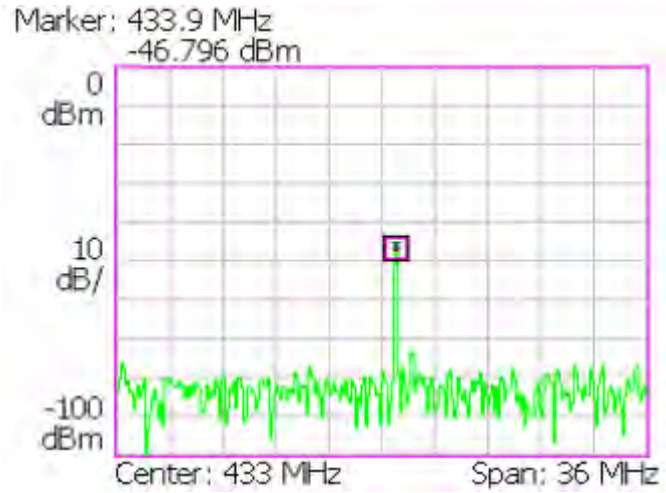
Wireless Signal Strength sent out by module, measured by Spectrum Analyzer

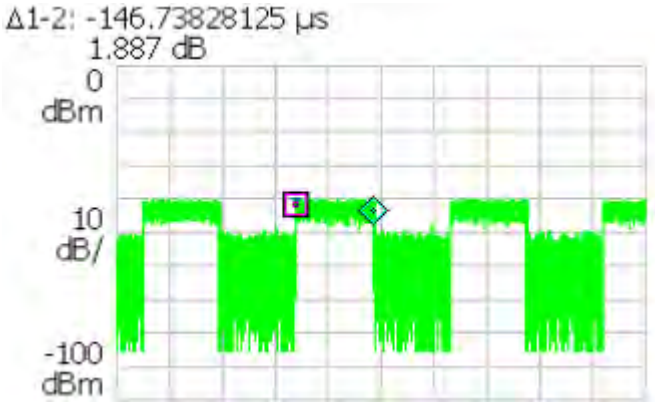


Antenna Radiation Patter showing high gain

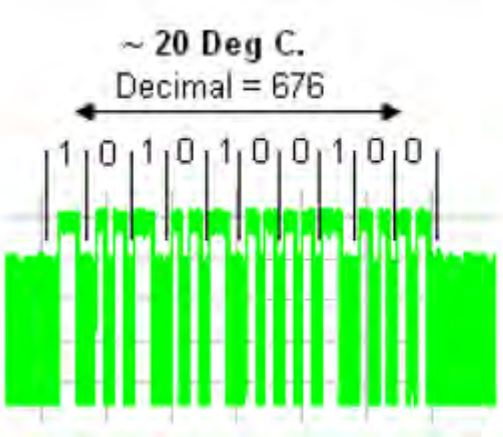
Communication Measurements

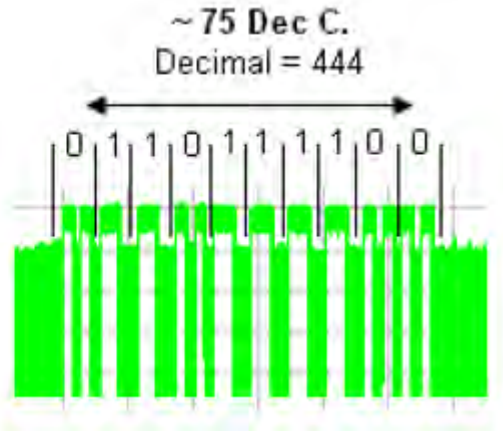
- Carrier Frequency:
  - 433.9 MHz
- Bit Encoding:
  - Miller type
- Bit Transmission rate:
  - 6.8 kbps (Gen-2 > 5kbps)
- Modulation Type:
  - Amplitude Shift Keying
- Modulation Duty Cycle:
  - 50%





Sensor Measurements

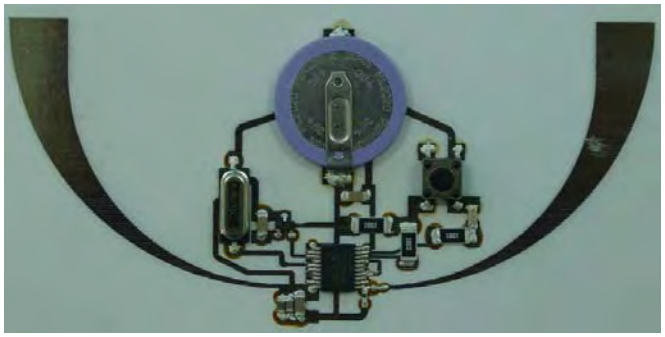




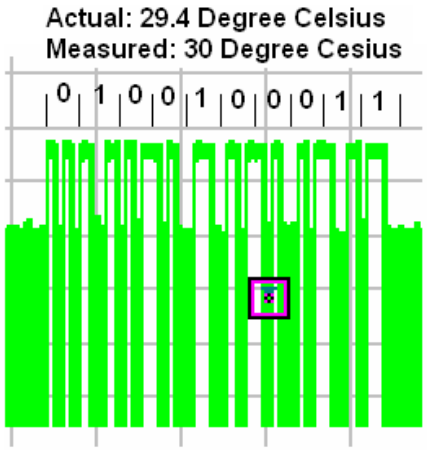
Temp (°C)	Sensor Output Actual (V)	Sensor Output Meas. (V)	A/D Output Actual (Dec)	A/D Output Meas. (Dec)	Diff (°C)
20	1.899	1.909	672.21	676	0.92
75	1.249	1.254	442	444	0.5

Wireless Sensor Module: 904.2 MHz

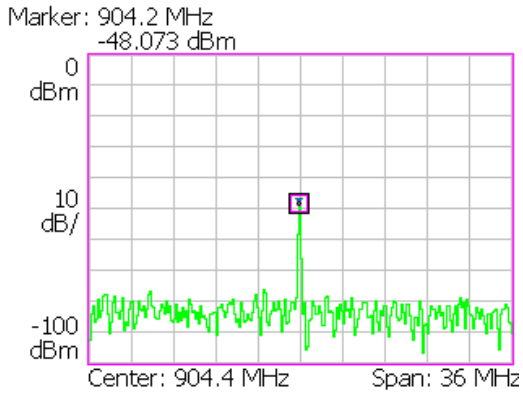
- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation



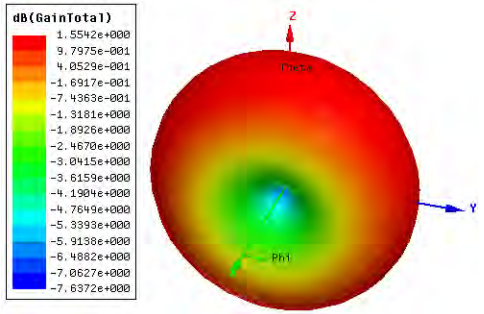
Circuit + Antenna on Paper



Wireless ASK modulated Temperature Sensor Signal sent out



Wireless Signal Strength sent out by module,



Antenna Radiation Pattern showing high gain

PIREAS RFID TESTBED

Active Reader (Mantis II)

XR 400 UHF Reader Kit

agile reader
(Infinity 510w)

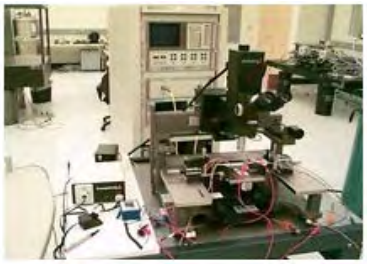
NIST
National Institute of Standards and Technology

NIST standards

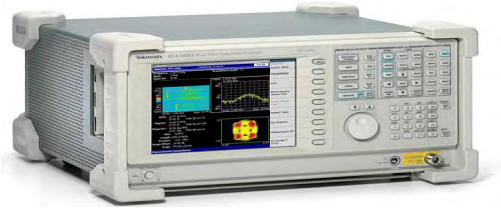
ZVA Vector Network Analyzer

Materials Inkjet Printer

R&S SMJ100A



HP Vector Network Analyzer



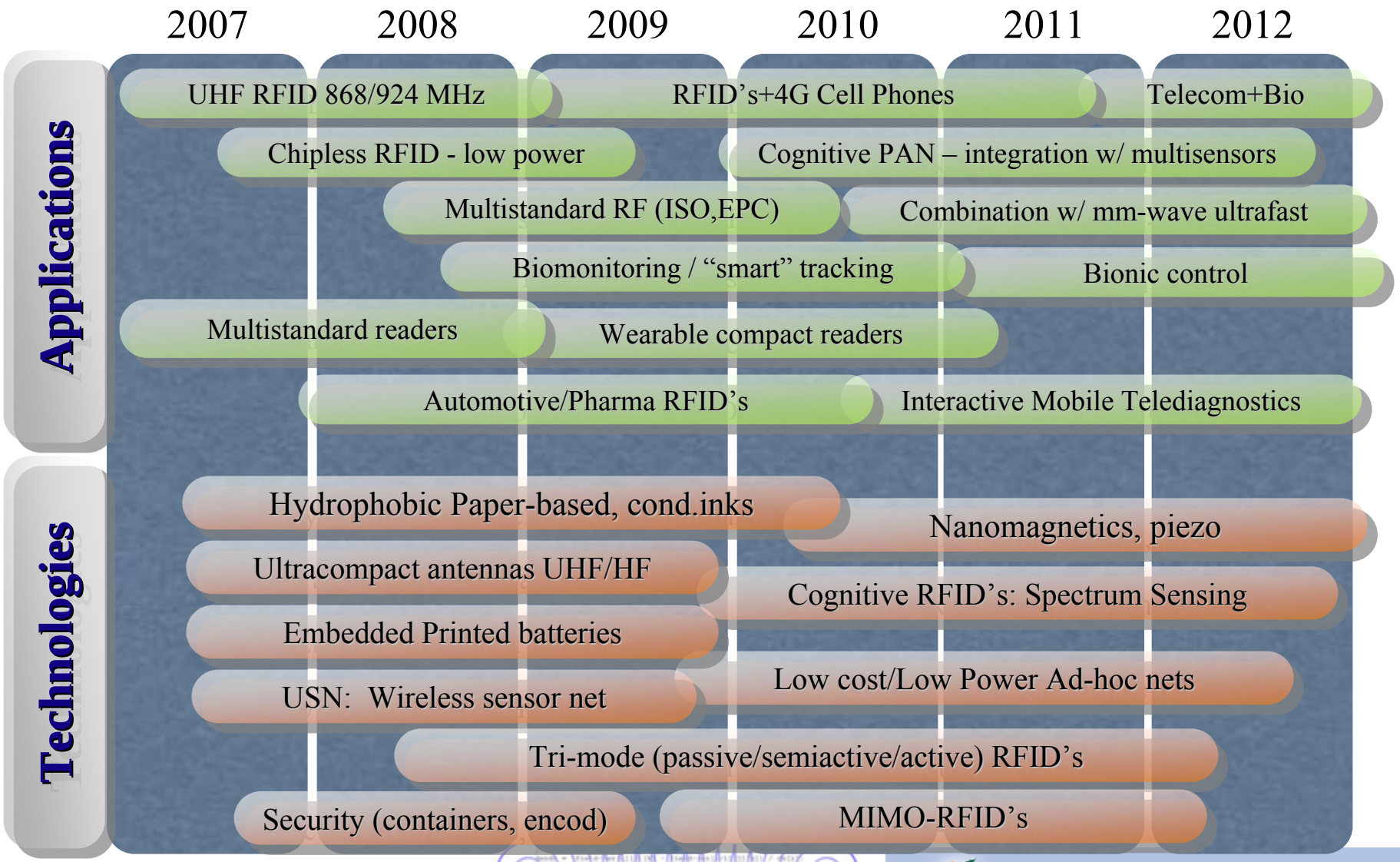
RSA3408A

Georgia Institute of Technology

ATHENA

GEDC Georgia's Home for Mixed Signal Technology

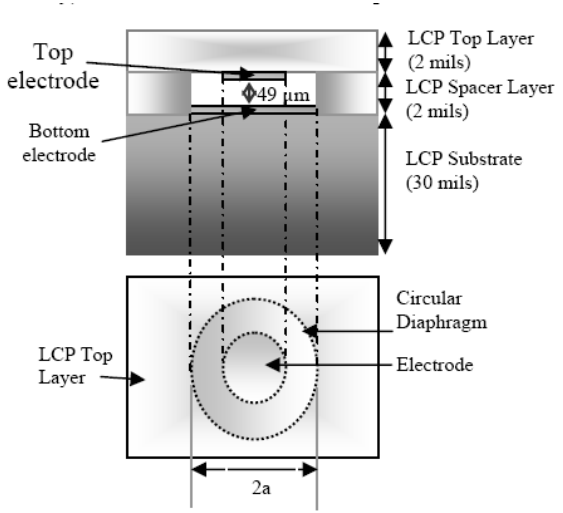
GEDC Roadmap: PIREAS



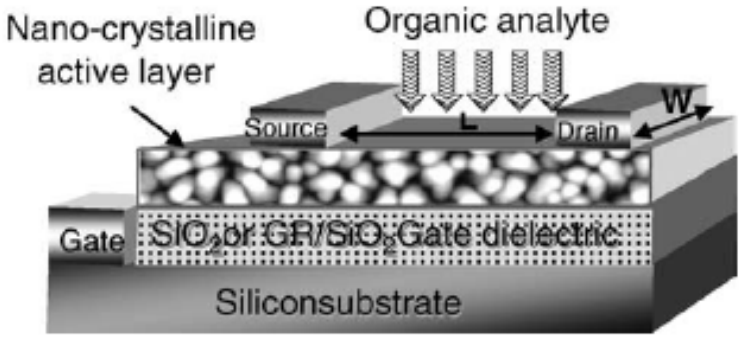
Integrated Sensors in RFID tags

Possibilities:

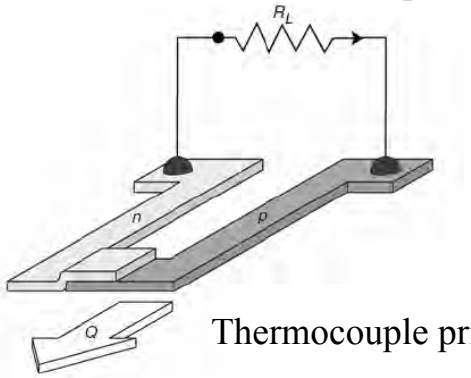
- **Pressure sensors** on organic material (Liquid Crystal Polymer)
- **Temperature sensors** using printed thermocouple pairs
- **Chemical sensors** using organic thin-film transistors (OTFT)



Pressure sensor on LCP principle



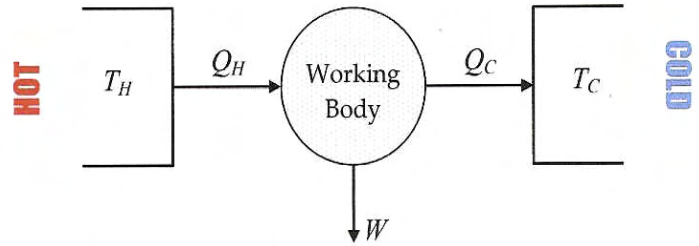
Chemical sensor OTFT principle



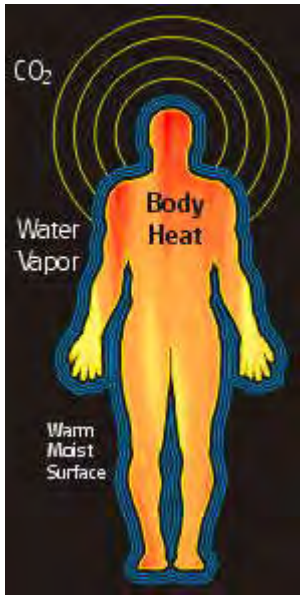
Thermocouple principle

Thin film batteries: Recharging

- Recharging methods:
  - RF charging trough energy collected at RFID tag
  - Power scavenging
    - Pressure → Using a piezoelectric printed collector
    - Light → Printed solar cells
    - Temperature (human body heat) → Using a modified Carnot cycle *(projected efficiency of 50%)*



Carnot system

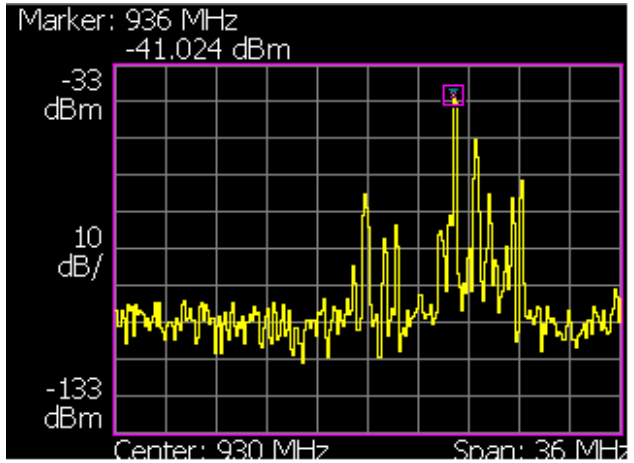


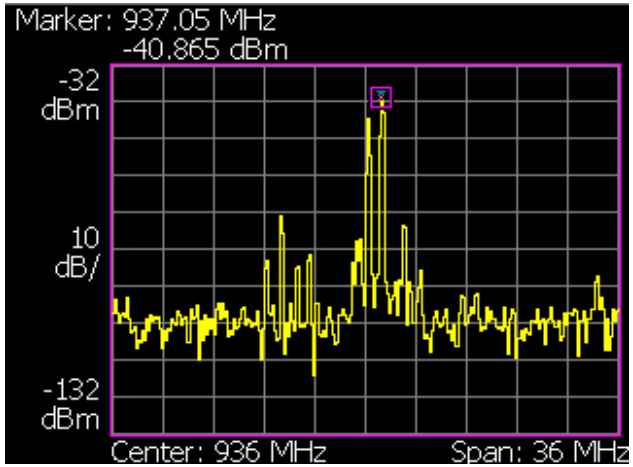
Sources of energy in a human body

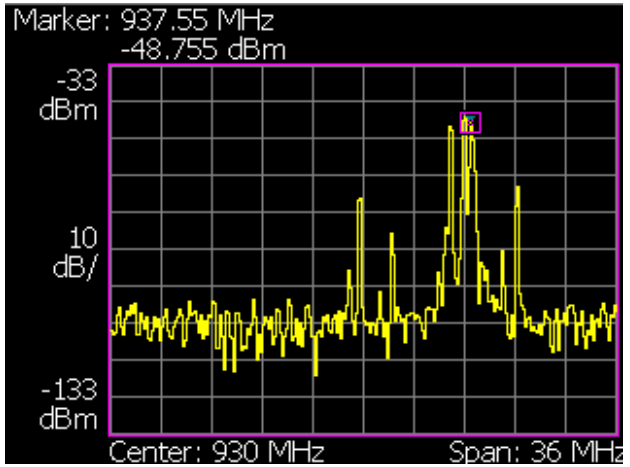
Solar cell

Power Spectrum Measurement

- Measurements carried out at 3 different locations
- Measurements also carried out in-between vehicles to determine vehicle effects on radiation



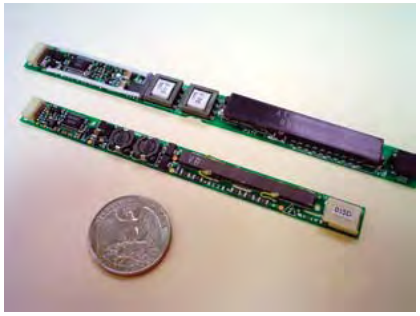




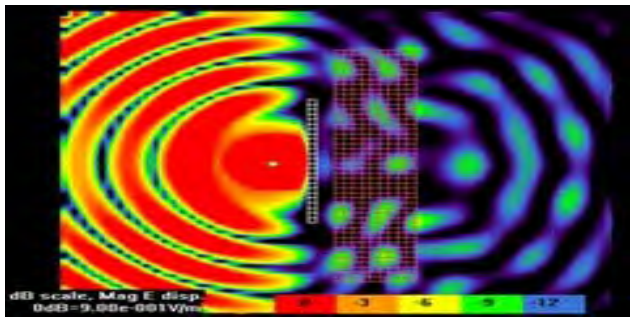
Scavenging Potential Solutions

- Compact Photo Cells (n=30%)
- Piezoelectricity (n=45-60%)
- Wireless Scavenger (n=35-45%)

(Power converter/ Supercapacitor w/ or w/o battery)



✓ The presence of the battery (200-300um thickness sandwiched between two paper layers) guarantees the better/longer energy storage, but leads to bulkier and more expensive designs.

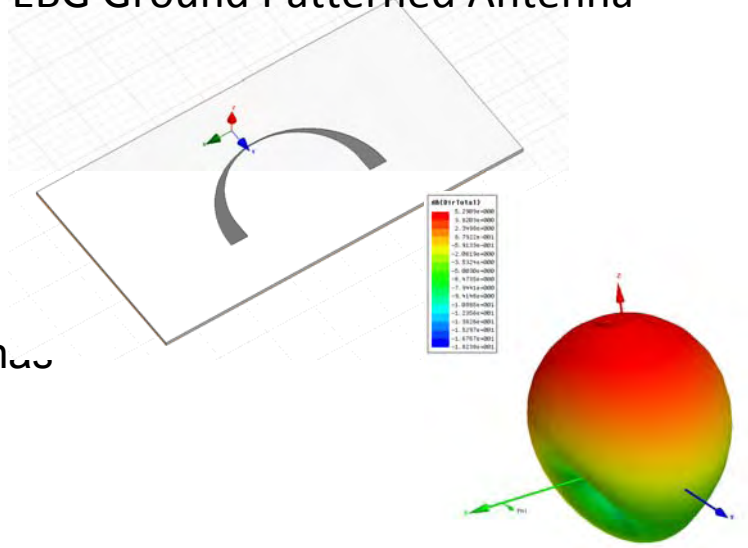


Wireless/RFID technology for cargo/containers

Challenges:

- Extremely **Lossy Environment** due to the scattering caused by the presence of numerous cargo/metal
- **Bandwidth** of operation of RFID
- **Multipath** effect of wireless signals
- **Power** Constraints
- **Material** (substrate for electronics) and packaging

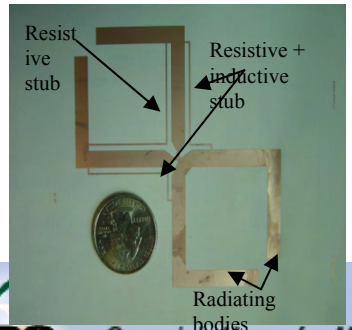
EBG Ground Patterned Antenna



Proposed Solution:

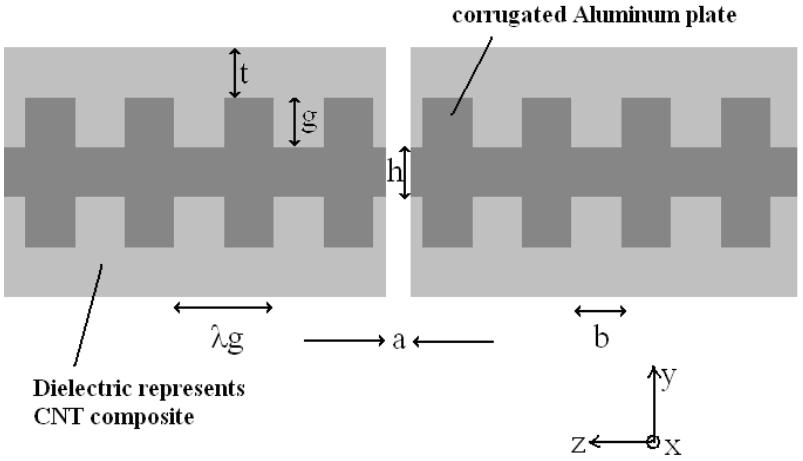
- EBG (Electro Magnetic Band-Gap) enabled Antennas to be mounted onto containers will reduce the loss that is introduced by metallic containers.
- Dual Polarized Antennas to account for losses induced by environment such as multipath
- Wideband Antennas for Global operation
- Active and semi-active RFID operations
- Thin film batteries for active RFID with power scavenging techniques
- Packaging

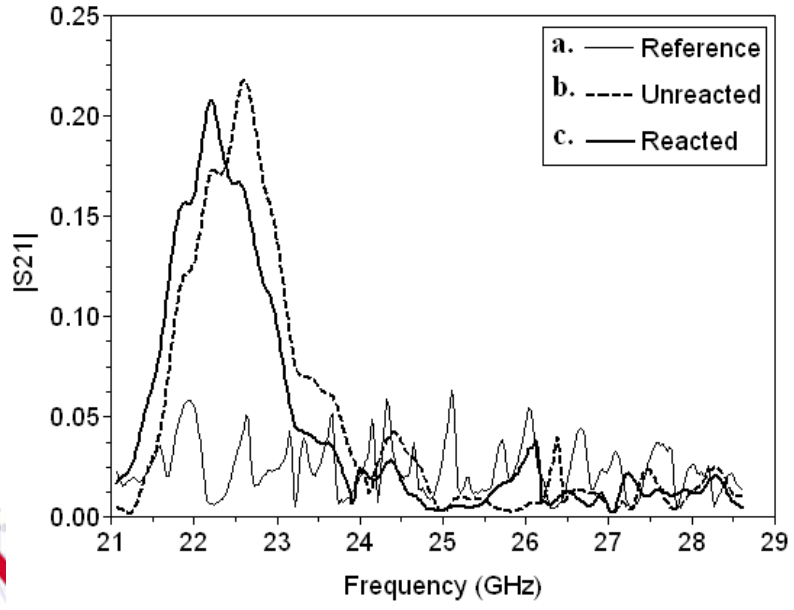
Dual Polarized Antenna



Ultrasensitive (ppb) Chemical Sensors

- Based on Carbon Nanotubes (CNT) and Plasmon Theory
- Can detect presence of different gases (O2, CO2, NH3, …) in ppb instead of commonly used gas sensors (ppm) improving detecting capability by 3 orders of magnitude
- Easy to integrate with "magic cubes" in the order of 2x2x2 mm3 around 25 GHz
- Easy to inkjet-print the corrugated metal plate on top of a paper substrate on a thin layer of CNT's
- Detectability is based on observable frequency shift based on the gas (+2% NH3, -0.9% for CO2)
- Can be integrated with DNA bio-sensors within the same "magic cube" size (detectability of presence of a person based on tiny saliva/breathing particles/hair)



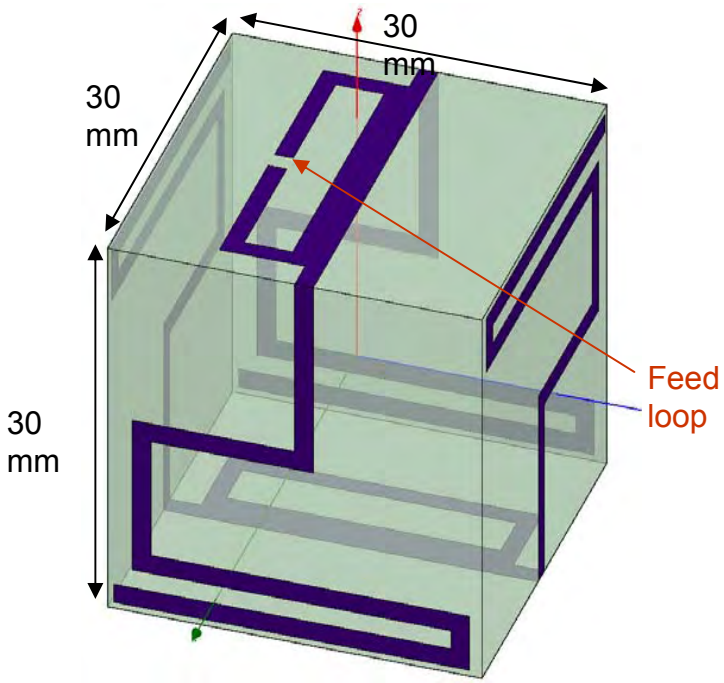


“Smart Skin”-Crack Detection

- Inventory Control (through multi-hopping on closely attached RFID’s)
- Investigation of numerous items of Bohemian crystal of various curvature radii (diameters ranging from 2’’ to 14’’, wearable and/or portable with heights ranging between 0.5-5’’ and weights between 0.5-6 lb). “Credit-card” passive RFID’s offer a range of 3-10’ in for 900 MHz operation). RFID’s on the curved side do not deteriorate the radiation pattern significantly (worst case range: 2.5-6 in). Crystal crack identification (above 0.2’’ for almost planar, 0.1’’ for high-curvature was possible for a read-range of 3-5’). Challenge is the item tracking for item spacings below 5’’ and crack detection below 0.2’’. [18 cracked – currently destroyed – samples; some results in DARPA effort]
- Potential future-step: add a “smart” RFID-enabled printed sensor in the interior of glasses and bowls for accurate drink quality control checking and/or crack identification.
- ***Significant RFID benefit: item tracking of very expensive items, crack scan and anti-counterfeiting***
- Major challenges: RFID has to be conformal, very lightweight and with a small trace. Items like small glasses and miniatures allow only for a 1’’x1’’ RFID with a potential range up to 2 in without space for power source/scavenging. Polarization diversity for detection of cracks parallel to polarization <0.2in and transverse to polarization <0.5in.
- Other local items could include local containers such as embedded (Matryoshka) dolls that allow for much larger item RFID’s or secure-perimeter RFID’s.

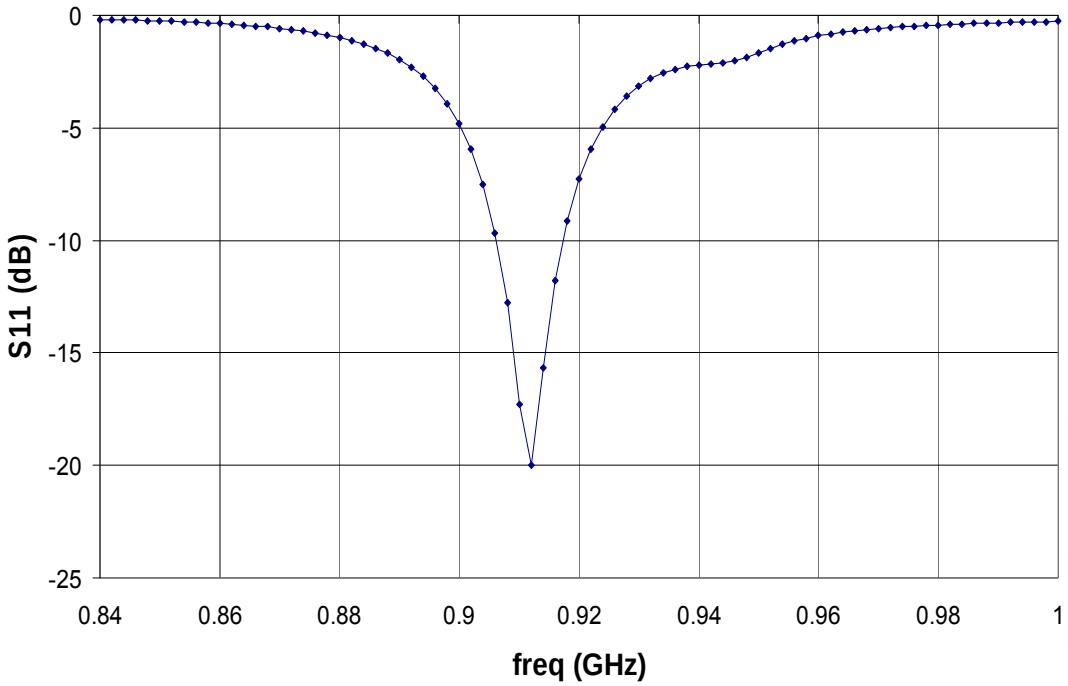
3D-”Magic Cube” Antennas

- Typical RFID/Wireless Sensor antennas tend to be limited in miniaturization by their length
- What if used a cube instead of a planar structure to decrease length dimension?
- Interior of cubic antenna used for sensing equipment as part of a wireless sensor network
- Can lead to the implementation of UWB sensors and the maximization of power scavenging efficiency, potentially enabling trully autonomous distributed sensing networks



Meander line antenna on paper substrate

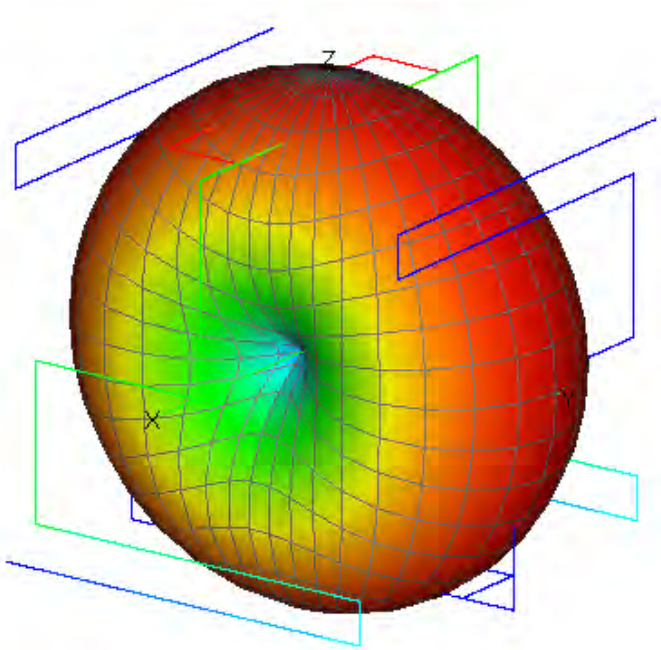
3D-Antenna parameters



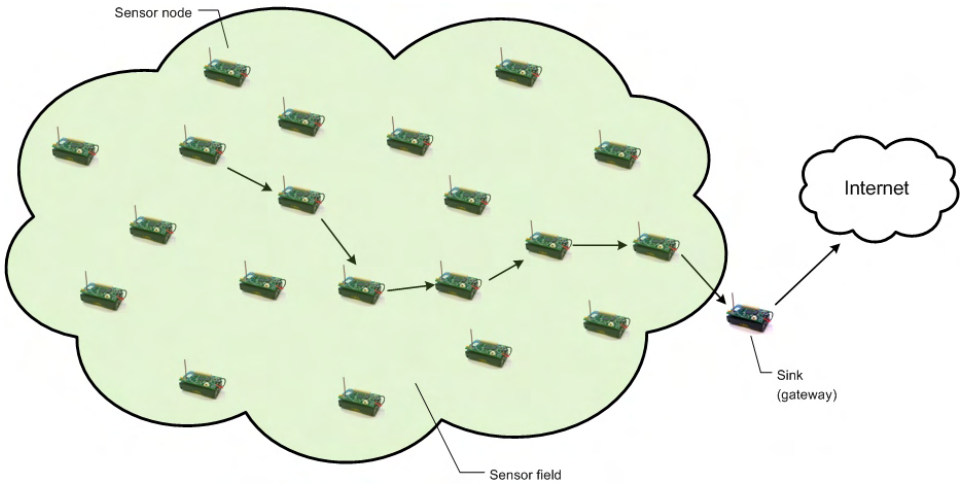
S_{11} of cubic antenna matched to TI RFID IC chip with input impedance of 380Ω with 2.8pF capacitance

Omnidirectional radiation pattern

Directivity of 2.53 dBi at resonance



Wireless Sensor Networks



Multi-hop communication plays a major role in the routing protocols forming the aforementioned network.

The advantages of deploying multi-hop routing protocols are:

- Path loss effects and shadowing can be effectively overcome, thus providing coverage over large ranges, assuming the node density is high enough.
- The energy efficiency of communication is improved (less power consumption than the traditional single hop communication).
- The wireless network is self-organized and capable of sustaining its functionalities without any interruption because of node failures or blockages due to power outage, physical damage or environmental interference.