Master's Thesis

A Dual-Resonant Microstrip UHF RFID "Cargo Tag" with a CPW Structure for the Feed and Matching Circuit

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Committee

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Dr. James Stiles
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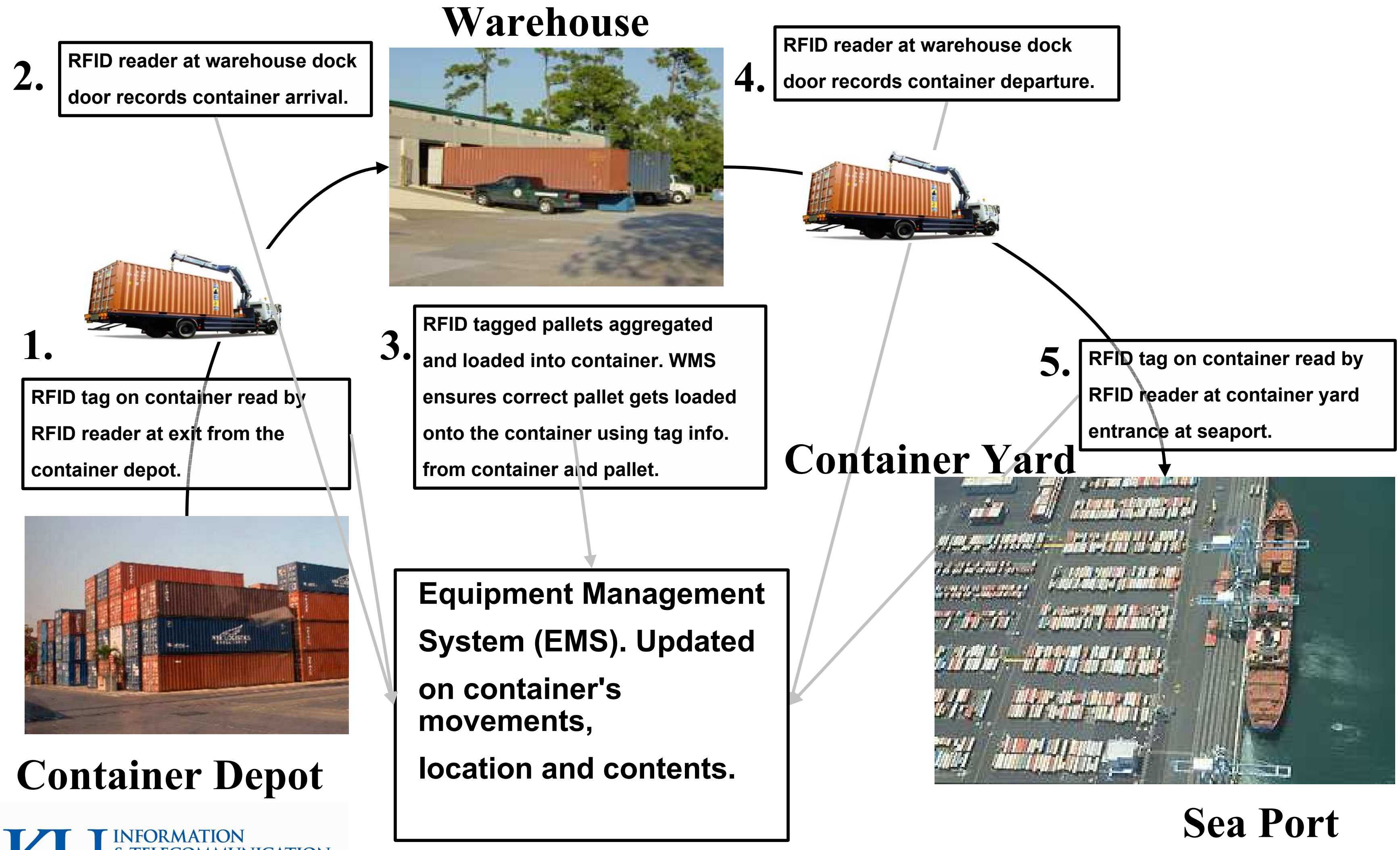
Cargo containers



Container Depot

1. RFID tag on container read by RFID reader at exit from the container depot.

Warehouse

2. RFID reader at warehouse dock door records container arrival.

3. RFID tagged pallets aggregated and loaded into container. WMS ensures correct pallet gets loaded onto the container using tag info. from container and pallet.

4. RFID reader at warehouse dock door records container departure.

Container Yard

5. RFID tag on container read by RFID reader at container yard entrance at seaport.

Sea Port

Equipment Management System (EMS). Updated on container's movements, location and contents.

Why put passive RFID on Cargo Containers?

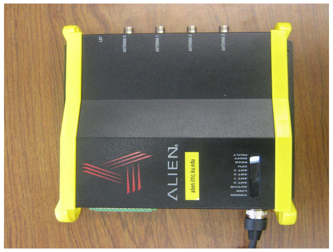
- Passive UHF RFID
  - No line of sight required
  - (Relatively) cheap
  - Long-life
  - Read at distance
  - Growing adoption

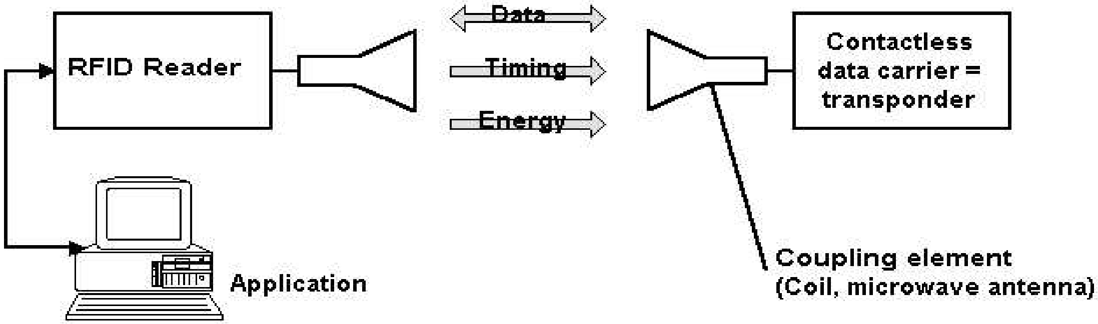
- Scan at distance in work flow

- Maintain EPC grouping
  - Item -> case -> pallet -> container -> ship

Passive UHF RFID- How does it work?

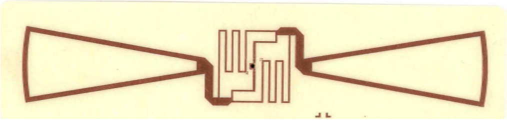
- Tag
- Reader
- Host
- Backscatter





Limitations of Passive UHF RFID for Tagging Cargo

- Dipole antennas’ performance degrade on metal [2][3][4]



- Microstrip antennas are a possible solution to the metal problem

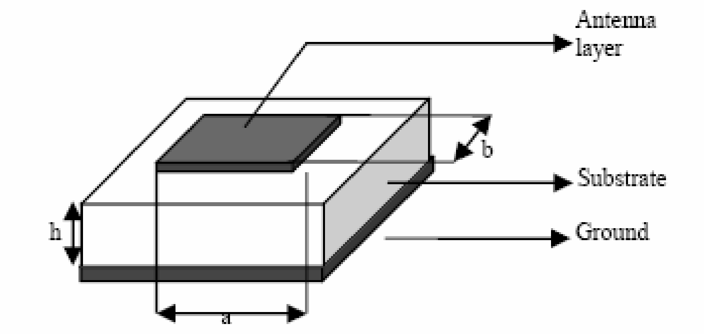


Photo by Megan E. Gowen

- Frequency of Operation is different for different geographical regions
- Ex. 865-869 MHz in Europe, 902-928 MHz in the U.S.
- Microstrip antennas: trade-off performance, bandwidth

Thesis Statement

"To design and build a feasible dual-resonant passive UHF RFID tag that can operate on large metal assets over a wide frequency band and to subject the design to a rigorous theoretical analysis in order to completely characterize the antenna."

Publications

Related to this work:

Supreetha Aroor and Daniel D. Deavours , " A dual-resonant microstrip-based UHF RFID 'Cargo' tag ," in *Proc. IEEE International Microwave Symposium*, Atlanta, GA, June 2008

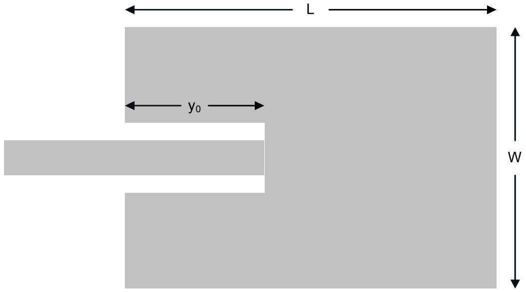
Other:

Supreetha R. Aroor and Daniel D. Deavours, "Evaluation of the state of passive UHF RFID: An experimental approach," *IEEE Systems Journal*

Previous Work

- Completely planar microstrip antenna[6]

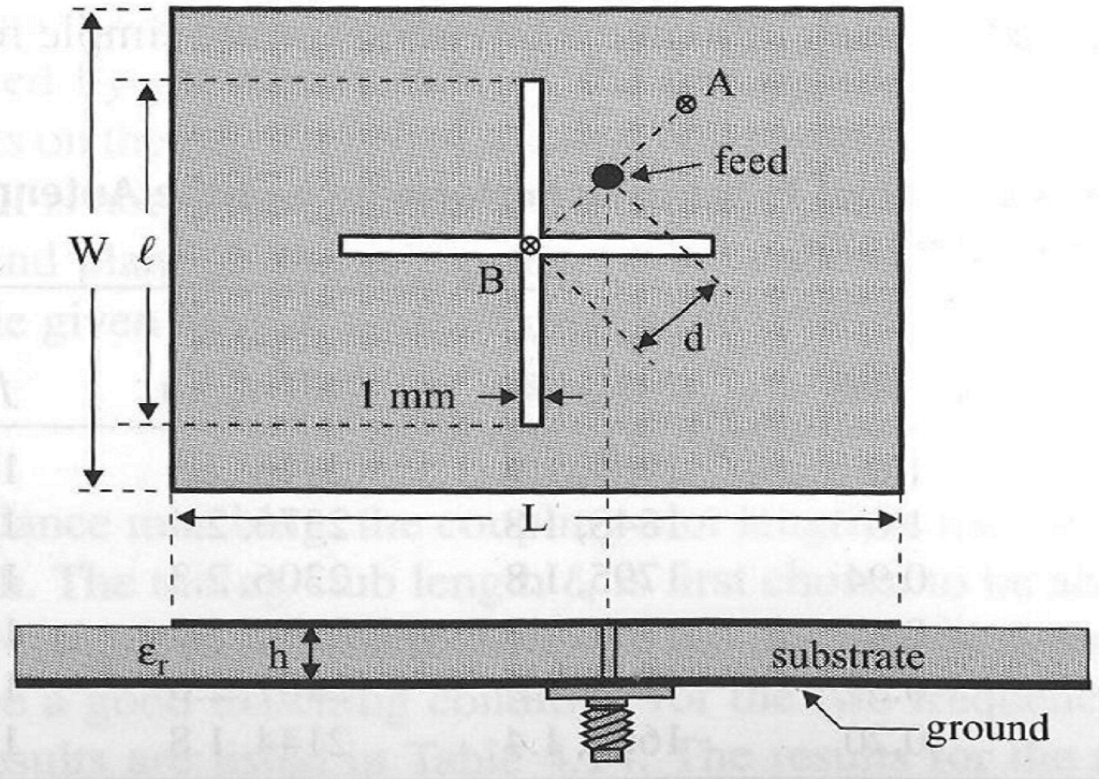
- Inset feed



- Low IC Resistance [8-14 Ohms]

  Solution: Place the matching circuit inside the antenna

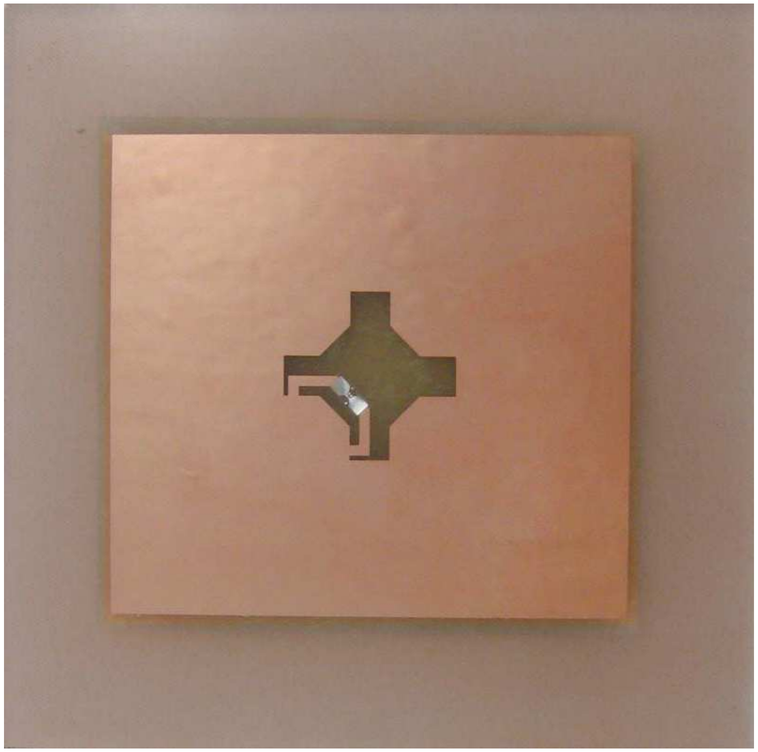
Inspirational Work



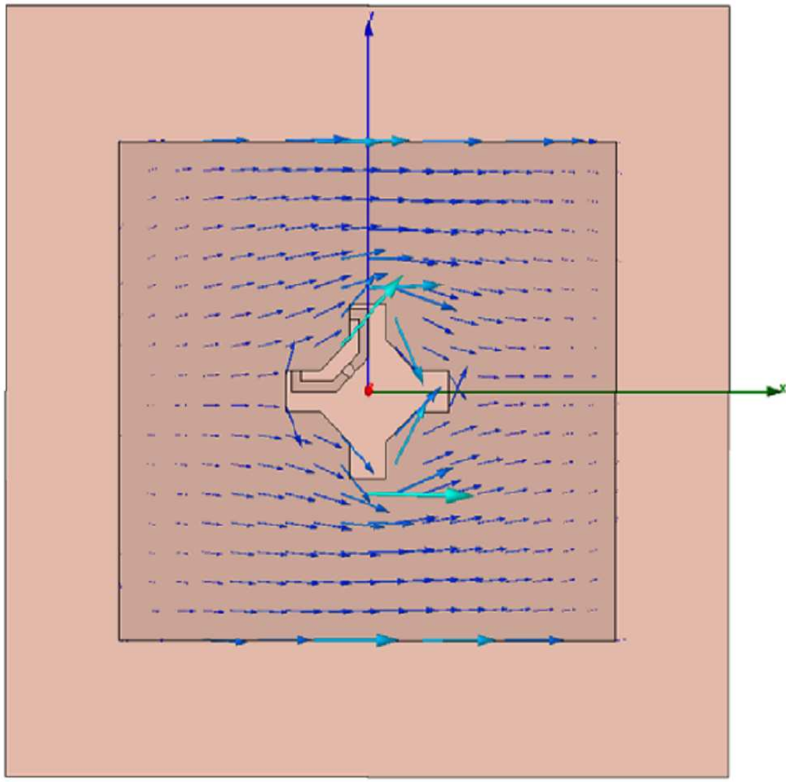
K. L. Wong and K. P. Yang, “Small dual-frequency microstrip antenna with cross slot,” Electronics Letters 33, Nov 6, 1997[8]

Putting it all together

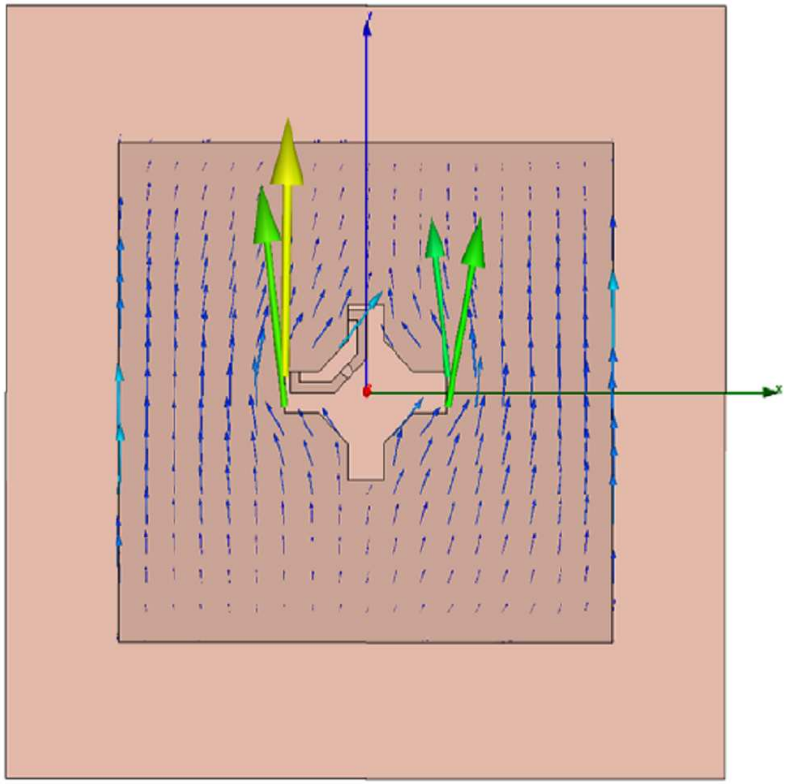
- Series edge-feed microstrip antenna
- Can place match inside the antenna
- Can use rectangle, feed on diagonal
  - –Excites TM_{10} and TM_{01}
- Can place a cross slot to reduce form factor



Simulated Currents



867 MHz

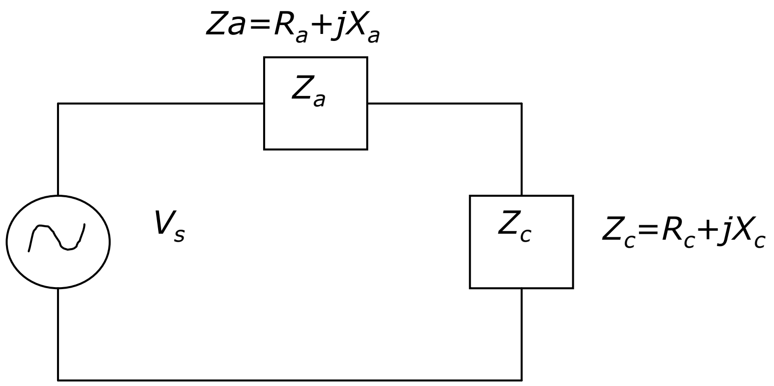


915 MHz

Power Transfer

- Power Transfer Efficiency[14]

$$\tau = \frac{4R_a R_c}{|Z_a + Z_c|^2}$$



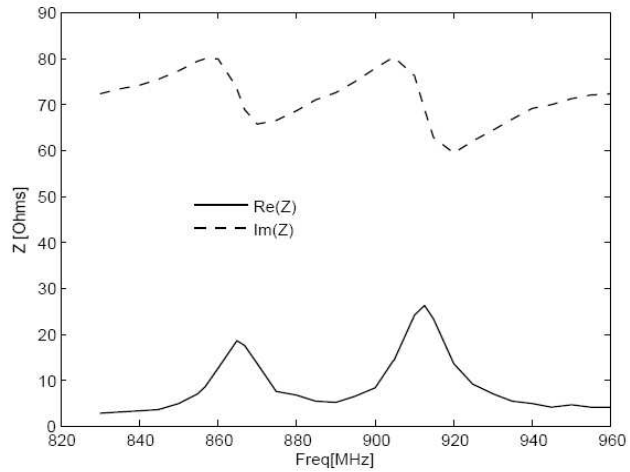
- Maximum Power Transfer
  $Z_a=Z_c$*

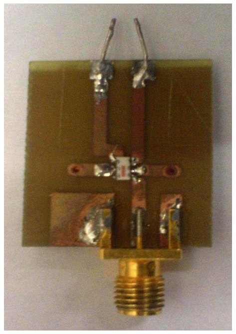
- τ =1 for maximum power transfer

- TI chip impedance: 13-*j*65 Ohms

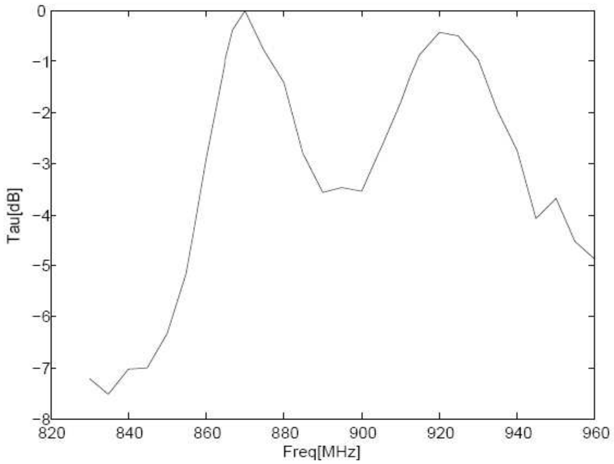
Measurements and Results

Measured Impedance





Measured Tau



- Friis equation for RFID transponders:

  P_{th}=-13 dBm, G_t=6 dBi, G_r=5.4 dBi, ρ=-3 dB, P_t=30dBm

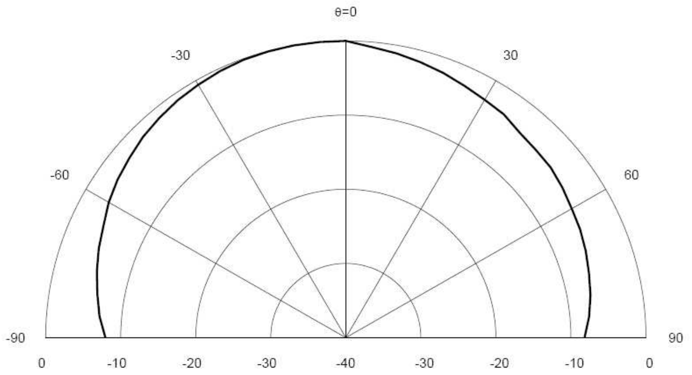
$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r \tau\rho}{P_{th}}}$$

- Expected read distance is 9.7 meters[32 feet]

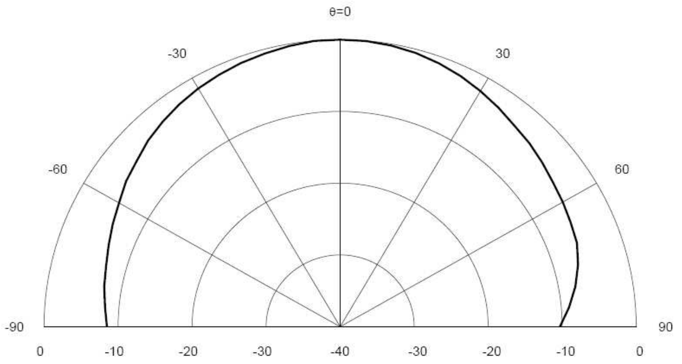
  With 3 dB ground reflection-13.7 meters[45 feet]

- Measured: 18.3 meters[60 feet]

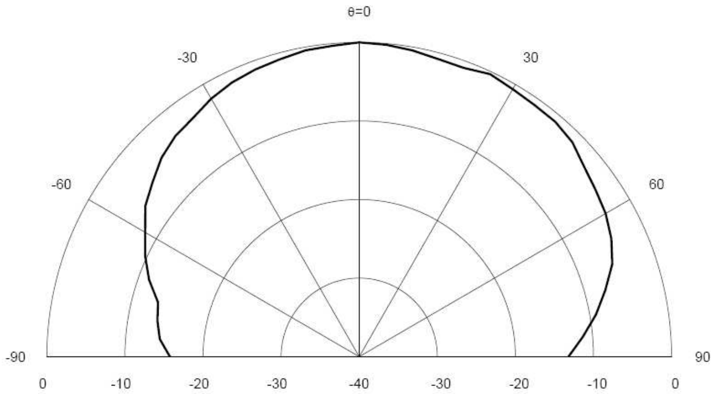
Measured Radiation Pattern



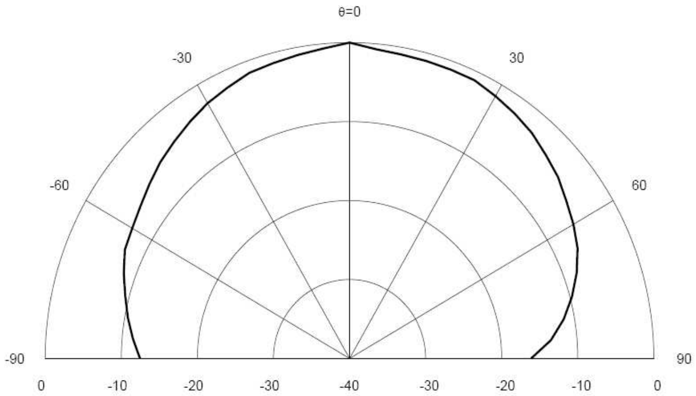
E-plane,867 MHz



H-plane,867 MHz

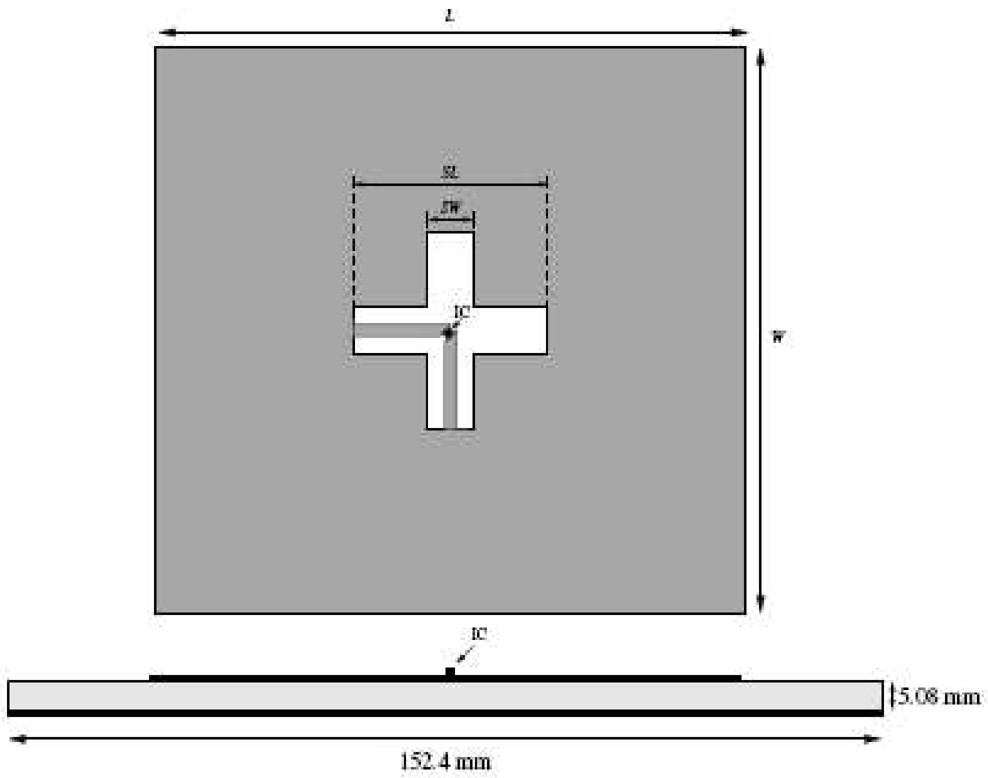


E-plane,915 MHz



H-plane,915 MHz

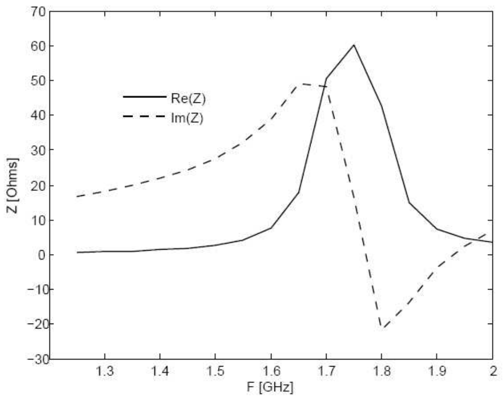
Modified Design

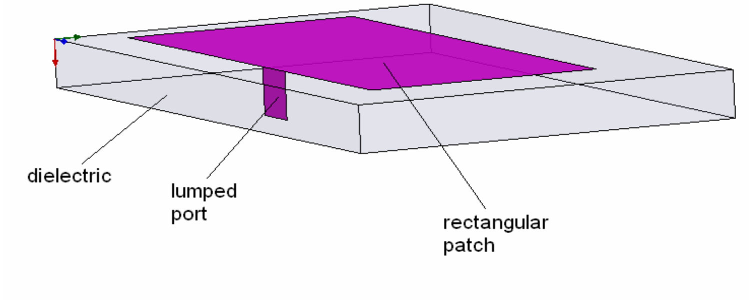


- Employs rectangular cross slots
- CPW Structure for feed and matching circuit
- Easier to subject to a rigorous theoretical analysis
- Circuit Model

Microstrip Antenna Circuit Model

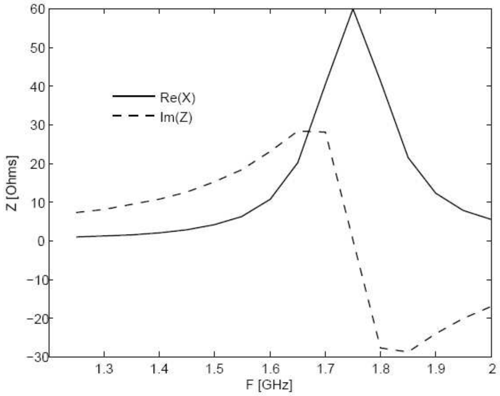
- Rectangular Patch: Impedance Graph





HFSS Simulation. The ground plane is below the substrate

- Parallel RLC Impedance Graph. First find R and Q. Compute L and C.



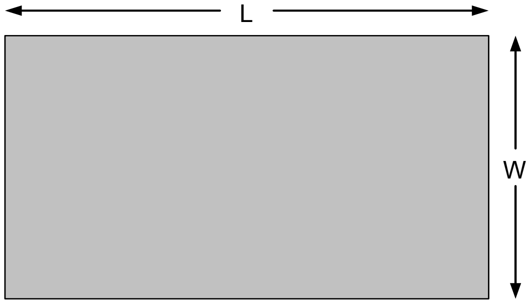
$$Q = \frac{R}{\sqrt{\frac{L}{C}}} \qquad f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Initial Step

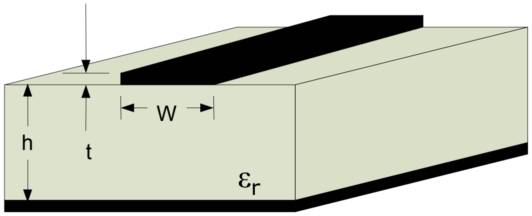
Determine the dimensions of rectangular patch for required resonant frequencies

Ex. Cavity model

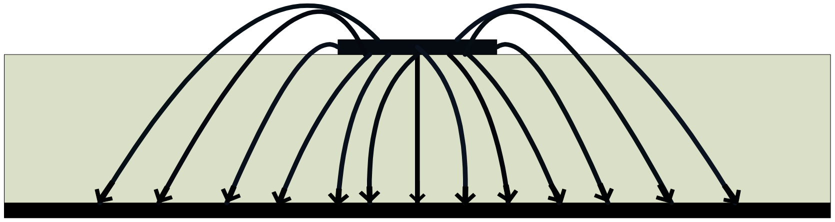
$$f_{r10} = \frac{1}{2L\sqrt{\mu\varepsilon}} \qquad f_{r01} = \frac{1}{2W\sqrt{\mu\varepsilon}}$$



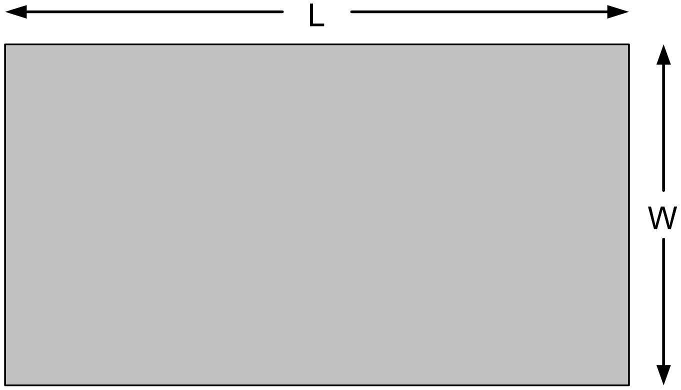
Transmission Line Model



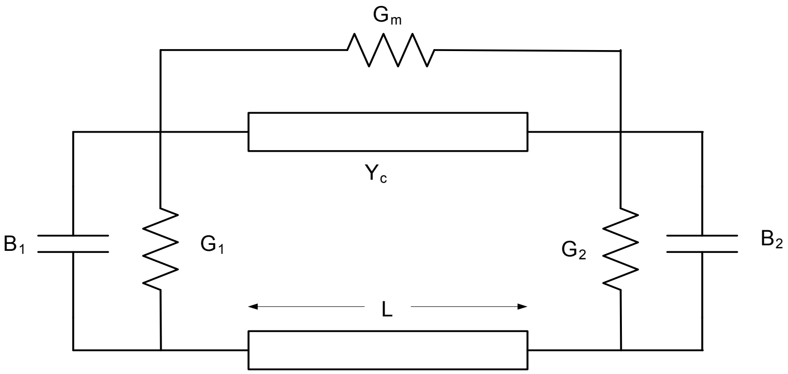
Microstrip Transmission Line



Fringing Fields



Rectangular Patch: Top view



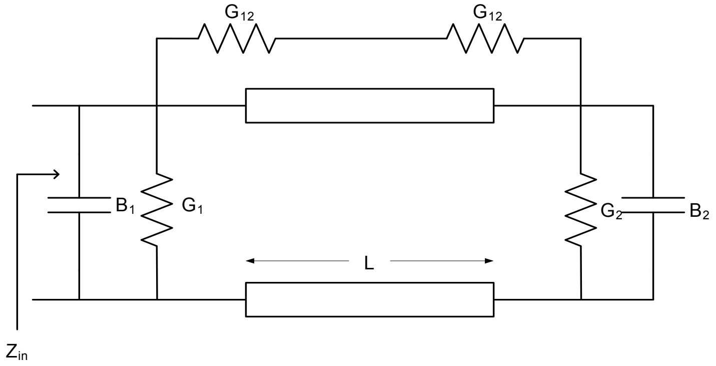
Transmission Line Model[10]

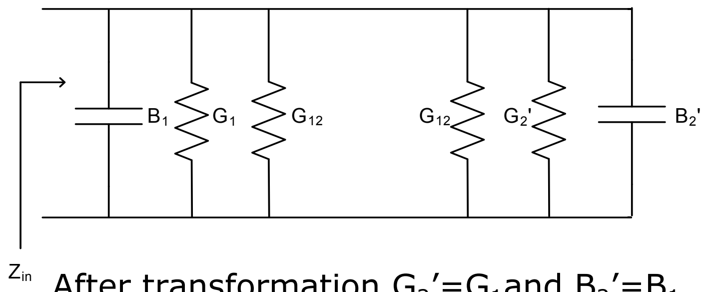
Radiating Input Resistance

The values of G_1, G_{12} and R_{in} can be calculated using [10][11][12]:

$$G_1 = \begin{cases} \frac{1}{90}\left(\frac{W}{\lambda_0}\right)^2 & W << \lambda_0 \\ \frac{1}{120}\left(\frac{W}{\lambda_0}\right) & W >> \lambda_0 \end{cases}$$

$$G_{12} = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\left(\frac{k0W}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0(k_0 L\sin\theta)\sin^3\theta d\theta$$





After transformation, $G_2' = G_1$ and $B_2' = B_1$

$$R_{in} = \frac{1}{2(G_1 + G_{12})}$$

For 867 MHz,
G_1= 0.97 mS, G_{12}= 0.35 mS R_{in}=385 Ohms

For 915 MHz,
$G1$=1.2 mS, $G12$= 0.43 mS Rin=303 Ohms

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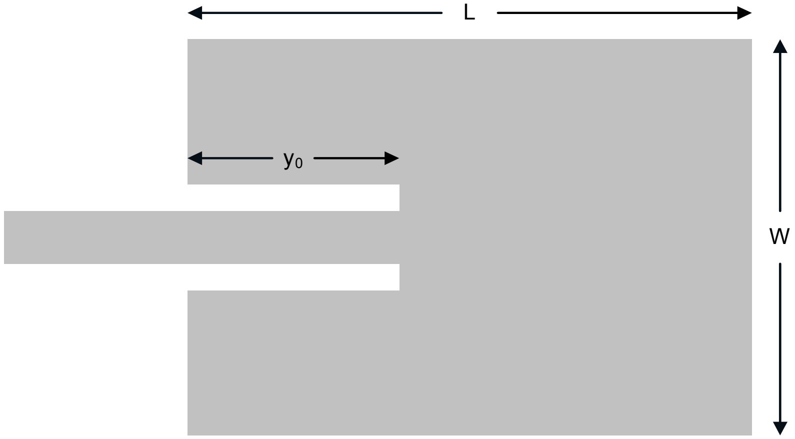
Input Resistance for Inset Feed



Rectangular patch with Inset Feed

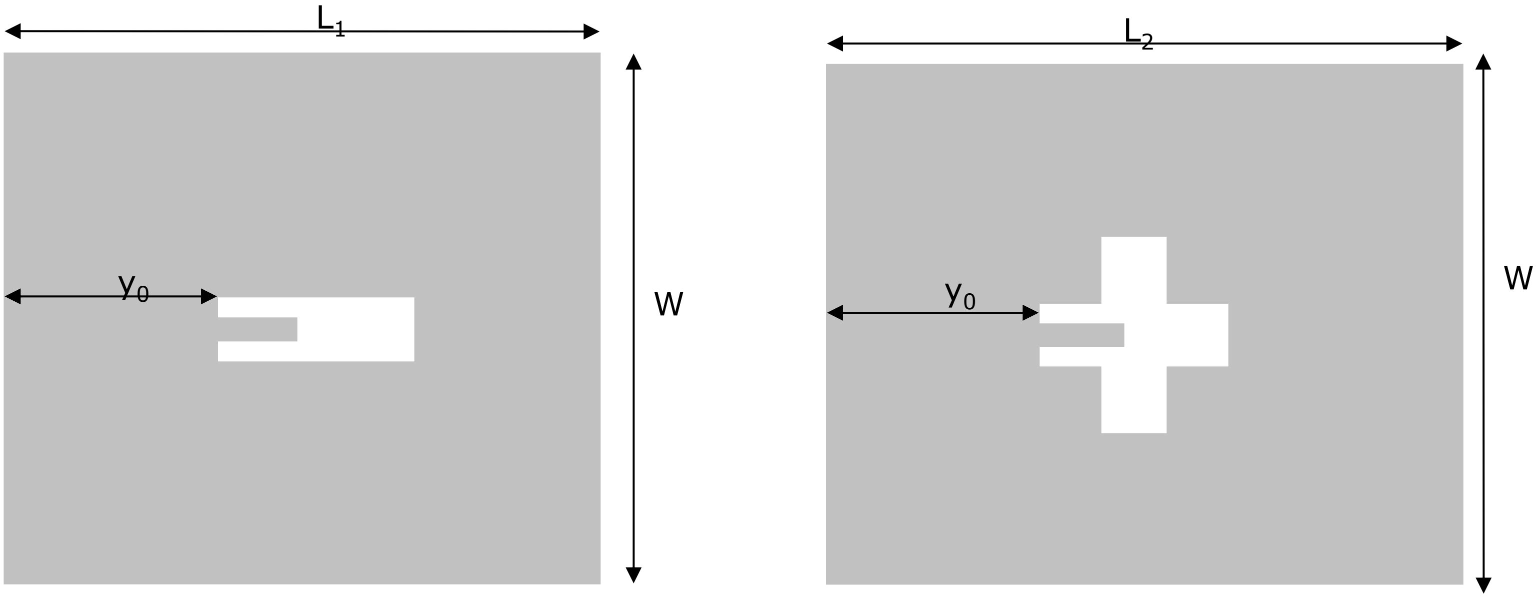
The input resistance for an inset fed rectangular patch is given by[10][13]:

$$R_{in(y=y_0)} = R_{in(y=0)} \cos^2\left(\frac{\pi y_0}{L}\right)$$

where,

$$R_{in(y=0)} = \frac{1}{2(G_1 + G_{12})}$$

Input Resistance for Inset Fed Rectangular Patch with Cross Slot



Antenna 1 Antenna 2

- Where $L_{eff}=L_1$ such that Antenna 1 and Antenna 2 have the same resonant frequency

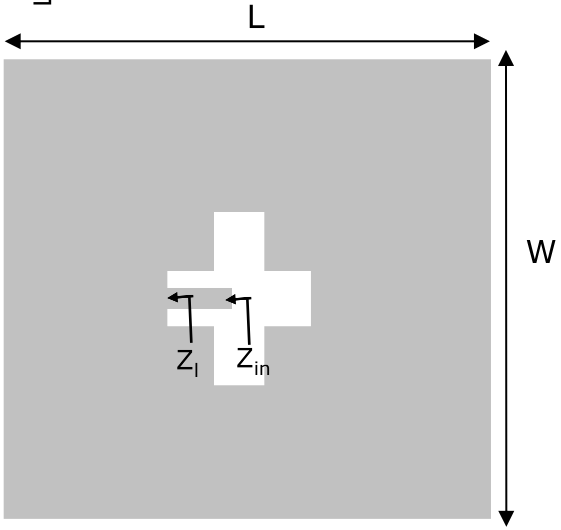
$$R_{in(y=y_0)} = R_{in(y=0)} \cos^2\left(\frac{\pi y_0}{L_{eff}}\right)$$

- L_{eff}[867 MHz]=111 mm, R_{in}=39 Ohms,L_{eff}[915 MHz]=106 mm, R_{in}=37 Ohms

Next Steps

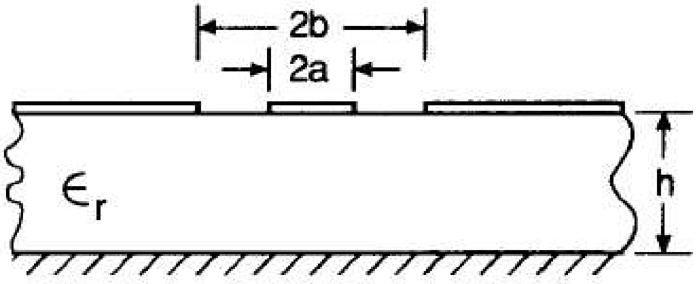
- Transmission Line Equation

$$Zin = Z_0\left[\frac{Z_l + jZ_0\tan\beta l}{Z_0 + jZ_l\tan\beta l}\right] \quad ,\beta l \text{ small, } Z_l << Z_0, \quad Zin = Z_l + jZ_0\beta l$$



- Find feed length, *l* by modeling the feed as a CPW.

CPW Characteristic Impedance



CPW with a ground plane

2a=1 mm

2b=SW=9 mm

Z_{0cp}=155 Ohms

l=17.8 mm

β=24.15

$jZ_0\beta l=j67$

$$Z_{0cp}=\frac{60\pi}{\sqrt{\varepsilon_{re}}}\frac{1}{K(k_1)/K'(k_1)+K(k_6)/K'(k_6)}$$

Where, $\varepsilon_{re}=1+q(\varepsilon_r-1)$

$$k_6=\frac{\tanh(\pi a/2h)}{\tanh(\pi b/2h)}$$

$$q=\frac{K(k_6)/K'(k_6)}{K(k_1)/K'(k_1)+K(k_6)/K'(k_6)}$$

$$\frac{K(k)}{K'(k)}=\frac{\pi}{\ln[2(1+\sqrt{k'})/(1-\sqrt{k'})]}\qquad \text{for } 0\le k\le 0.707$$

$$k_1=a/b$$

$$\frac{K(k)}{K'(k)}=\frac{1}{\pi}\ln[2(1+\sqrt{k'})/(1-\sqrt{k'})]\qquad \text{for } 0.707\le k\le 1$$

Input Resistance Challenge

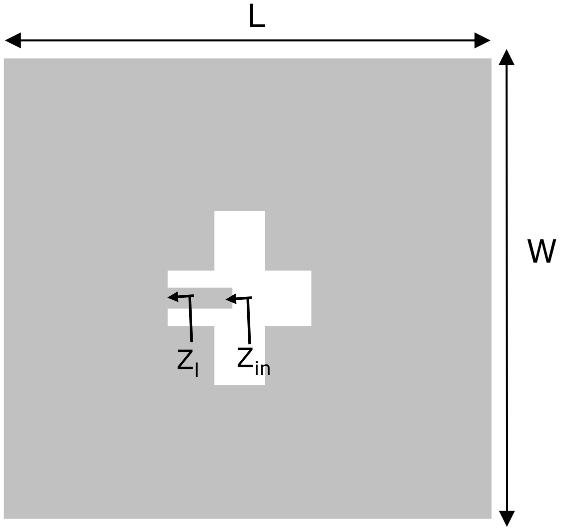
- The input resistance decreases along the length of the feed
- R_{in}[867]=16 Ohms, R_{in}[915]=15 Ohms
- Cannot be modeled as a CPW transmission line
- Use simulated resistance values

Predicted

Z_l	39+j0
Z_{in}	39+j67

Measured, HFSS,probe

Z_l	38+j4
Z_{in}	16+j72



Quality factor

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}}$$

$$Q_c = h\sqrt{\pi f \mu \sigma}$$

$$Q_d = \frac{1}{\tan\delta}$$

$$Q_{rad} = \frac{2\omega\varepsilon_r}{hG_t / l} K$$

$$G_t / l = G_{rad} / W$$

$$K = L / 4$$

For the cargo tag, $Q_t \approx Q_{rad}$

Q[867]=45

Q[915]=38

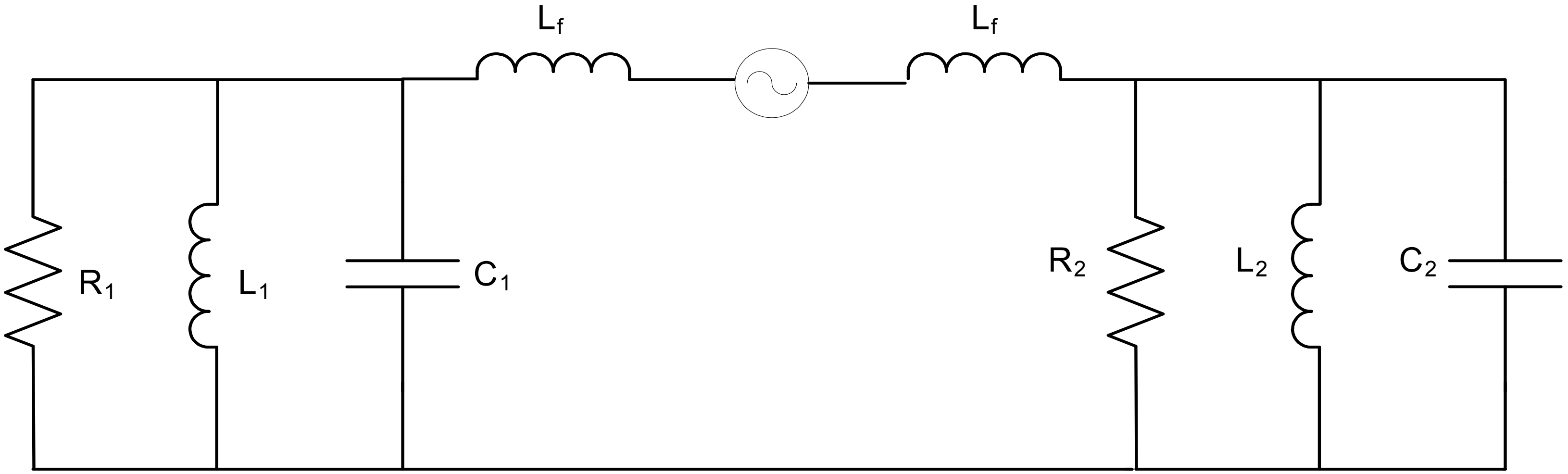
Find L and C as:

$$L = \frac{R}{Q\omega_0} \qquad C = \frac{Q}{R\omega_0}$$

Putting it all together

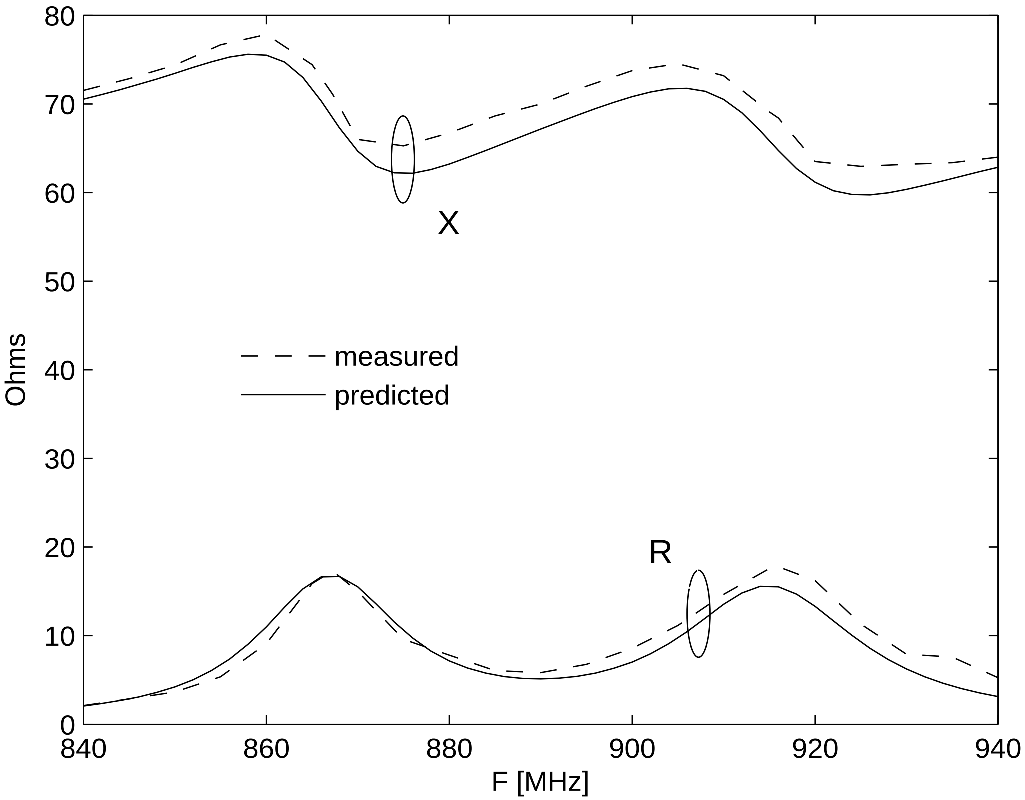
- Find the dimensions for resonance at 867 MHz and 915 MHz
- Find the slot length for the required input resistance
- Find the slot width and feed length, *l* , for the required reactance
- Calculate the quality factor, *Q*
- Knowing *Q*, *f*, and *R,* calculate the values of L and C for each resonance
- The two parallel RLC circuit are in series with two inductors used to model the feeds.
- Draw the circuit model
- Predict the impedance

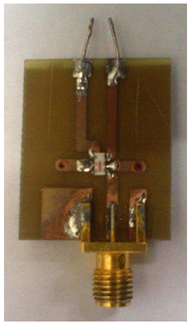
Circuit Model



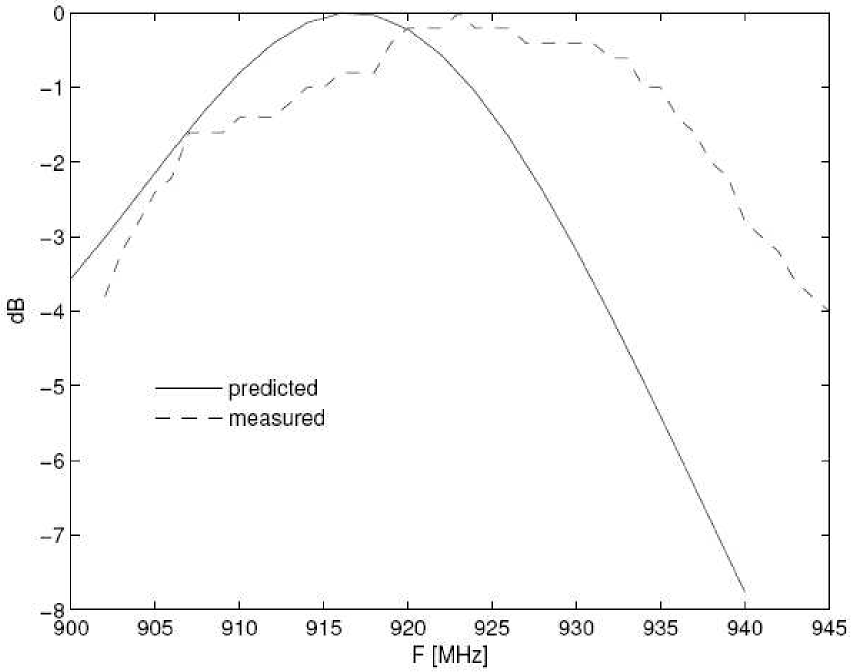
R_1 =16 Ohms, R_2 = 15 Ohms, L_f = 6.0 nH, L_1 = 68 pH, C_1 = 445 pF, L_2 = 65 pH, C_2 = 521 pF.

Predicted vs. Measured Impedance





Predicted vs. Measured Performance



Predicted:

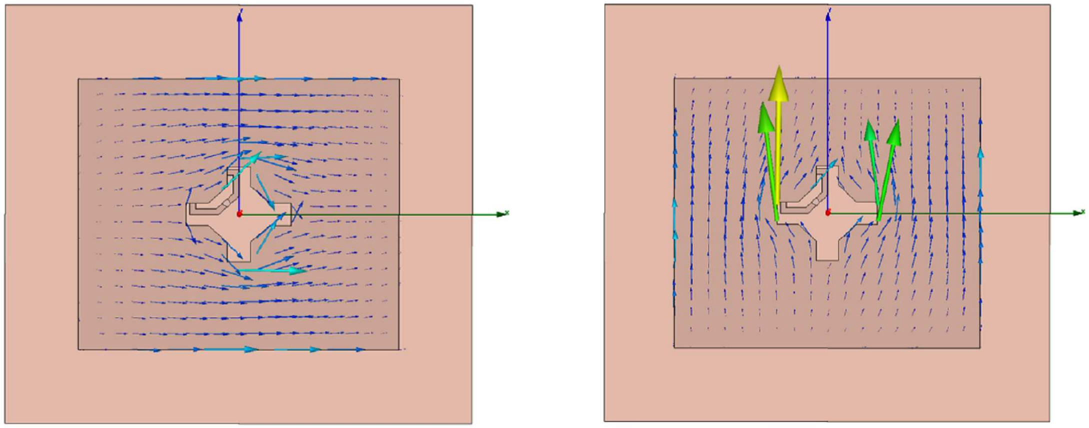
- Calculate tau over a range of frequencies.
- Normalize maximum performance to 0 dB

Measured:

- Place IC on the antenna.
- Place the tag at a distance of 2 m from the reader antenna and measure the turn-on power.
- Normalize the maximum performance to 0 dB

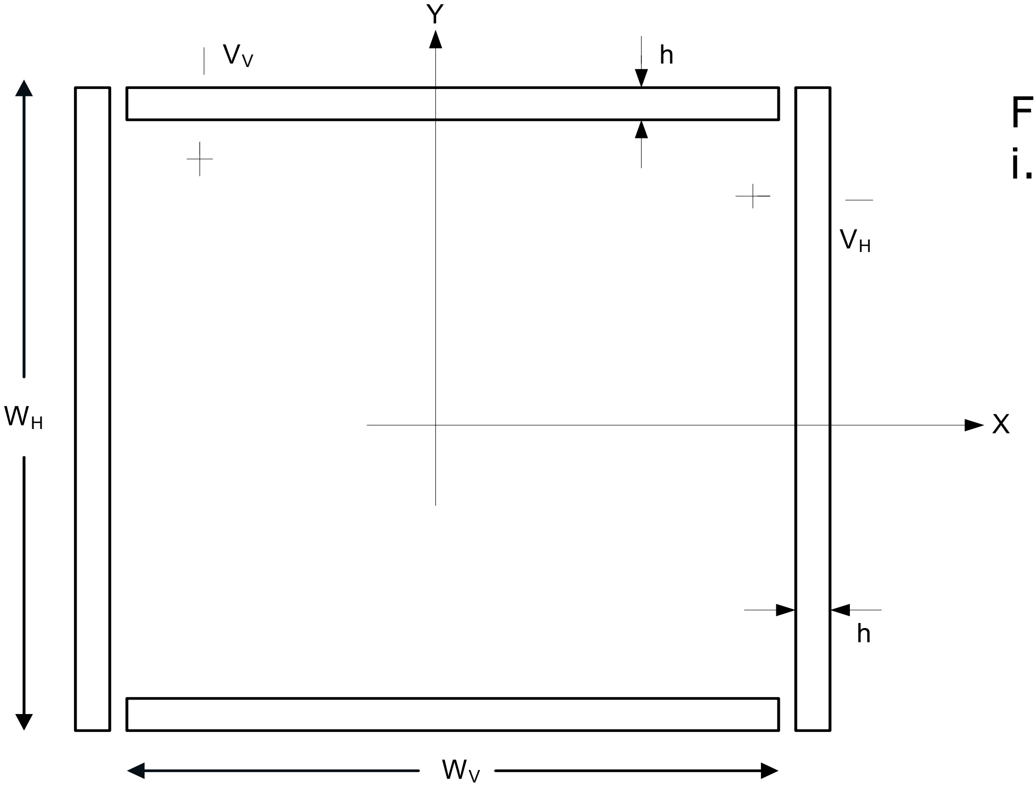
Polarization

Recall,



- Horizontally polarized and vertically polarized
- Can we characterize the polarization with the circuit model?

Aperture Field Model for the Cargo Tag



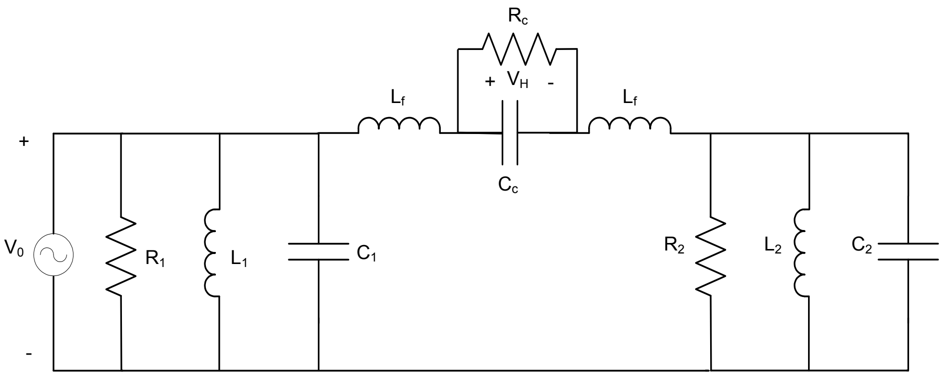
For broadside polarization, i.e., θ=0,φ=0[15]:

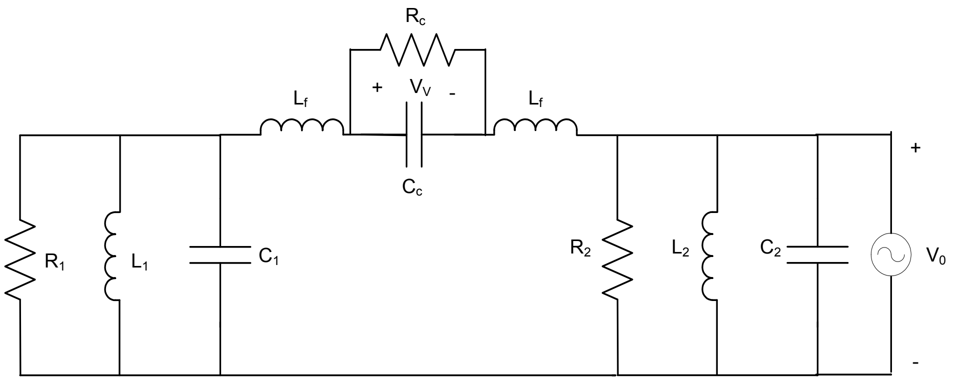
$$E_H = -jk_0 V_H W_H \frac{e^{-jk_0 r}}{2\pi r} F_3$$

$$E_V = -jk_0 V_V W_V \frac{e^{-jk_0 r}}{2\pi r} F_3$$

$$\frac{E_V}{E_H} = \frac{V_V}{V_H}$$

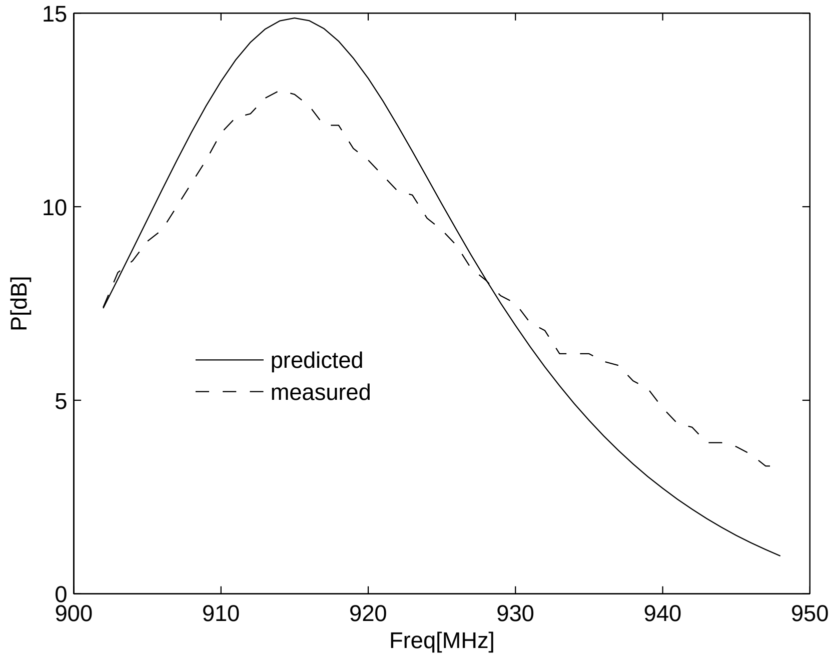
Polarization Models





Apply circuit analysis to find V_H and V_V for a range of frequencies

Predicted vs. Measured Vertical to Horizontal Polarization Power Ratio



$$\zeta = \frac{P_V}{P_H} = \frac{V_V^{\;2}}{V_H^{\;2}}$$

P[dB]=10logP_V/P_H

Conclusion

- The proposed antenna design was simulated and validated using impedance and read distance measurements
- The antenna is dual-resonant and operates over a majority of the world's frequency range utilized for passive UHF RFID
- The design was modified to have a CPW feed structure and matching circuit
- A rigorous theoretical analysis was performed to give insight to the working of the antenna
- An accurate circuit model was found and validated with impedance and polarization prediction and measurement
- Open question: Why does the input resistance decrease along the feed length?

Future Work

- Explore the input resistance challenge
- More accurate impedance measurements
- More efficient IC’s to double the read distance
- Smaller form factor

References

1. S. Aroor and D.D. Deavours , " A dual-resonant microstrip-based UHF RFID' cargo' tag ," in *Proc. IEEE International Microwave Symposium*, Atlanta, GA, June 2008
2. D. M. Dobkins, The RF in RFID: Passive UHF RFID in Practice. Burlington, MA: Newnes, 2007.
3. D. M. Dobkins and S. Weigand, "Environmental effects on RFID tag antennas," in IEEE MTT-S International Microwave Symposium, Long Beach, CA, Jun. 2005, pp. 4–7.
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Thank you

Questions?