Passive RFID Sensing for Rotorhead Maintenance - WISP Platform

Dr Maciej Zawodniok

Team: Anthony Wellnitz, George Harris, Shadi Ebrahimi

Collaborators: TDA-I

Missouri University of Science and Technology

Missouri S&T

Outline

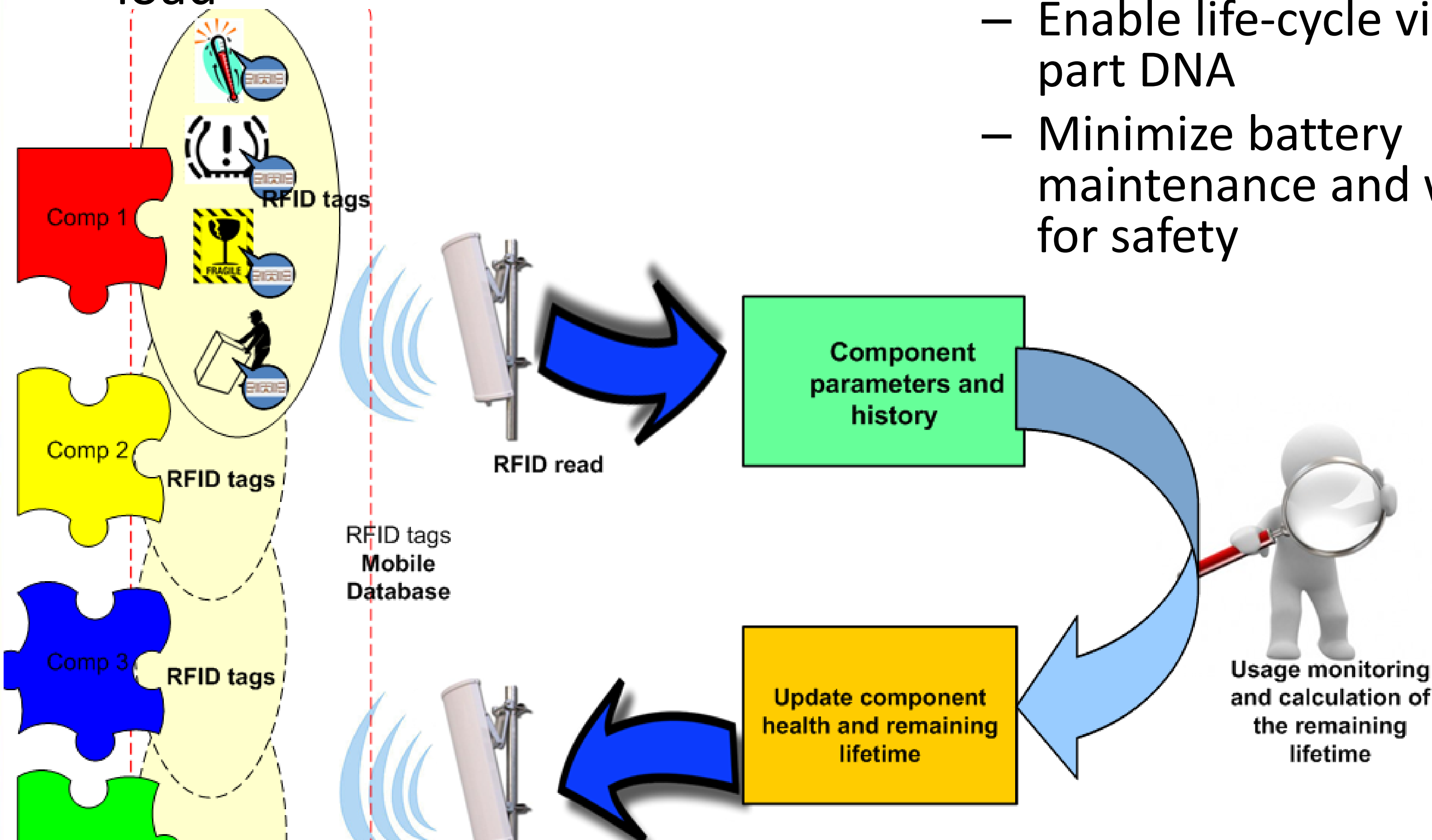
- Motivation and background
- Proposed approach
- Results
  - Case 1
  - Case 2
  - Case 3

Motivation

- Besides traditional logistics applications ...
- RFID based IoT enables accurate prediction of remaining life of components
  - Reduce maintenance costs by on-time repair and reuse of components
  - Avoid catastrophic failures
- The proposed ISN-based solution improves reliability of RFID in metal-reach environment,
  - e.g. shipping container, engine compartment, assembly line

Part DNA with RFID Tags

- Cumulative damage of a part throughout its life cycle can be assessed by monitoring the fatigue under a cyclic load
- Wireless, battery-free sensors are preferred to monitor asset health
  - Tracking and inventory
  - Enable life-cycle visibility = part DNA
  - Minimize battery maintenance and wiring for safety

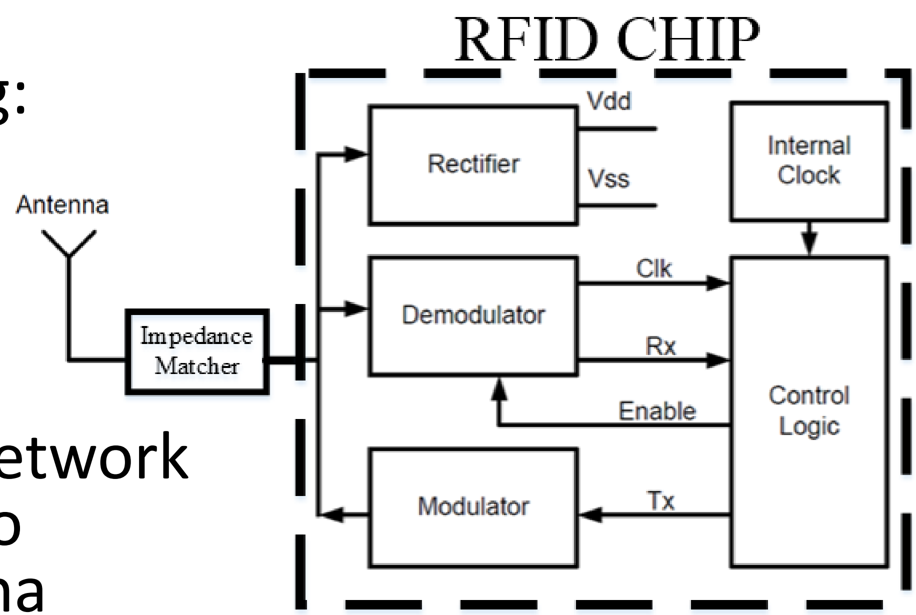


Introduction

- Accurate life-cycle tracking of aircraft components or other high value moving assets such as fleet vehicles is crucial for operational availability and overall readiness.
  - Cost savings on maintenance and operation
  - Increased reliability and safety
  - Avoid catastrophic failures
  - Increased reuse of parts without jeopardizing reliability
- Metal-reach environments, mutual coupling with nearby ferromagnetic objects, and mutual interference between tags create problems with communication between tags and reader.
- The proposed Impedance Sensing Network (ISN) based solution improves reliability of RFID tags in metal-reach environments
  - Overcoming challenges of deployment in systems with many interfering components and unfriendly environments

Background

- The passive RFID tag in the UHF harvest low amount of power (mW)
- Main components on a tag:
  - Rectifier
  - De/Modulator
  - Control/Memory Unit
  - Internal Clock
- An impedance matching network is placed on the antenna to match the chip and antenna
- RFID tags that do include impedance matching networks are designed for specific environments and do not operate outside of their design constraint



Challenges and Goal

Interference

- Multiple tags

Mutual coupling

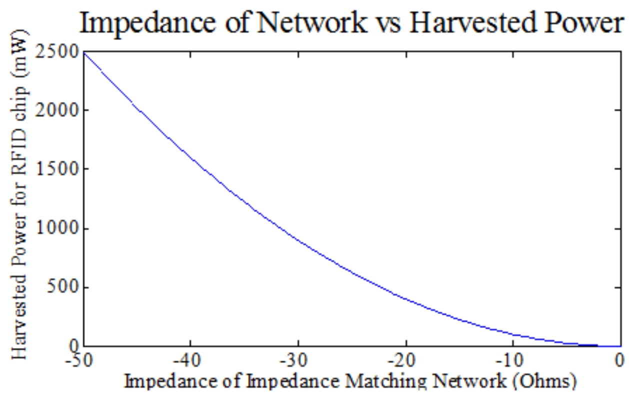
- Objects
- Nearby tags

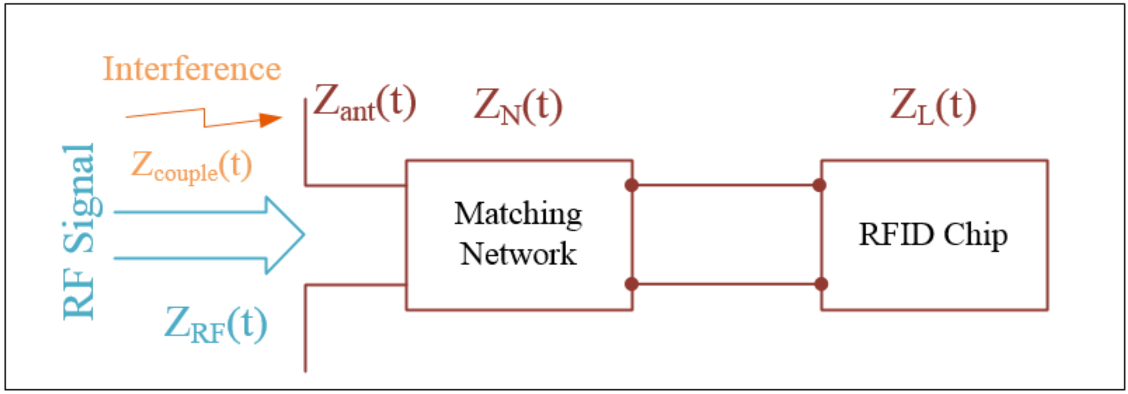
Improve antenna performance

- Modulation depth

Improve RFID Communication by tuning load impedance and antenna loading

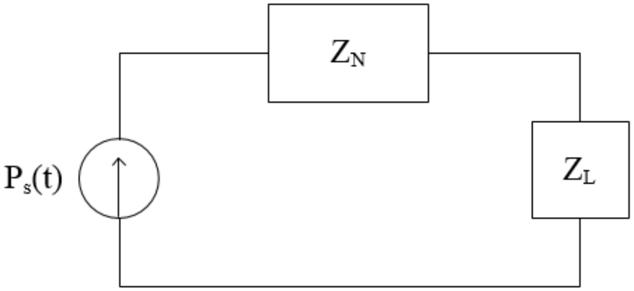
Impedance vs Power Transfer





$$Z_{tot}(t) = \frac{Z_N(t)||Z_L(t)}{Z_{ant}(t) + Z_N(t)||Z_L(t) + Z_{couple}(t)}$$

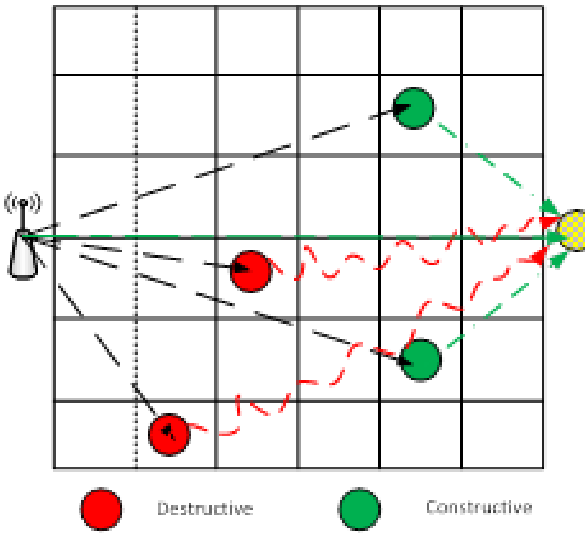
$$P_s(t) = \frac{\left[\frac{Z_{tot}(t)}{2\sqrt{2}} Vs(t)\right]^2}{Z_L(t)} \qquad \Gamma = \frac{Z_{tot}(t) - Z_{RF}(t)}{Z_{tot}(t) + Z_{RF}(t)}$$

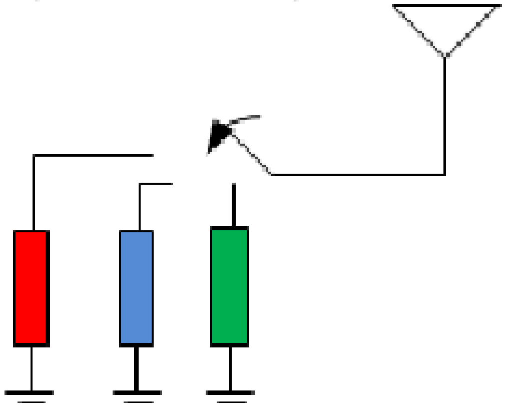


- Matched impedance between antenna, ISN, and RFID chip maximizes energy transfer
- A mismatch of impedances can result in varying performance:
  - Minimum scattering (reduce interference)
  - Maximize modulation depth
  - Alter impedance of other tags through mutual coupling
  - Change offset of scattered signal received by other tags

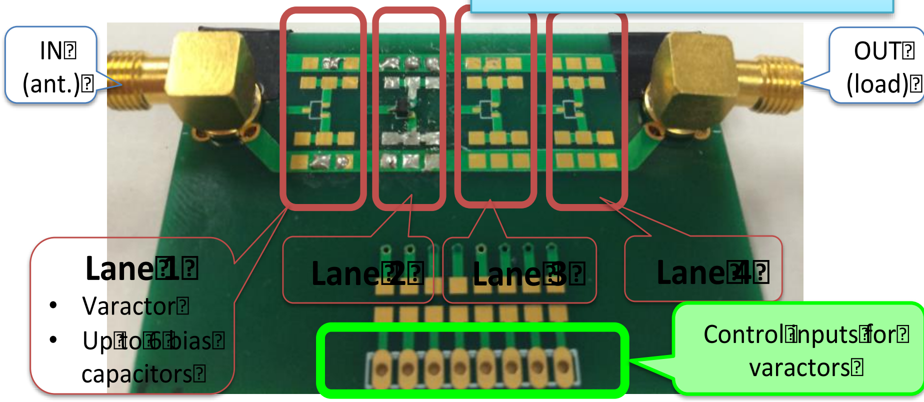
Tuning Impedance

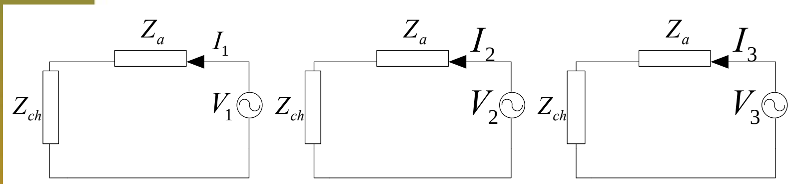
- Mutual coupling with environment creates challenge for RFID system in aircraft parts tracking
  - RFID tag on RF reflective and absorbing material
  - RFID tag behind an obstacle
  - Neighboring tags reflect incident RF signal from reader thus interfering with communication
- The Impedance Switching Network (ISN)
  - Connected between antenna and RFID chip
  - Designed to compensate for mutual coupling
  - Online tuning of the impedance
- Overall, the ISN improves communications in non-ideal scenarios





ISN Board Design

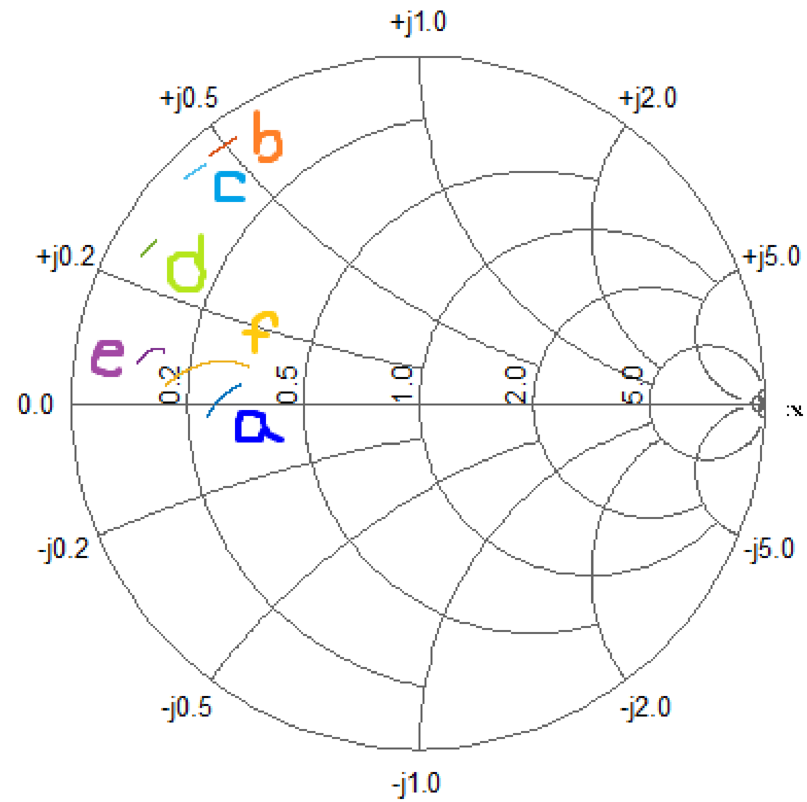




$$\begin{pmatrix} I'_{tag_1} \\ I'_{tag_2} \\ \vdots \\ I'_{tag_{N-1}} \\ I'_{tag_N} \end{pmatrix} = \begin{pmatrix} I_{tag_1} \\ I_{tag_2} \\ \vdots \\ I_{tag_{N-1}} \\ I_{tag_N} \end{pmatrix} + \frac{1}{Z_a + Z_{ch}} \begin{pmatrix} 0 & Z_{11} & Z_{12} & \cdots & Z_{1P} & \cdots & 0 & 0 & 0 \\ Z_{21} & 0 & Z_{21} & Z_{22} & \cdots & Z_{2P} & \cdots & 0 & 0 \\ Z_{32} & Z_{31} & 0 & Z_{31} & Z_{32} & \cdots & Z_{3P} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & Z_{N-1.P} & \cdots & Z_{N-1.2} & Z_{N-1.1} & 0 & Z_{N-1.1} \\ 0 & 0 & 0 & 0 & Z_{NP} & \cdots & Z_{N2} & Z_{N1} & 0 \end{pmatrix} \begin{pmatrix} I_{tag_1} \\ I_{tag_2} \\ \vdots \\ I_{tag_{N-1}} \\ I_{tag_N} \end{pmatrix}$$

ISN Gen 2 Board Characterization

- Assembled and tuned the ISN Gen 2 board
  - Several combination of capacitances have been tested with VNA (network analyzer)
  - Performance varies from simulations; hence, more tuning required
  - Suitable configuration and range of impedances identified and tested with antenna

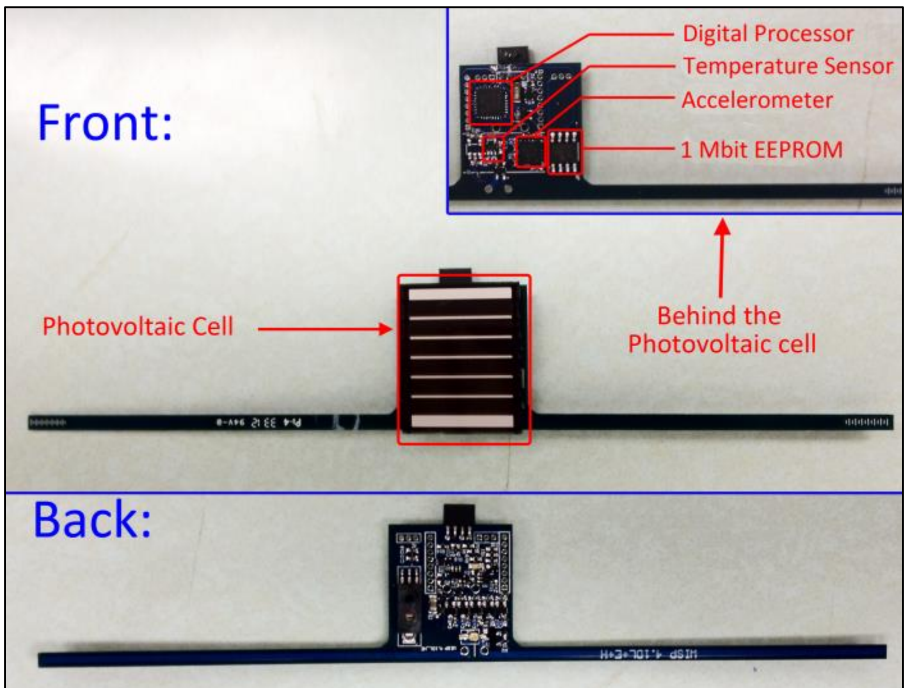


- a.) Generation II board without components
- b.) Board with all specified components
- c.) Lane 4 capacitors removed
- d.) Lane 3 capacitors removed
- e.) Lane 2 capacitors removed
- f.) Lane 1 capacitors removed/only varactors left on all lanes

WISP - Passive RFID Tag with Multimodal Sensors

» In comparison with common commercial RFID tags, the tags should have the following features listed in the table.

Key Features	Commercial Tags	Preferred Tags
Power Source	Passive/Active	Passive
Functionality	Transmit identified data only	Transmit both identification and sensors data
Memory	Typically from 64 bits to 24 Kbyte	Large enough for target application
Flexibility	Fixed function	Extensible
Range	Typically limited with 3m (Passive tags)	Long enough for target application

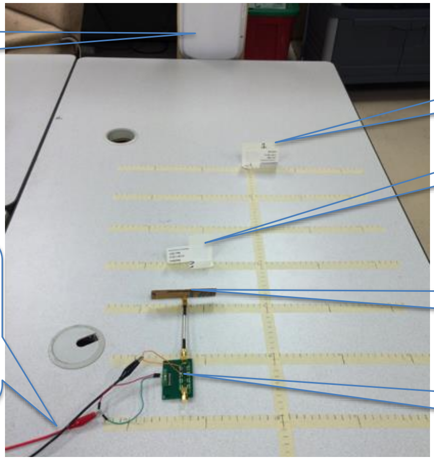


» Passive UHF RFID Tag is designed and fabricated with

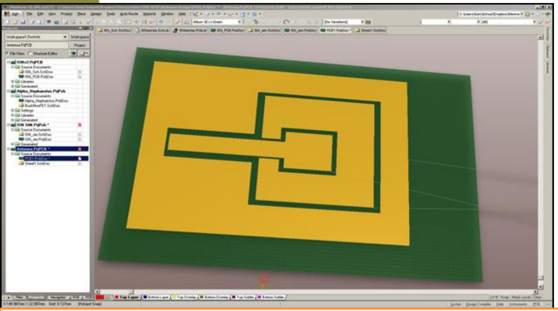
- 3-axis Accelerometer
- Two temperature sensors
- An 1M-bit EEPROM
- A Photo voltaic cell (optional)
- Range (when acquiring temperature data):
  - 4m: without voltaic cell
  - >8m: with voltaic cell

Simulation and Experimental Verification

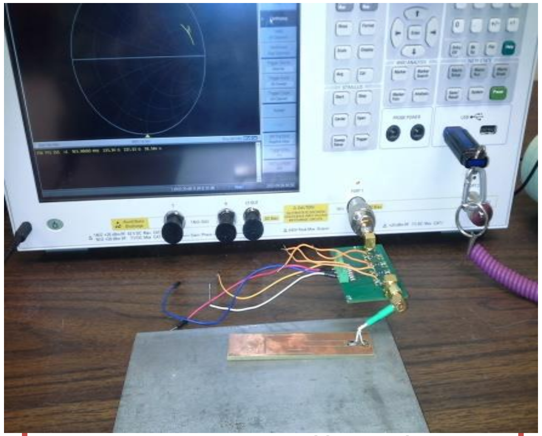
- Successful initial tests in the laboratory and on a rotor-head
  - Case 1: Secondary tags that improve performance through mutual coupling (with ISN)
  - Case 2: Metallic object attached to antenna
  - Case 3: Rotor head testbed



Case 1: Laboratory setup for testing multiple tags scenario



Design of ISN with RFID antenna and WISP tag



CASE 2: Metallic object attached to antenna

Rotor-head assembly with RFID tag placement

Case 1: Secondary Tags with Adjustable Impedance

- Performance evaluation shows the read-rate improvement with the modified tag
  - We consider a combined performance for various positions of the modified tags (i.e. 6 modified tags switching to modified impedance, one at a time, with the best case considered as the effective read rate)
  - The modified tag changes the RF signal propagation (reflection coefficient, phase shift). As a result the modified signal is constructively interfering at the target tag thus covering some nulls.
  - A fixed impedance used in this preliminary experiments limits the benefit of the modified tag. Our simulation results from the propagation and mutual coupling models demonstrate that by changing the impedance among optimal values can potentially improve performance even further.

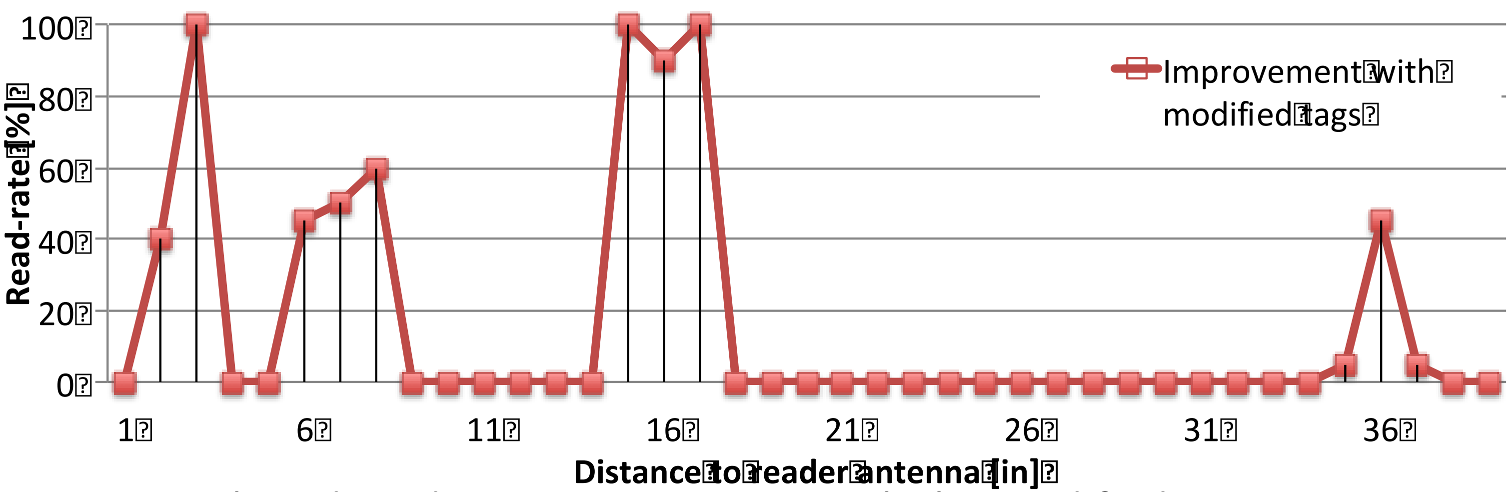


Fig. 6. Combined read-rate improvement with the modified tag

Case 1: Signal Strength Measurements

- The experimental power measurements for the modified tag are presented in the figure below
  - The simulation results are shown for comparison.
  - The difference in results demonstrate that the models while following general trends do not adequately model the real scenarios

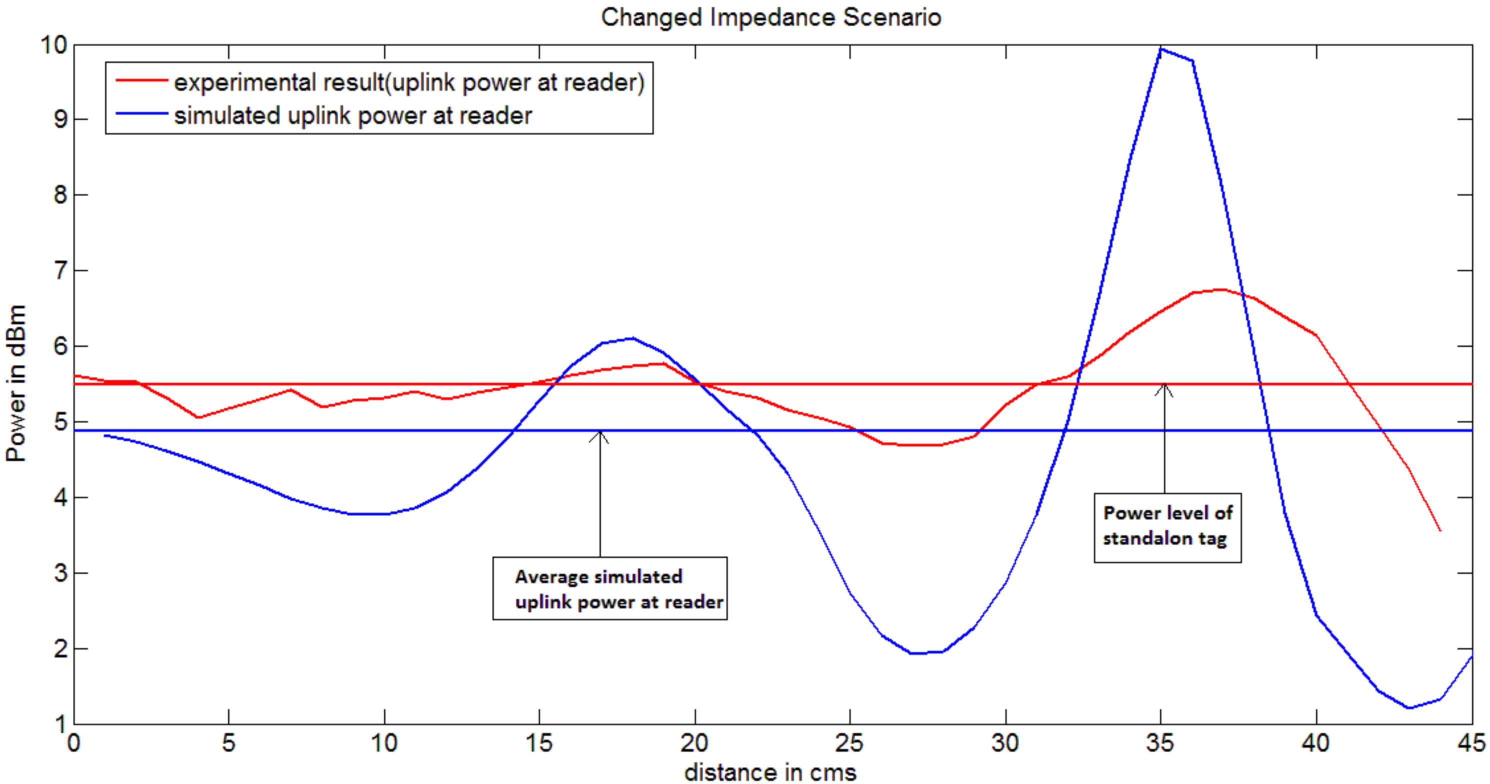
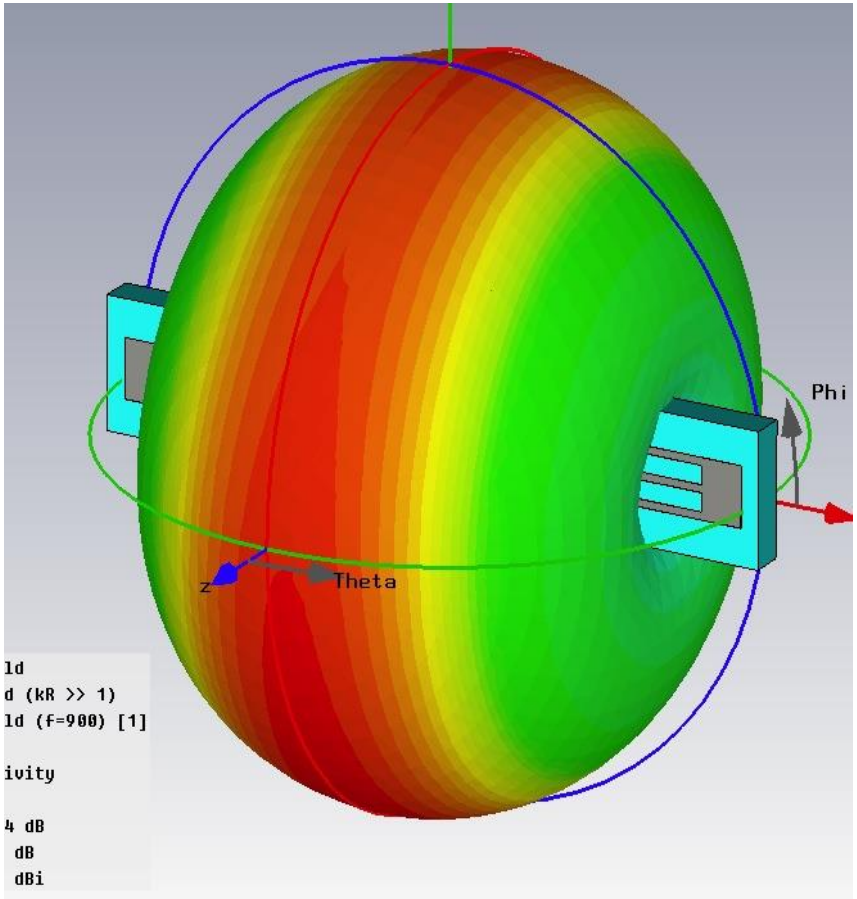


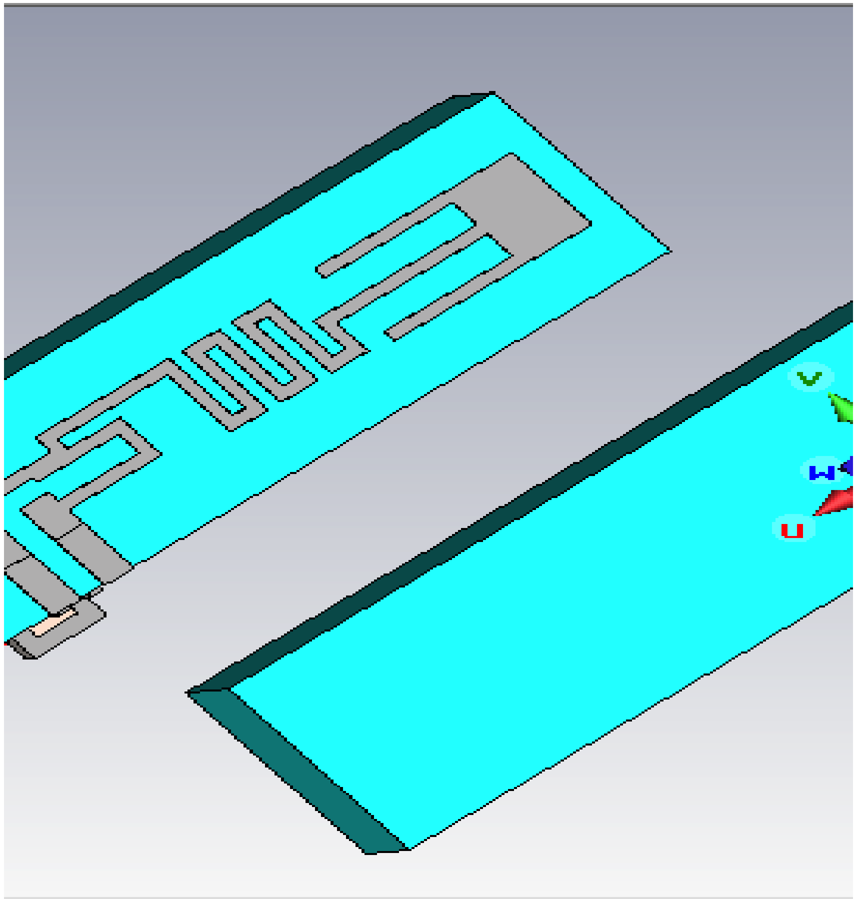
Fig. 7. Signal strength variation with distance – simulated and experimental results

Case 1: Simulating Mutual Coupling for RFID

Antenna pattern of the Alien 9640 tag

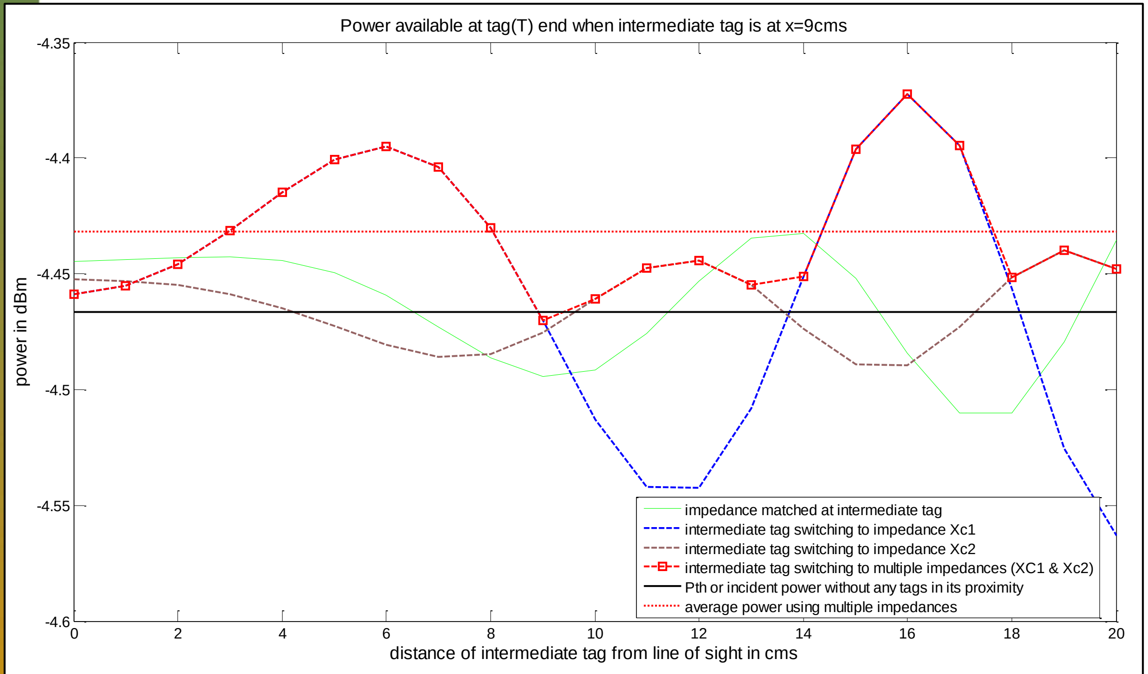


Simulated RFID tag



Case 1: Selecting Optimal Impedance Values

- In random deployment and environment the position of a modified tag affects read rate
  - Single impedance value leads to poor performance which will result in nulls. It is observed in the Fig. 9 where for distance of 10-14 cm the received power is low for impedance Xc1 (blue line).
- Higher power levels and thus improved read-rate can be achieved by dynamically switching impedance between complementing values
  - Figure 9 shows the combined performance when switching the chip impedance of the intermediate tag to Xc1 and Xc2 depending on position.



- We have modeled and simulated the scenario in order to select impedance values that optimize the performance

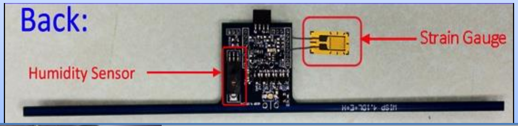
Fig 9. Intermediate tag switching to multiple impedances when it is at x=9cms

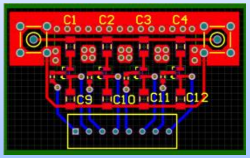
More Tests and Tuning …

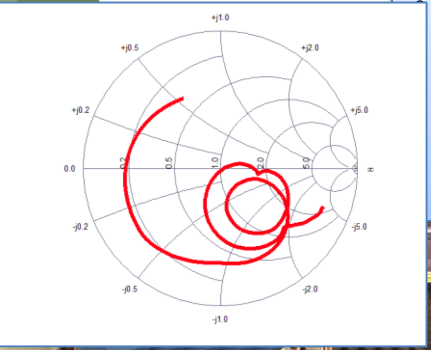
- Win-win with ISN board
  - Target tag changes its impedance to maximize communication performance with reader (minimize coupling with metallic objects)
  - Other tags should either become invisible or create constructive interference – by tuning their impedance network
- ISN board design, simulations, and experimental validation completed

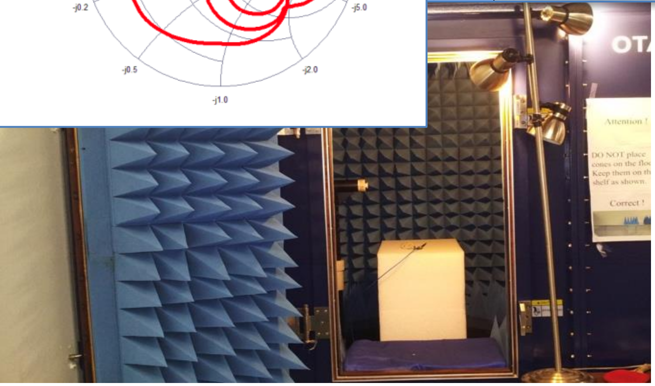
- Evaluation of existing tags on a rotor-head assembly
- The ISN board tuned for RFID (905-920MHz)
- Basic design suitable for other frequencies

- The ISN Gen 2 board has been redesigned and connected with WISP tags:



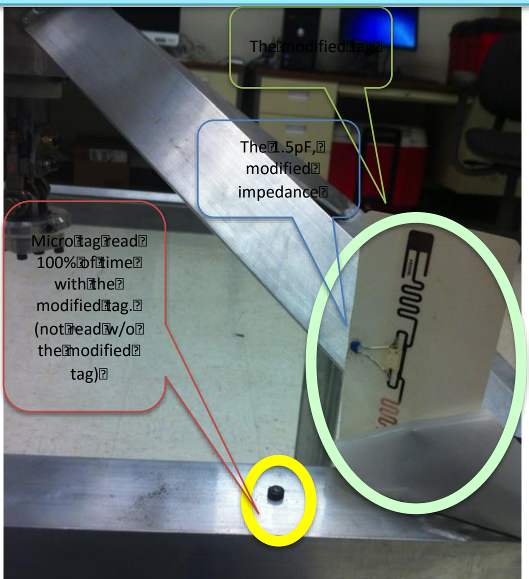




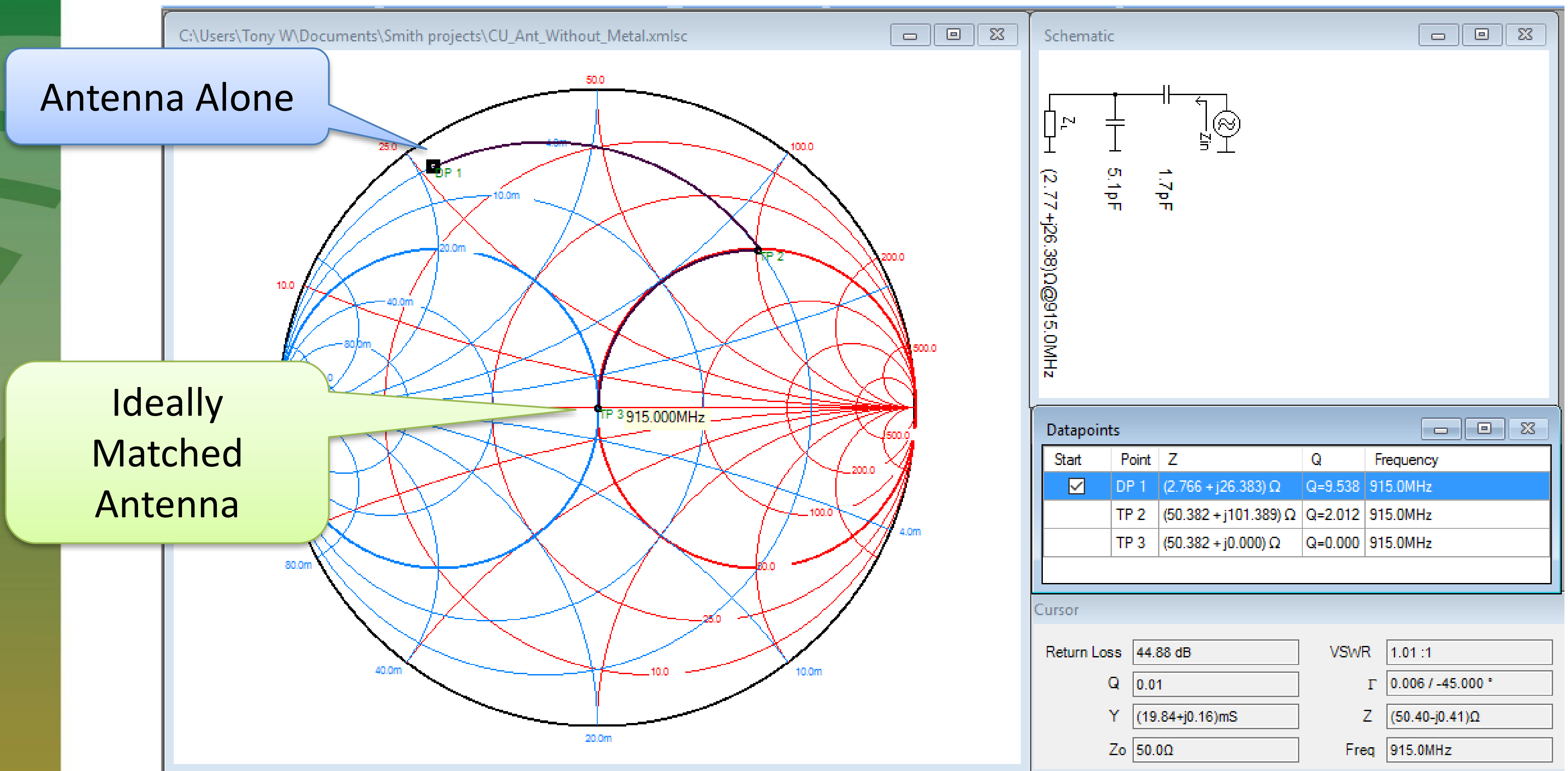


Tests in anechoic chamber

- Successfully tested the ISN board – it countered the unwanted mutual coupling from nearby tags or metallic objects
- 80% improvement in read rate in confined engine compartment



Case 2: Impedance Matching for Antenna



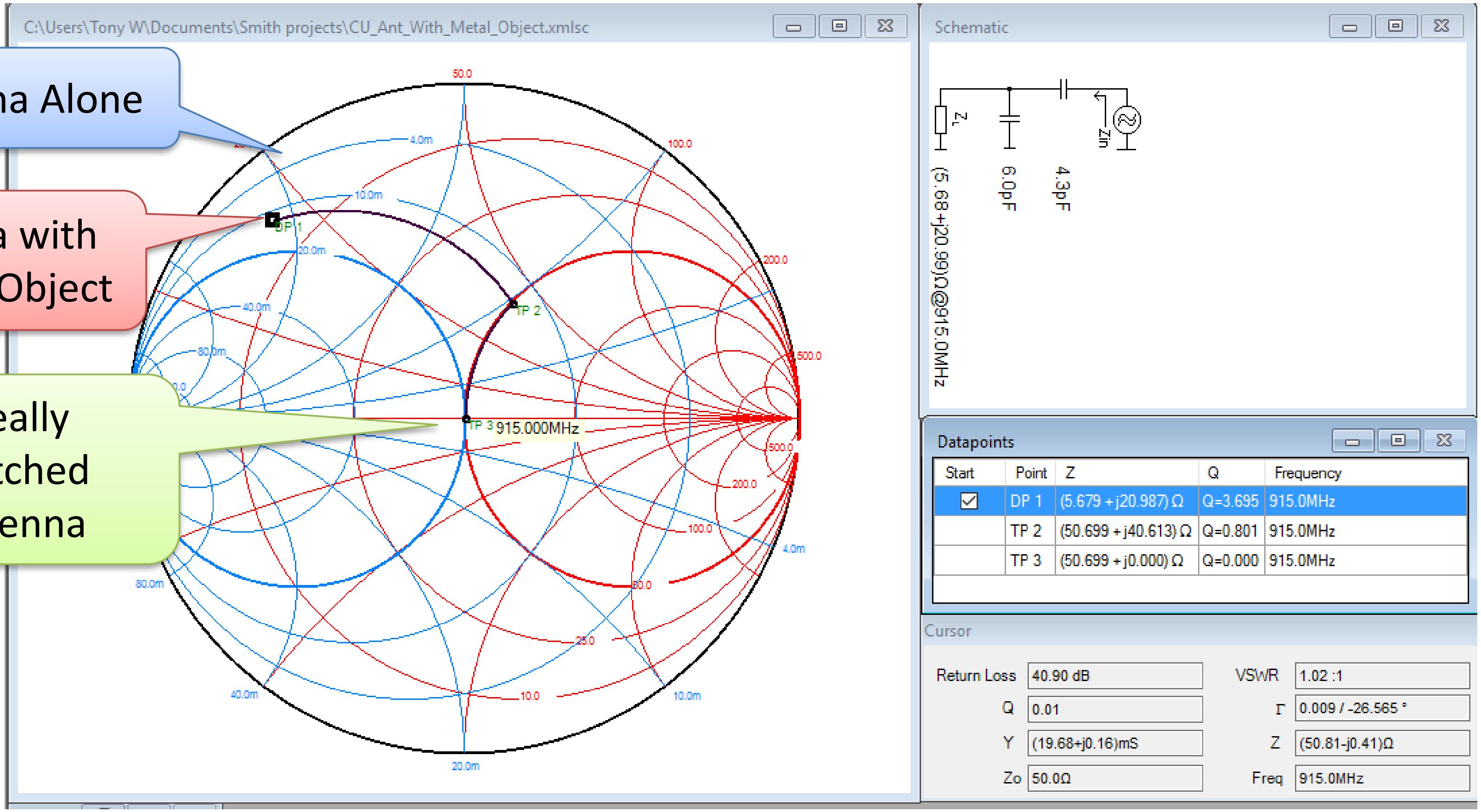
- Ideal matching circuitry example with antenna alone

Case 2: Impedance Matching with Metallic Object

Antenna Alone

Antenna with Metallic Object

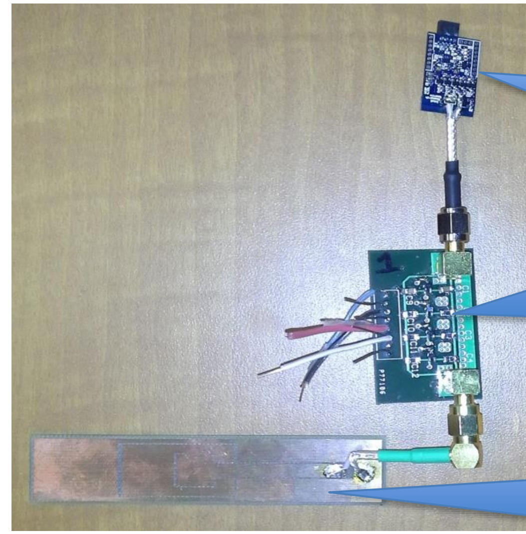
Ideally Matched Antenna



- Small change in capacitance of the impedance matching components (series and parallel capacitors)

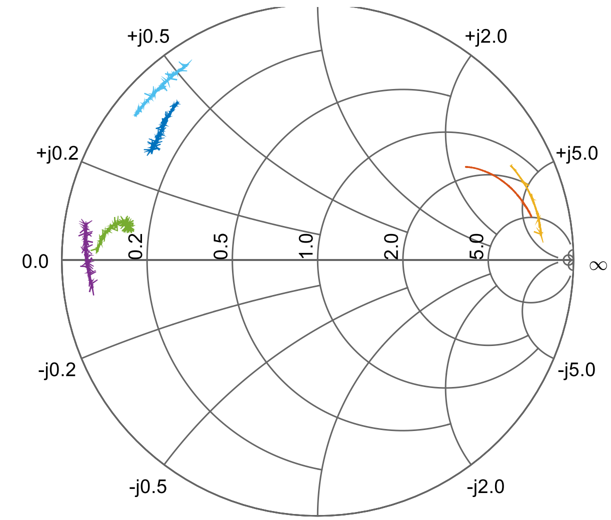
Case 2: Characterization with RFID Antenna

- ISN Board Gen 2 with various antennas
  - Measurements using VNA
  - Scenarios include
    - Varying impedance
    - Introducing a metallic plate near antenna
    - Testing few antenna including wire, custom, bowtie, dipole

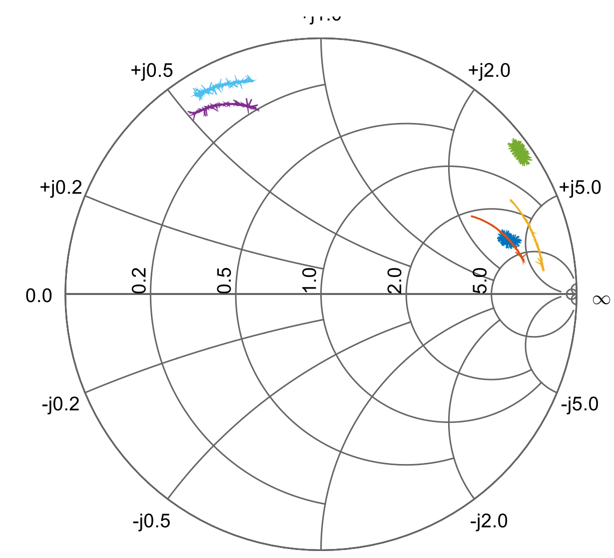


Case 2: Different Antenna Results

- Changing antenna results in different impedance characteristics
- Tuning is needed to compensate for the antenna variation



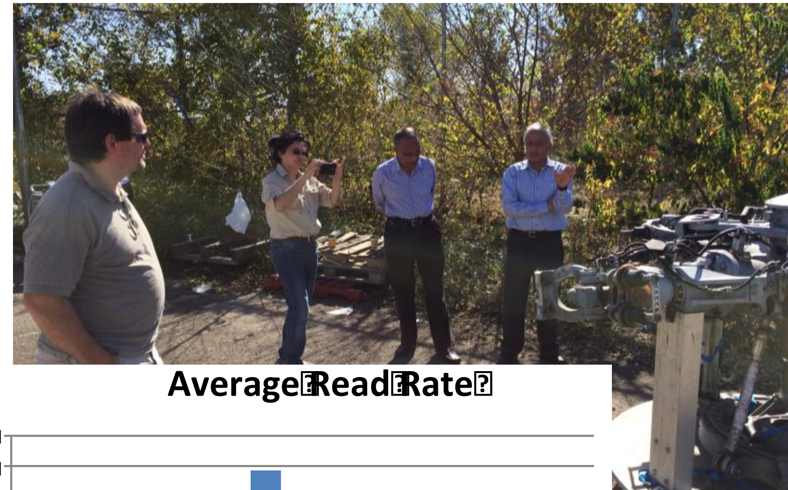
Smith chart with all measurements for the wire antenna

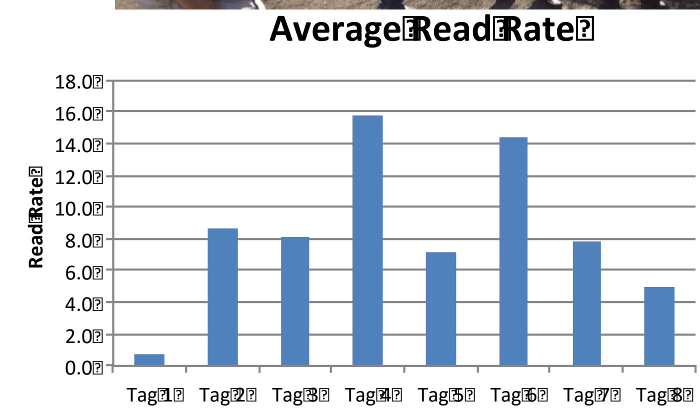


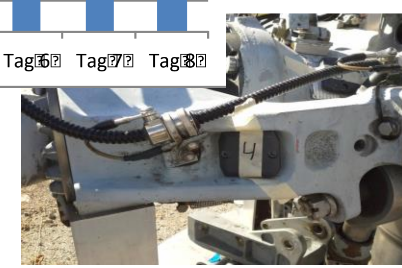
Smith chart with all measurements for the RFID antenna

Case 3: Tests on Rotor-head

- Ironside tags performed well when attached to metallic components
  - However, the effective range was limited to **2m**
- In contrast, the proposed ISN+WISP tag worked up to **5m**

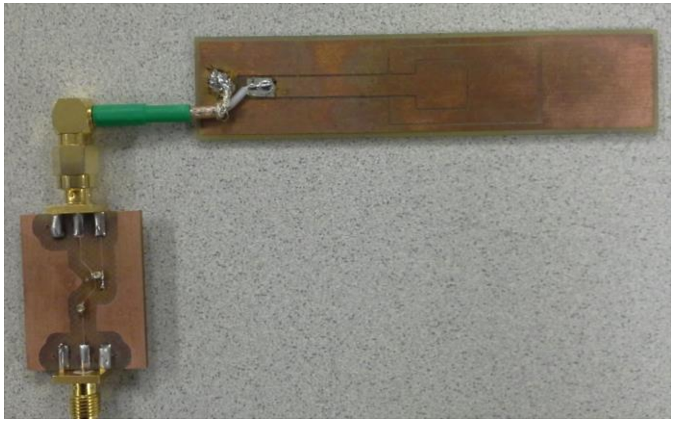


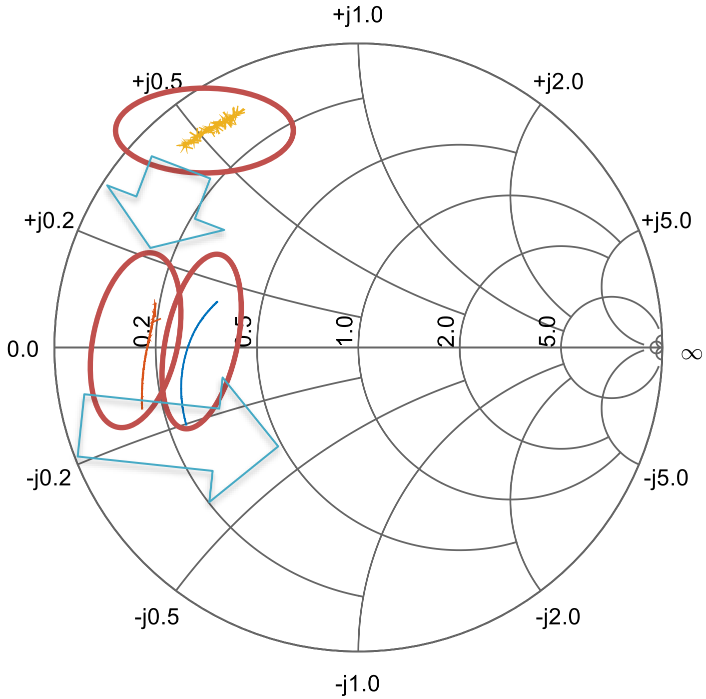




Further Revisions

- Redesign of the ISN board with the goal to integrate it with the antenna is ongoing
- New ISN board – shown on figure to right – was able to bring the impedance close to the ideal (middle of the Smith chart)





Thank you!
Q&A

Missouri University of Science and Technology