ISA107.4 Wireless Sensors for Turbine Instrumentation Working group

Daniel Sexton
RF Instrumentation and Systems Laboratory
GE Global Research
Niskayuna, NY

Contributors:
Kirk Gallier –
GE Energy Greenville, SC
Nilesh Tralshawala-
GE Energy Schenectady, NY
Scott Herber-
GE Aviation Cincinnati, OH

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ISA107.4 Scope

The Subcommittee's focus is to define scalable architectures, system components, and protocols that allow secure reliable wireless connectivity for test cell based turbine engine measurements.

The subcommittee will address multi-tier wireless technologies including but not restricted to wireless mechanisms for data transmission and passive wireless sensing or technologies required for harsh environments as found in the operating power turbine test environment

The results of this Subcommittee may serve as a basis for future on-wing engine health monitoring or control systems.

This subcommittee will leverage the efforts of existing committees (e.g. ISA84, ISA99, ISA100) and contribute to these committees as necessary.

ISA107.4 Purpose

Identify where shall the wireless interfaces need to be?

- Define the surrounding environment (inside or outside engine)
- Identify the radio frequency (RF) environment

Develop Multi-vendor interoperability support for various applications

- System integration support for critical and non-critical measurements
  - Common application interfaces
  - Common network management
  - Enhanced security management

Develop co-existence support

- With other network standards – possible
- Other proprietary networks – not addressable

Current Activities

Prepare a requirements Document

- What are the critical sense points where wireless can add unique benefit (ex: Turbine bucket & compressor blade strain & temperature)?
- How many measurement points are needed?
- How long must the sensor survive?
- How much can it effect the performance of the surface?
- What are the security aspects?
- What size engines will be covered?
- What are the regions of the world that the system must operate in?

Prepare a wireless network diagram

- Illustrate how a wireless instrumentation system would be constructed?

Future Activities

Prepare a technology assessment and gap analysis.

Determine where standards and best practices are needed and would be helpful.

For standards (Normative) – prepare a request for proposal, solicit vendor and user input and proceed with the standards development process.

Generate best practices documents (informative) as needed.

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Motivation for creating a standard

1. System simplification
2. Compatibility between various vendor equipment
3. Consistency in measurements
4. Reduced testing time and costs

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Issues with Wireless Sensor Networks

- Availability of Spectrum
- Noise (Other emitters, electronics, lightning, etc.)
- Multipath – reflections/Blocking & Shadowing
- Channel fading/ Scattering rain, snow, fog, dust, smoke …
- Path loss = $10\mathrm{Log}[(4\pi/\lambda)^2 D^n]$ n=2 for free space, >2 indoors
- Frequency α 1/Penetration Depth Frequency effects antenna size and efficiency
- Self Powering
- Security
- Scalability
- Performance
- Difficult to configure
- World wide regulatory issues and differences
- Customer acceptance/lack of standards

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ISA107.4
Two application specific problems to solve

Level 0: Sensors and connectivity within the engine

The last foot,
Sensor to data concentrator

Level 1:
Wireless telemetry within the test cell
The next 50 feet

Power Turbine
Level 0: Application Requirements

1. 300 to 1000 sensors/engine
2. Compressor front: 250F
3. Compressor back: >850F
4. Hot gas path: >2300F
5. Life for testing only > 500hours
6. Size: HWL – 10x125x125 mils, conformable
7. Ability to time stamp
8. No batteries
9. No wires
10. For sensors attached to rotating parts, must not interfere with air flow.
11. FCC compliant
12. Temperature measurements (comparable to TC measurements)
13. Continuous strain measurements (comparable to industry standard strain gage sensors

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Sensor types

Temperature – 70%

1. Low sample rate: 1 sample/sec
2. Range of measurement:
3. Accuracy:
4. Resolution:

Strain/Vibration – 30%

1. Measurement bandwidth: 60Khz

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Passive Wireless Alternatives

Near Field	Far Field

LC Resonant
- Dielectric
- Cavities
- Lumped elements

Mechanical Resonators
- MEMS

Vernooy, D. Knobolchm A, Ahmad, F.,Sexton, D. “Remote Excitation and Readout of a High Q Silicon Resonator”

SAW Resonators

Long Interrogation range

Short Interrogation Range

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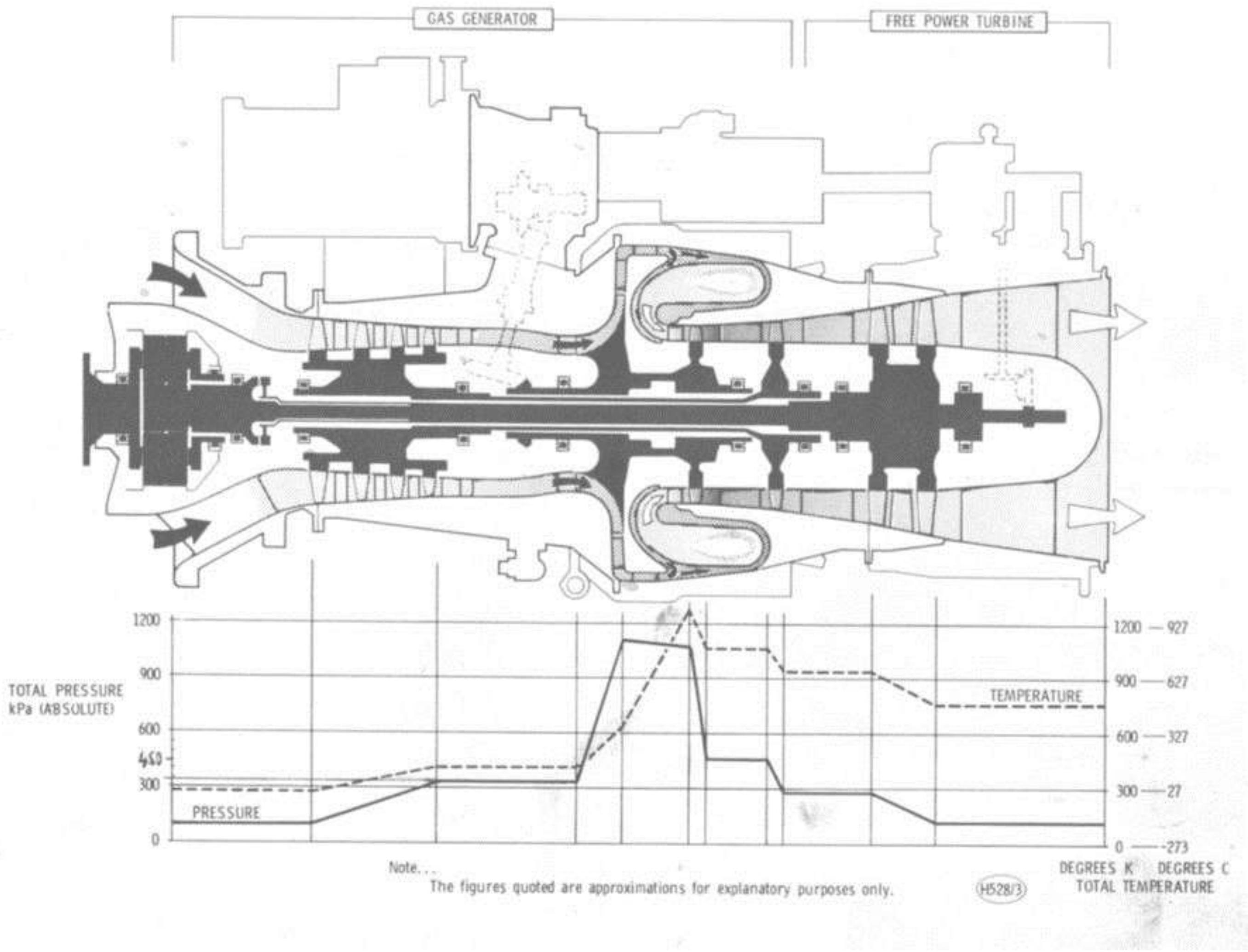
Application Physical Environment



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RF Propagation Analysis

$$\text{Loss dB} = -(20\log(\lambda/4\pi D_1) + 10N\log(D_1/(D_T - D_1)) + G_{TX} + G_{RX} + X_{\sigma 1}(t) + F(X_{\sigma 2}(t), X_{\sigma 3}) + P_l(t) + L_o$$

Where:

λ = Wavelength ($3 \times 10^8/2\pi f$)

D_1 = Initial Path Distance in meters

D_T = Total Path Distance in meters

N = Exponential Path Loss Factor

G_{TX} = Transmit Antenna Gain and Losses

G_{RX} = Receive Antenna Gain and Losses

$X_{\sigma 1}$ = Excess Large Scale Loss

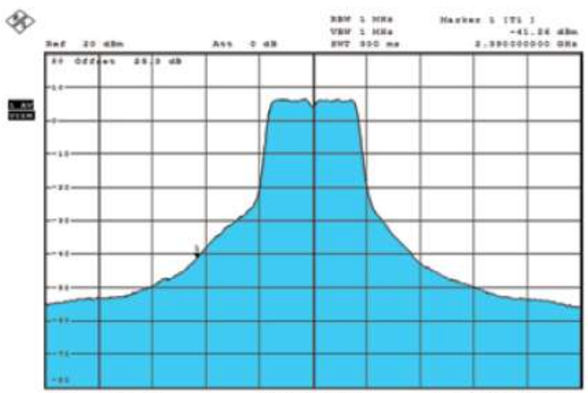
$F(X_{\sigma 2}(t),X_{\sigma 3})$ = Smoothing Function based on modulation type

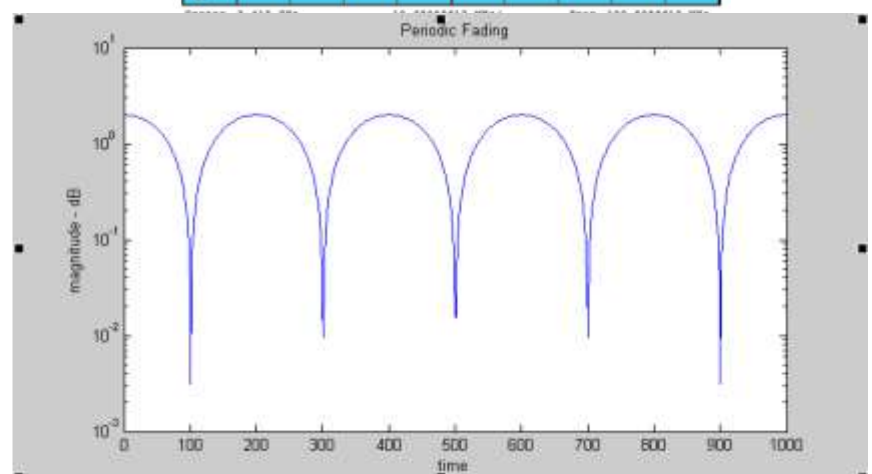
$X_{\sigma 2}$ = Small Scale Fading

$X_{\sigma 3}$ = Delay Spread

P_l = Antenna Polarization mismatch

L_o = Obstruction Losses





<u>Other Unique Application Factors</u>:

1) Time periodic fading
2) Doppler shift >±2.5KHz
   - Effects accuracy of frequency resonant structures

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RF Environment - Literature

Walton, E. Young, J. Moore, J. Davis, K. “EM Propagation in Jet Engine Turbines” Syntonics Corp.

Propagation Measurements from 2 to 12GHz on full scale aircraft engines (F110-GE-100 & GE CF6). Propagation losses were 10 to 20dB below free air losses, Excess delay spread of 17ns. Certain frequencies (>8Ghz) seem to provide better propagation, apparently due to the geometry of the structures within the engine.

Gruden, M Jobs, M Rydberg, A. “Measurements and Simulation of Wave Propagation for Wireless Sensor Networks in Jet Engine Turbines” IEEE Antennas and Propagation Letters Vol. 10, 2011

Multipath Fading study using both simulations and measurements on a ½ scale Jet Engine, actual rotation speeds of 20 to 60 rpm and scaled to 10,000 rpm. Rician distributed fading with K factors between 0.4 and 0.8 were observed. Through scaling, an estimated transmission window time of 21msec to 49msec for 60RPM (dependent on position) was observed. This should scale to 295usec.

RF Propagation – Frame 7 gas turbine

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GE Experimental Data: RF propagation thru Power Turbine

- Antenna inserted thru borescope ports & tuned in-situ.
- Receiver antenna in the exhaust duct
- Inter-stage measurements w/ both Tx & Rx antenna in different borescope ports
- Frequencies tested from 400MHz to 3GHz

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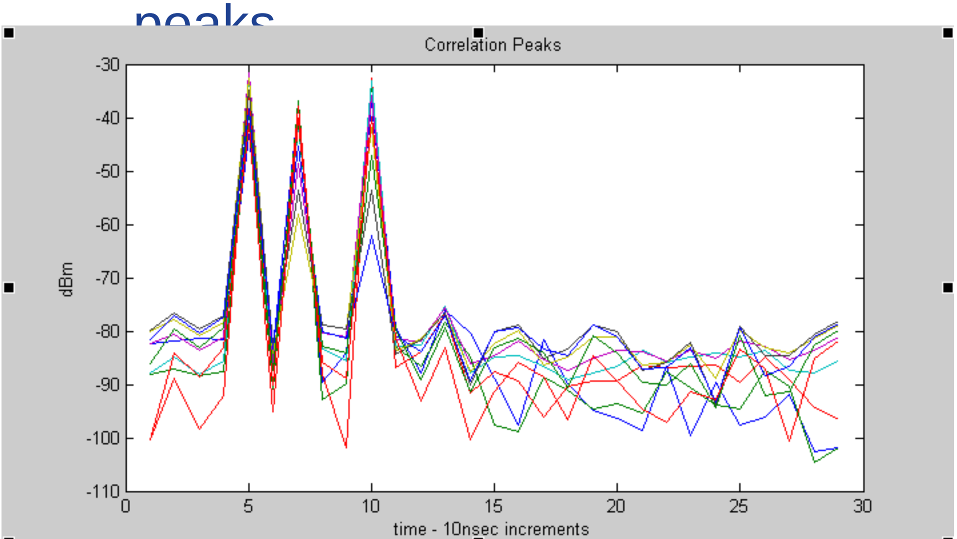
Results of Experiments

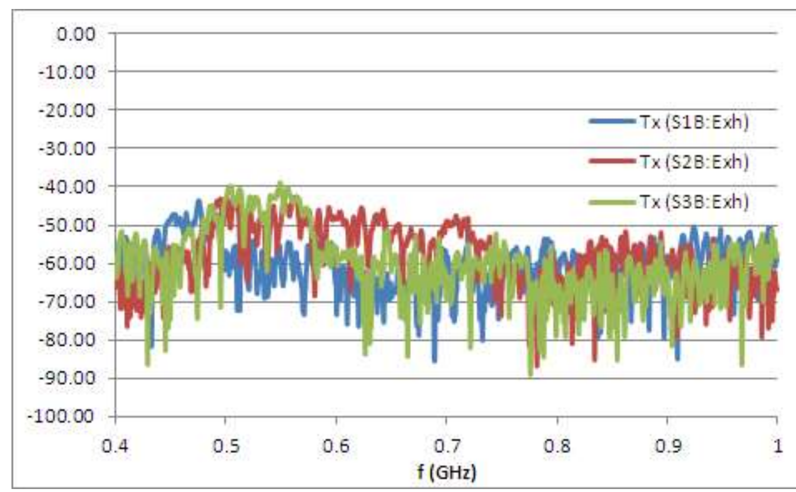
Insufficient analysis performed to date to publish complete results – preliminary findings follow:

1) Excess path loss 10 to 15 dB above free space (agrees with Walton et.al. findings). Relatively flat (with severe fading) from 400Mhz to 3GHz.

2) Able to interrogate sensor on last stage turbine bucket.

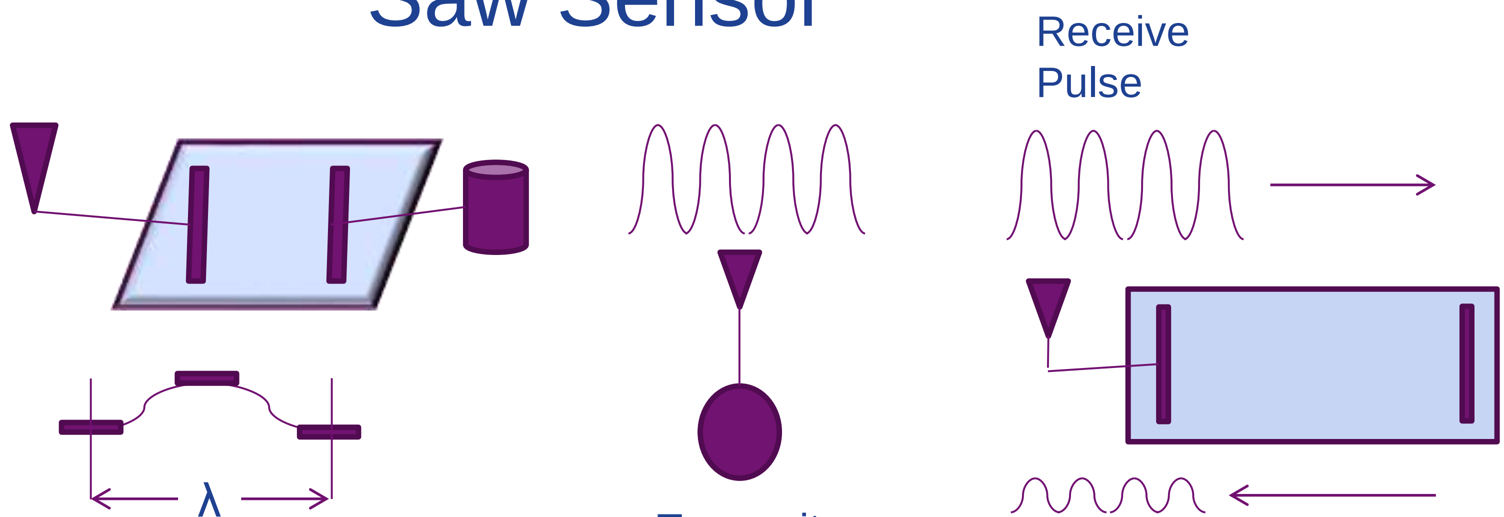
3) Direct Delay Spread Measurement at 2.4GHz: 3 distinct correlation peaks





Level 0 Technology Assessment

Saw Sensor



Brocato,, R. “Passive Wireless Sensor Tags”,
Sandia Report SAND2006-1288

Totally Passive Device

No Junctions, High temperature capable

Typical Saw Sensor Materials

- Lithiumniobate, Lithiumtantalate – Common for lower temperature operation
- Berlinite, Lithiumtetraborate, Langasite, Galliumliumorthophosphate – for applications approaching 1000°C

At higher temperatures, issues such as bonding, integrity of metallization, packaging, and coatings become limiting factors

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Companies Producing Passive Wireless Saw Devices

Hines, J. "Review of recent passive wireless SAW sensor and sensor tag activity" 978-1-4577-0972-2/11 IEEE

- Carinthian Technologies: http://www.ctr.at/en/home.html Lithiumniobate & Langasite sensors up to 900°C
- Senseor: http://www.senseor.com/ Temperature Sensors
- Environetix: http://www.environetix.com/ Temperature & strain sensors, rotating parts, 1000°C & 50kG force, nano-composite metallization for high temperature.
- Sengenuity: http://www.sengenuity.com/ Temperature sensors for switchgear up to 220°C
- Applied Sensor Research & Development Corporation: http://www.asrdcorp.com/ CDMA (coded) sensors for addressability. Temperature & strain sensors, up to 1000°C
- Transense Technologies: http://www.transense.co.uk/ Wireless tire pressure sensors and other sensors for the automotive market.
- RF SAW: http://www.rfsaw.com/Pages/default.aspx Supports a high density of coded SAW devices
- Fuentek/University of Florida: http://www.fuentek.com/technologies/SAW.php : Multi-sensor addressability, harsh environment

Back of the envelope link budget

Assume: 915MHz sensor (antenna size becomes large)
Read range: 3m
Free space path loss L = 20*log($\frac{4\pi d}{\lambda}$) = 41.2dB
Excess Path Loss (measured) = 15dB
Antenna Temperature: 600°C
Noise Power = -169dBm/Hz
Assume 80KHz sample rate (BW=80Khz); Noise floor = -120dBm
Assume 6 bit accuracy – required SNR=36dB (1.5%)
Reader Noise Figure = 2dB
Reader input power required = -82dBm (-120+36+2)
Reader antenna gain = 3dB
Sensor antenna gain = -10dB (small and close to metal)
Sensor Insertion loss = 20dB
Fading Margin = 10dB
Therefore - required transmit power = 84dBm – 200KW!
=-82-3+41.2+15+10+10+20+10+10+15+41.2-3=84.3
If you ignore the excess path loss, assume tag antenna gain of 0dB and no fading the transmit power requirement is: 14.3dBm – 27mW

A very crude estimate

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Design for success

1. Assure direct line of sight (no excess loss)
2. Eliminate/minimize or mitigate multipath (no fading margins)
3. Efficient antennas (larger area & away from metal)
4. Lower sample rate, multiple readings

Items 1,2 & 4 possible, item 3 is not.

What does this mean?

1) Interrogator antenna in same section with sensor.
2) Continuous strain measurements are not practical.
3) Near field options should also be explored.

Using previous estimation technique, temperature readings at a 1Hz rate could be practically supported. (Requires multiple readings integrated over time)

Level 0 Challenges

High Temperature Piezoelectric materials, metallization, adhesives

Bonding/adhesives (G force loading, Vibration)

RF Channel: Multipath fading & delay spread, time dependent fading.

Doppler (Speed of rotating parts)

Range (Near filed vs. far field)

Interference

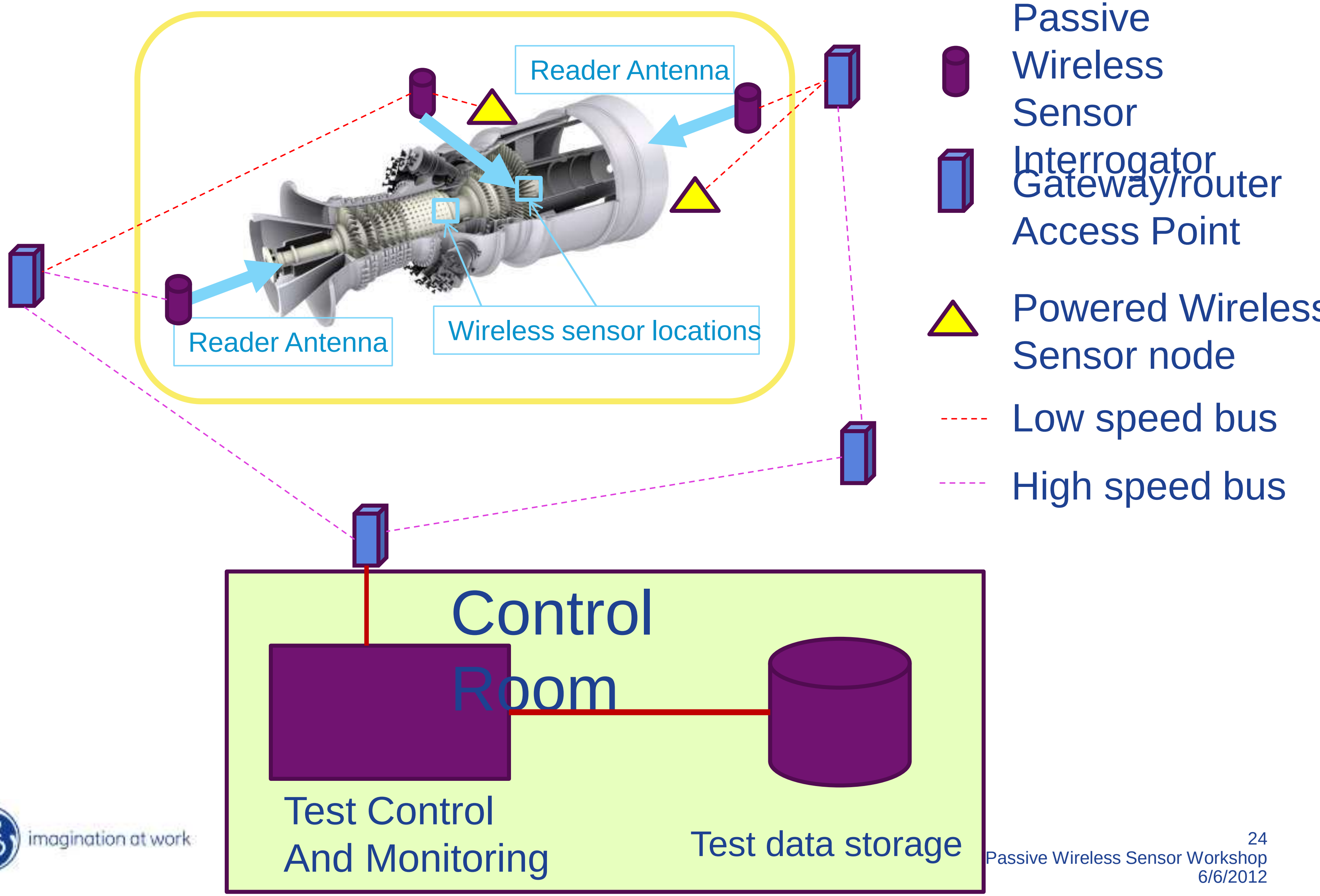
Regulatory (power and frequency restrictions)

Antennas (Size, efficiency, ability to radiate)

Scalability, Addressability of devices

Insertion loss

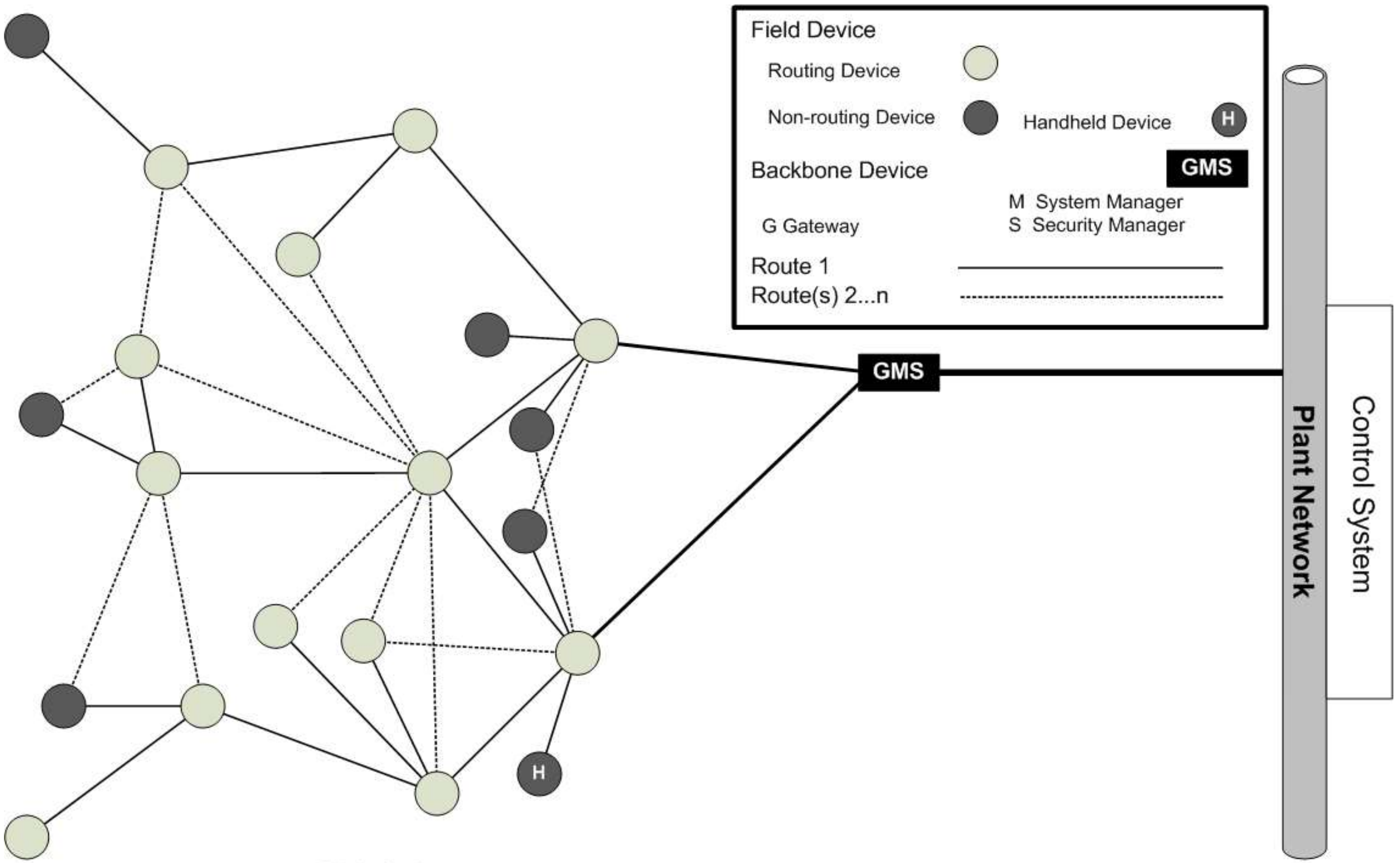
Wireless System Architecture – Level 1



Level 1 Requirements

1. Supports aggregated data throughput from all sensors.
2. Secure (FIPS140-2? Or higher, same data may be National Security Sensitive)
3. FCC compliant.
4. Reliable data delivery (no lost data)
5. Coexist with adjacent test cells and other plant networks.

Level 1 Alternatives – ISA100.11a



Additional Level 1 Technologies

- IEEE 802.11 (WiFi for backhaul)
- WiMax (Long range backhaul)

Thank you for listening
Any Questions?

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