Wireless Sensor Network Technologies for Applications in Nuclear Power Plants

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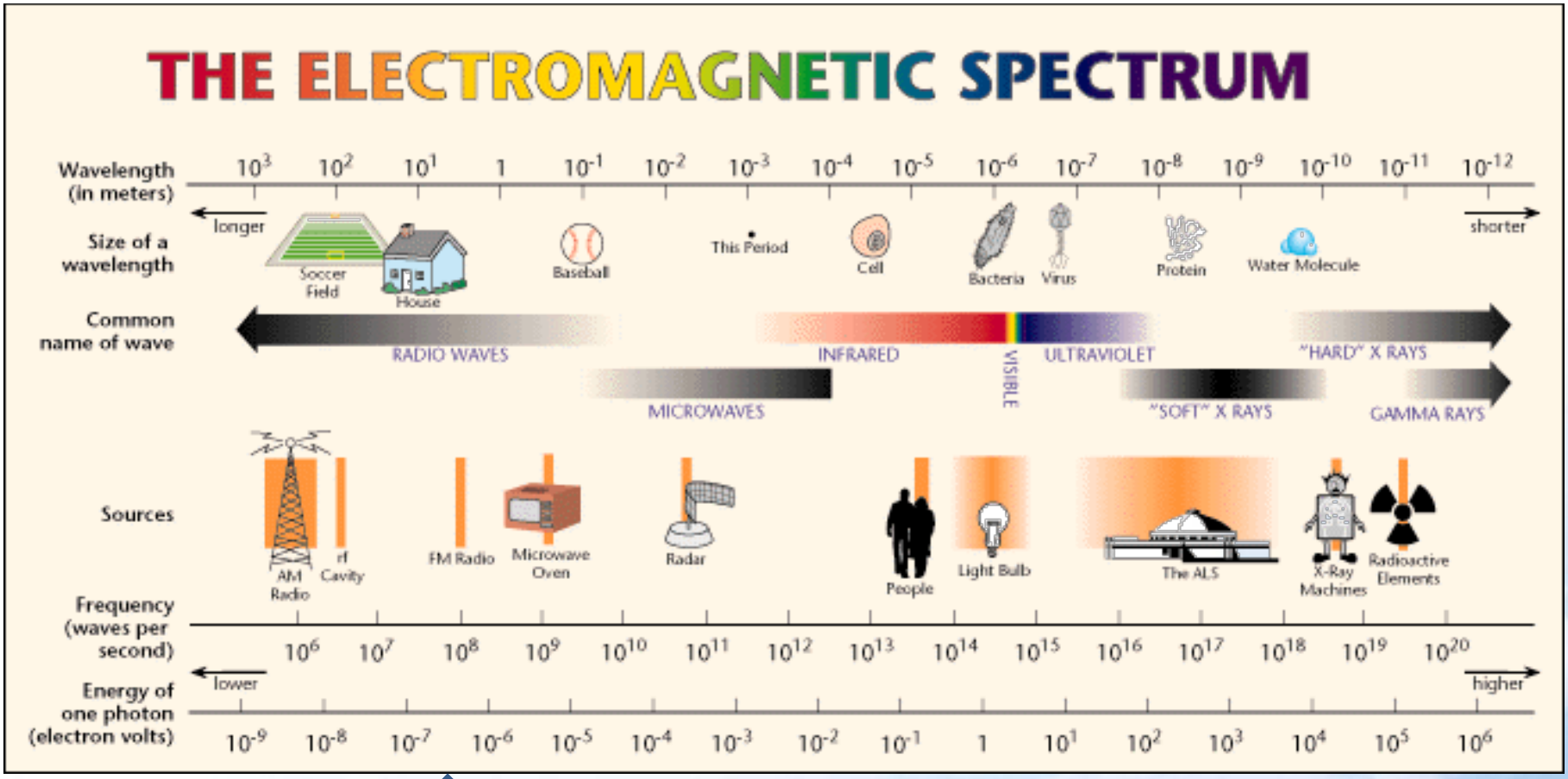
Dedicate this presentation to late Prof. Zhijian Zhang

Outline

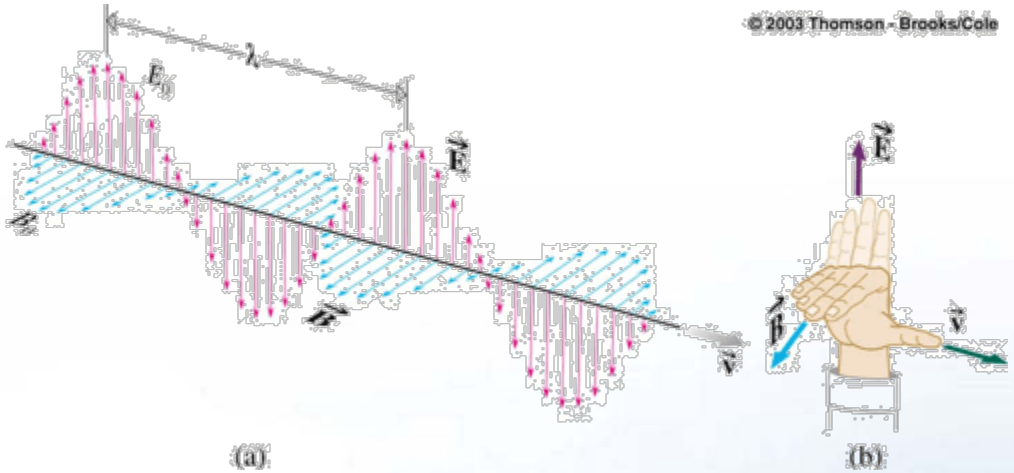
- Introduction to Industrial Wireless Sensor Networks
- Pros & Cons of Industrial Wireless Sensor Networks
- Special Needs in Nuclear Power Plants
- Applications of Wireless Sensor Networks in NPP
- Some Research and Development Work
- Conclusions

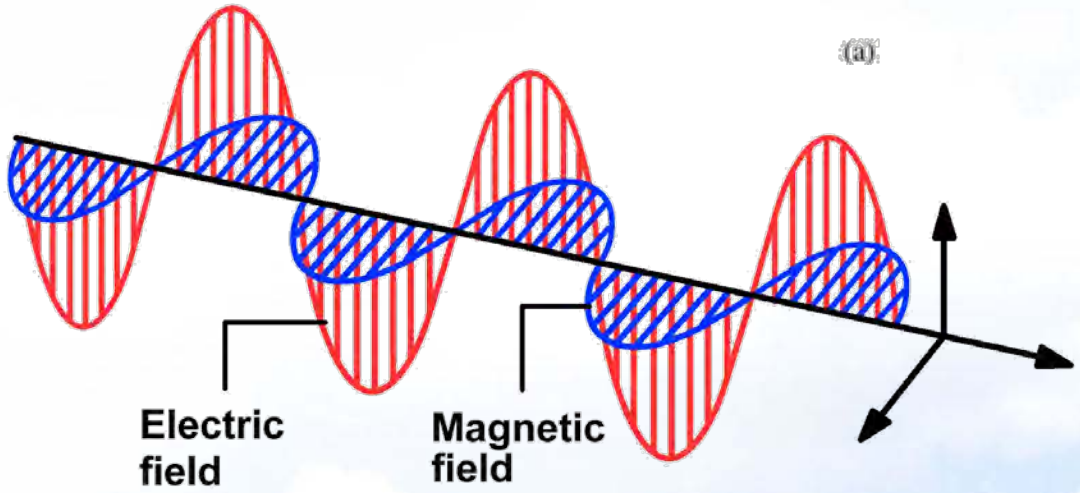
Spectrum of Electromagnetic Waves



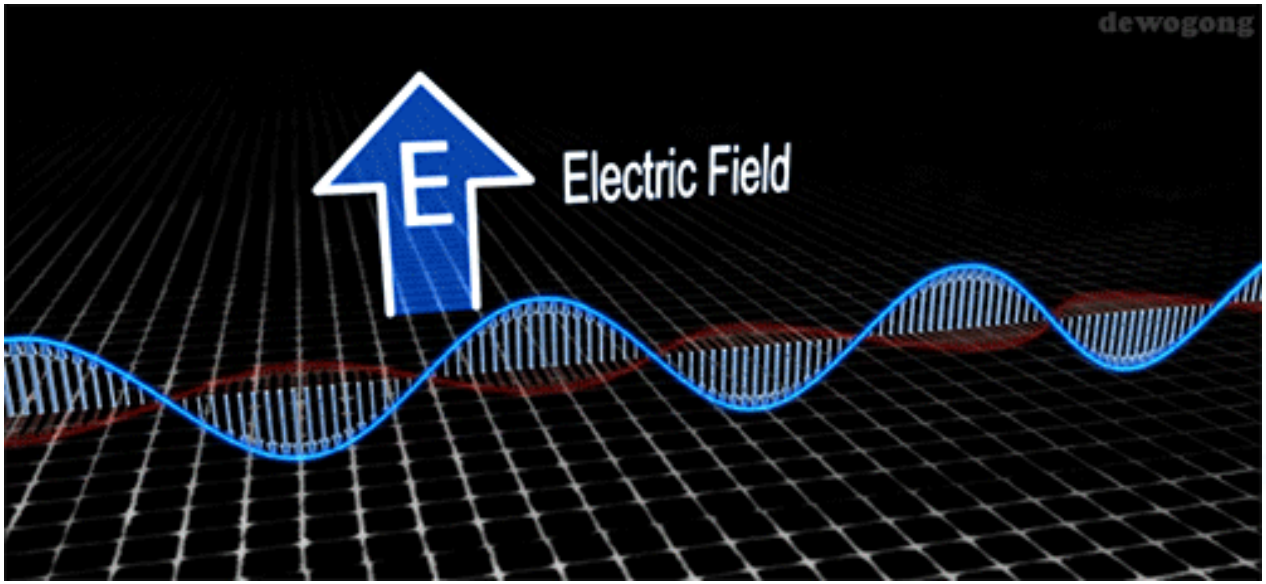
Spectrum of wireless sensors

Propagation of Electromagnetic Waves

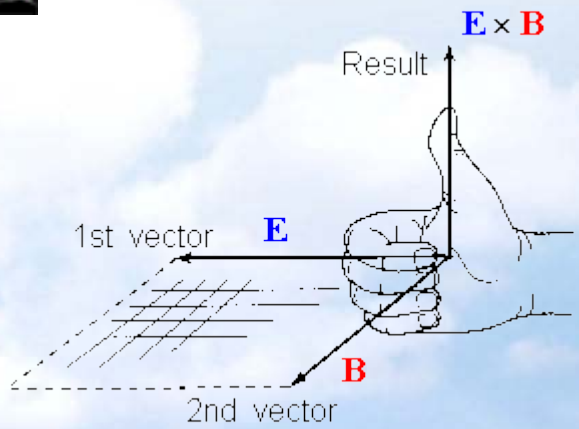




Electric and Magnetic Fields



Electromagnetic Wave Propagation

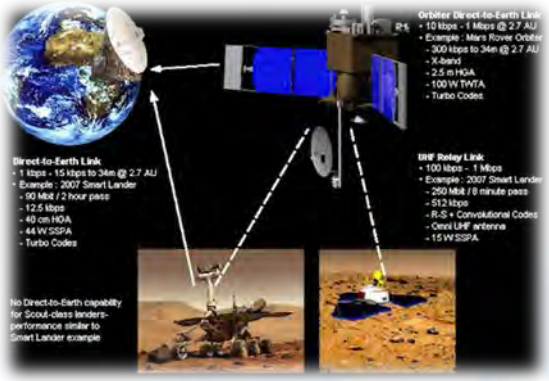


Advances in Wireless Communications

Telegraph & telephone → Radio & television → Video telephony → Satellite → Computer networks & the Internet

An early Morse telegraph machine & the first telephone

The first transatlantic wireless signal by Marconi in 1901, Signal Hill, St. John's, Newfoundland

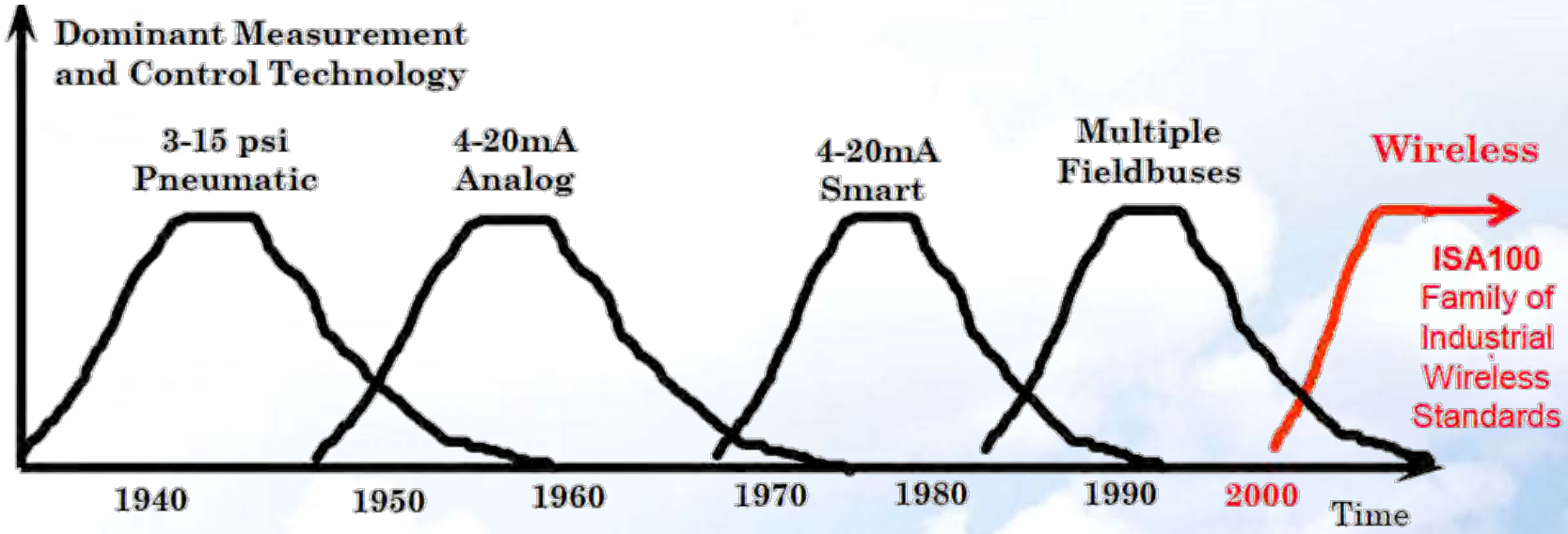


Space communication

Canada's first commercial Earth observation satellite, RADARSAT-1, launched in November 1995

Video conference

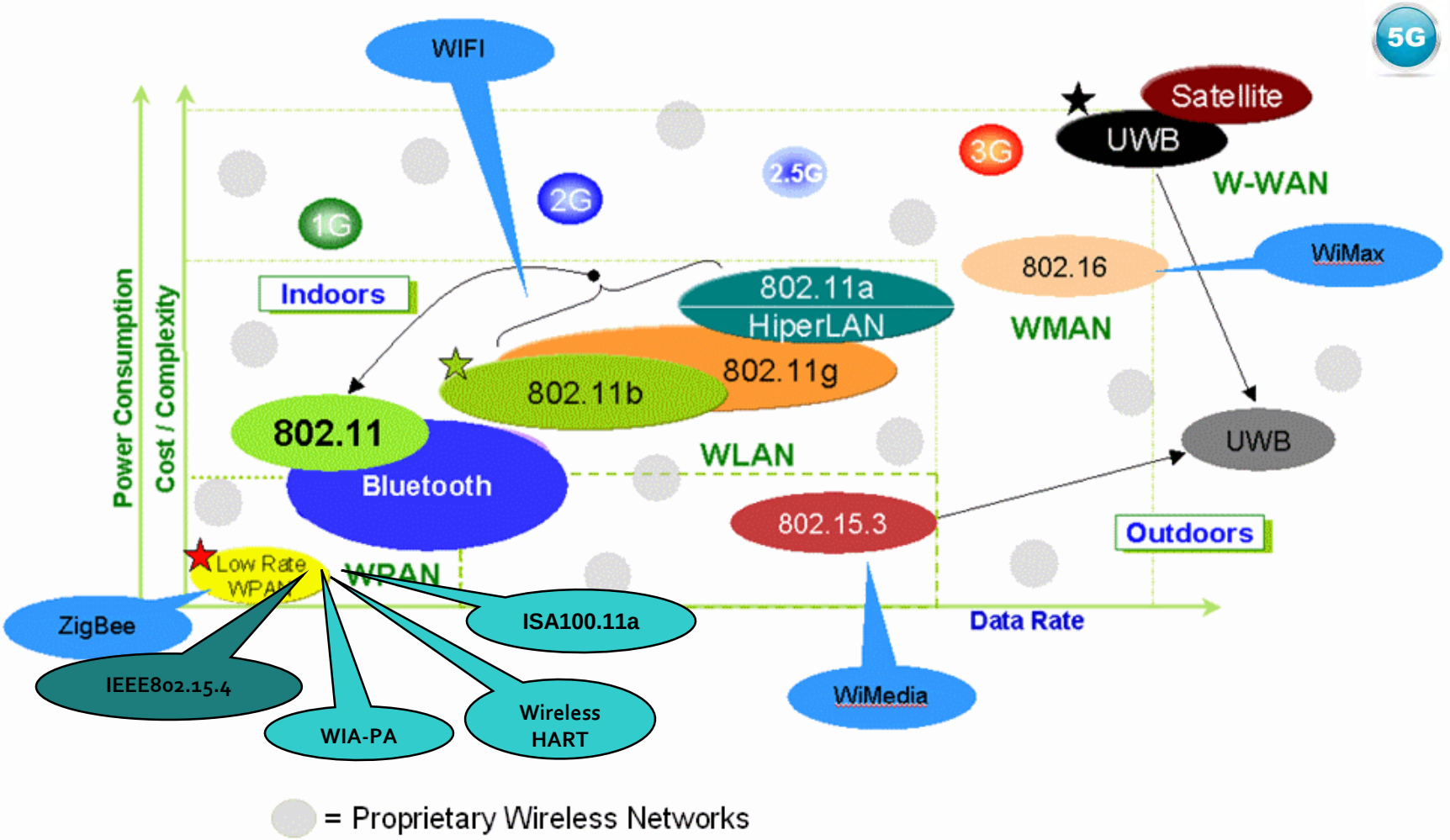
Advances in Control and Instrumentation



Why go Wireless ?

- lower installation costs
- lower maintenance costs
- reduced connector failure
- rapid deployment
- less or no wires
- increased mobility and collaboration
- convenience of use
- faster access to information
- easier network expansion
- easier network modifications
- access to difficult locations
- options for guest access
- new operation possibilities

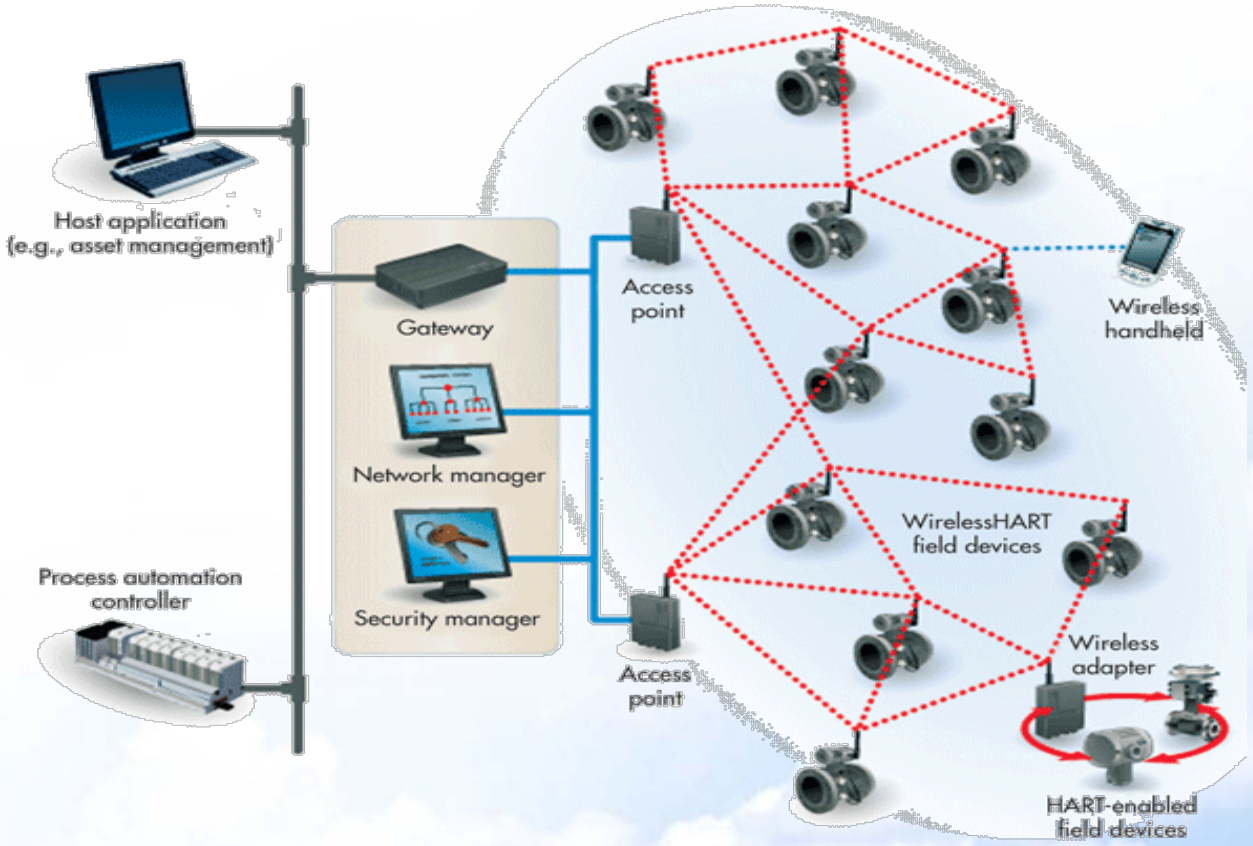
Wireless Landscape



Different applications require different wireless technologies

Industrial Applications of Wireless Sensor Network

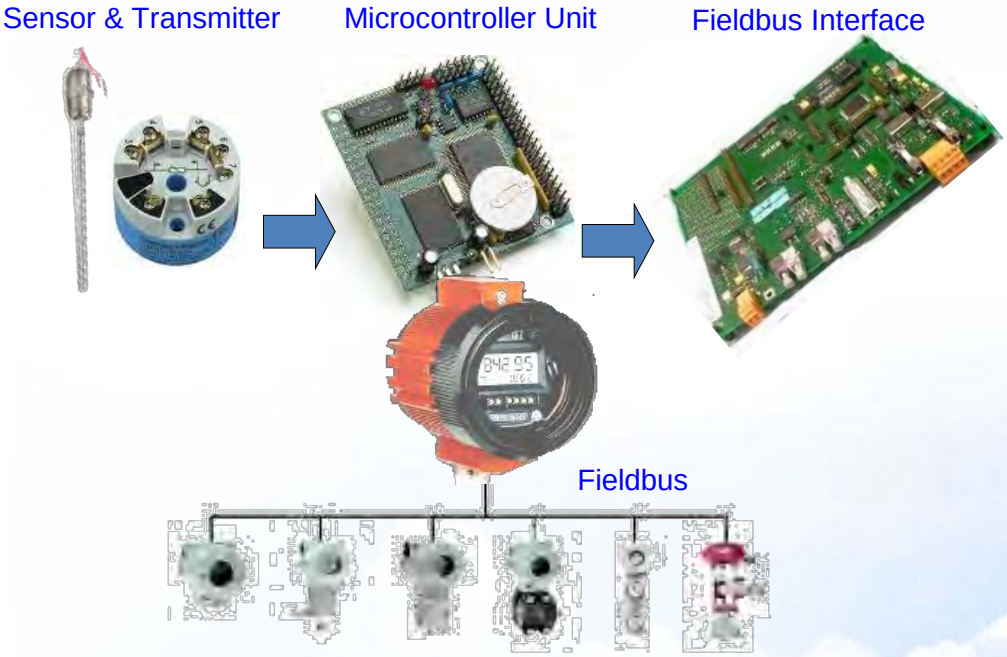
- **Industrial wireless sensor network (IWSN)**
  - Interconnected wireless sensors
  - Sensors measure physical process variables
  - Information transmitted to the control/monitoring station

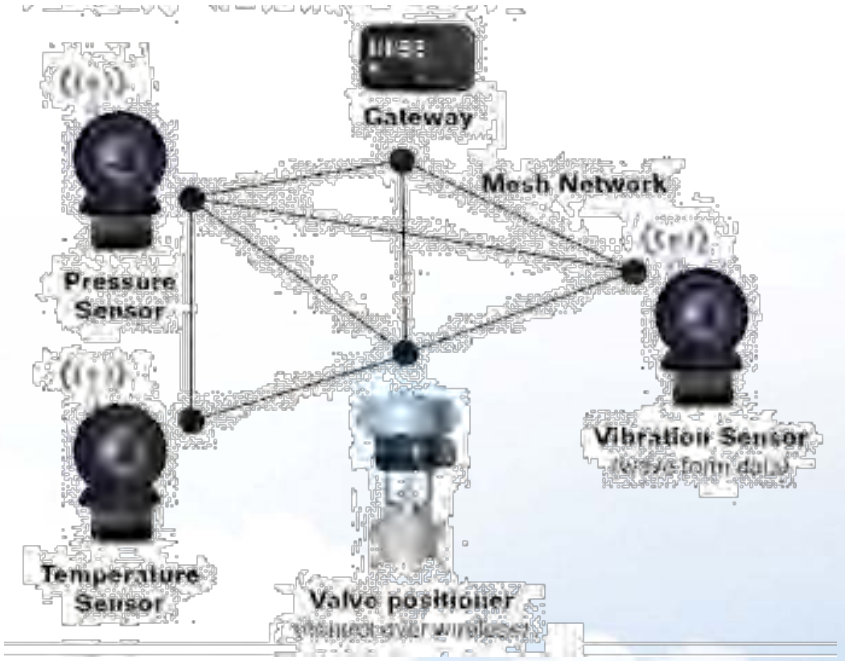


http://electronicdesign.com/content/content/74419/74419_f2.gif

WSN Modules

- **WSN modules**
  - Use low power
  - Communicate wirelessly
- **Offers**
  - Conveniences and cost-savings





Graphic source: http://www.automationworld.com/sites/default/files/styles/lightbox/public/field/image/GE%20Wireless%20Sensor%20Network.png?itok=8v3RKQvE

Standards and Protocols

- **International standards and protocols for IWSN**
  - ZigBee.
  - WirelessHART.
  - ISA 100.11a.

ZigBee

WirelessHART

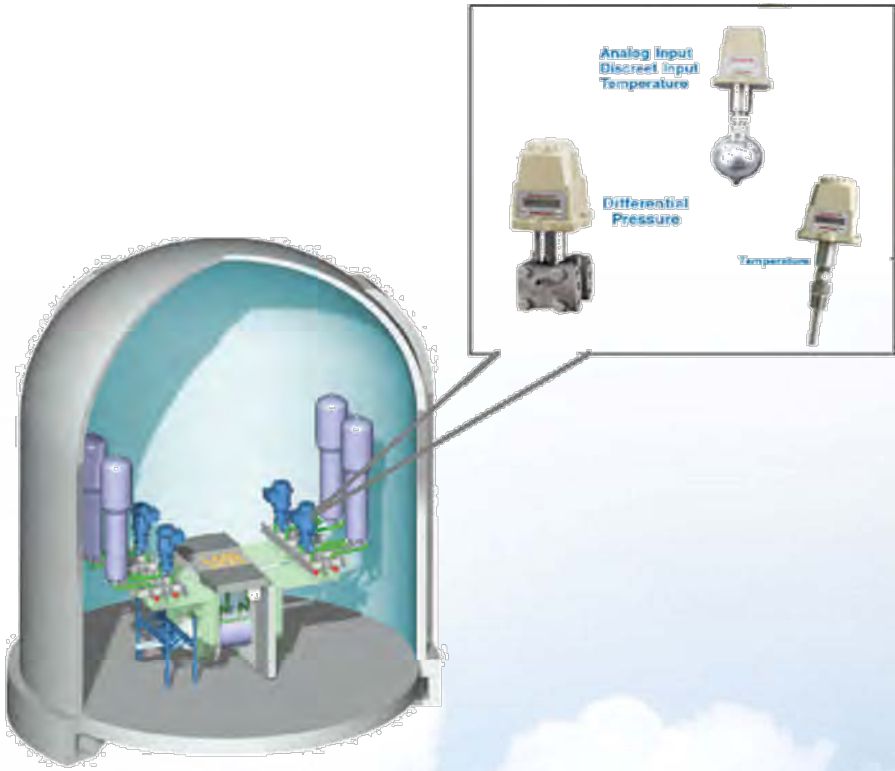
Industrial Versions of WSN Systems

Emerson process management
(WirelessHART)

Honeywell

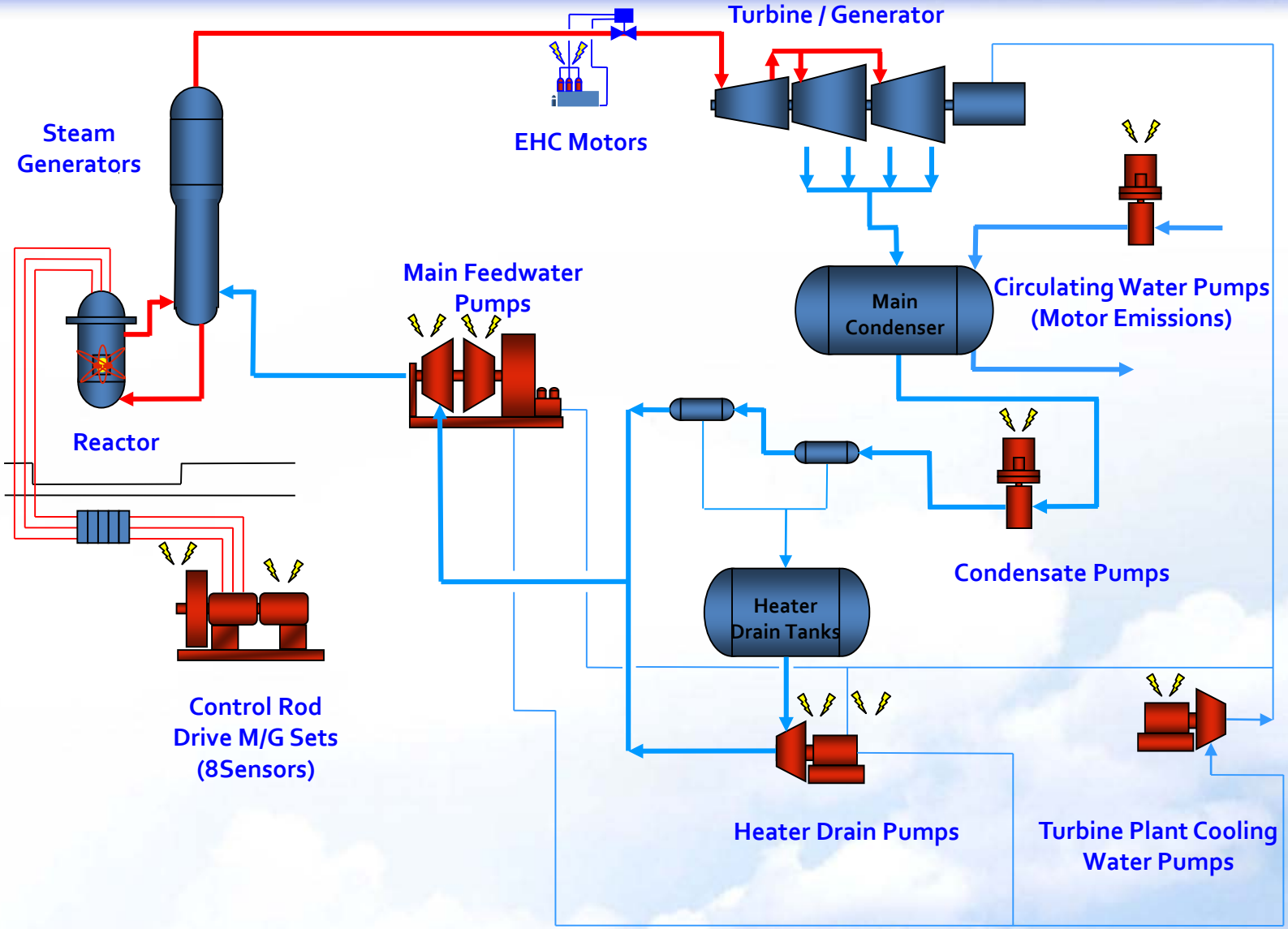
Potential Applications of IWSNs in Nuclear

- **Use of Industrial WSNs**
  - Process variables measurement
  - Equipment condition monitoring
  - Predictive maintenance
  - Remote diagnostics
  - Post-accident monitoring
- **WSNs in NPPs**
  - For monitoring applications.
  - Can be used in both primary and secondary systems.
- **WSNs offer**
  - Cost savings – wire in NPP is expensive (e.g., $2000/ft)
  - Convenience – wires can be difficult to install

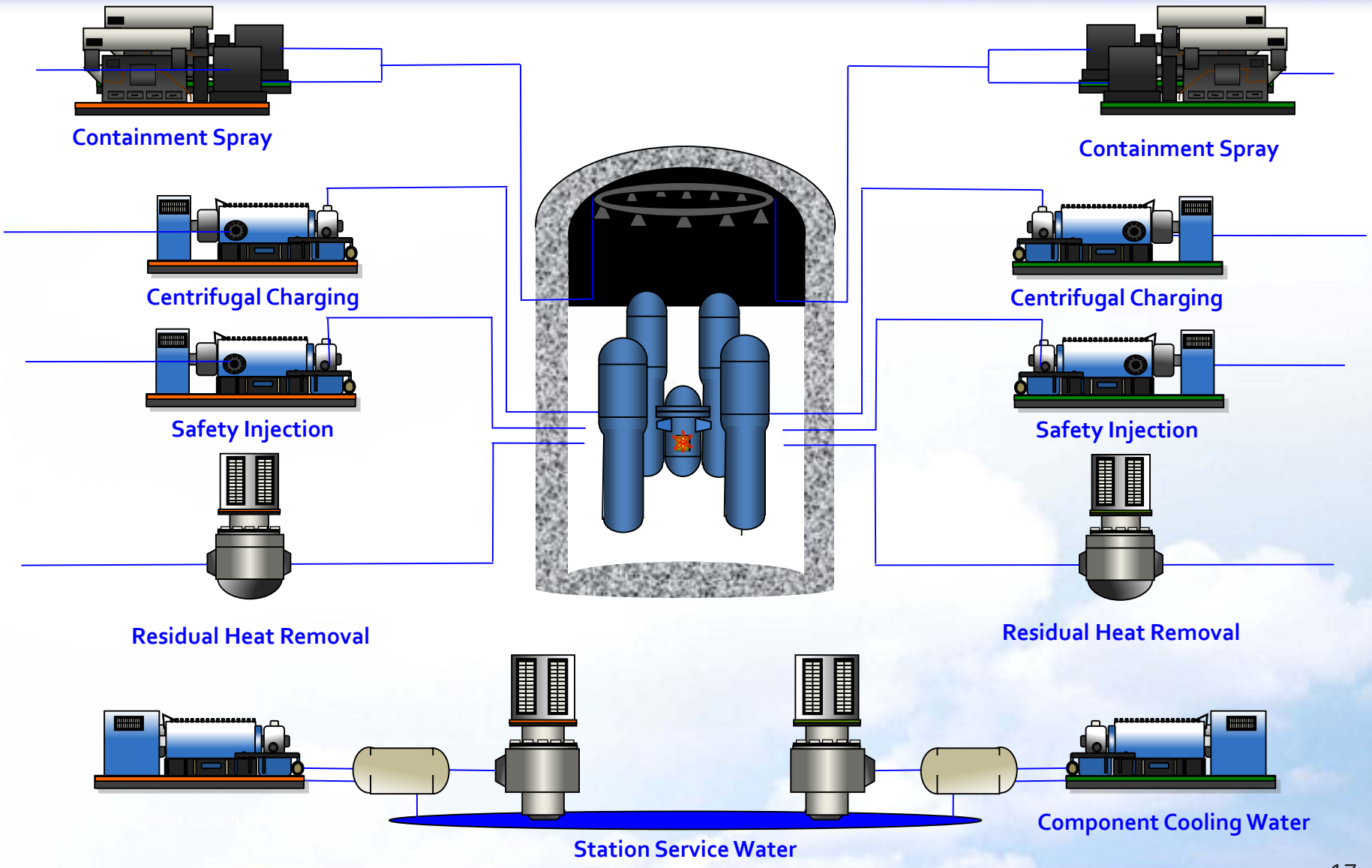


- **Applications of interests**
  - Equipment condition monitoring
  - Plant environment monitoring
  - Radiation level and dose monitoring

Wireless Equipment Monitoring System (Non-Safety Related)

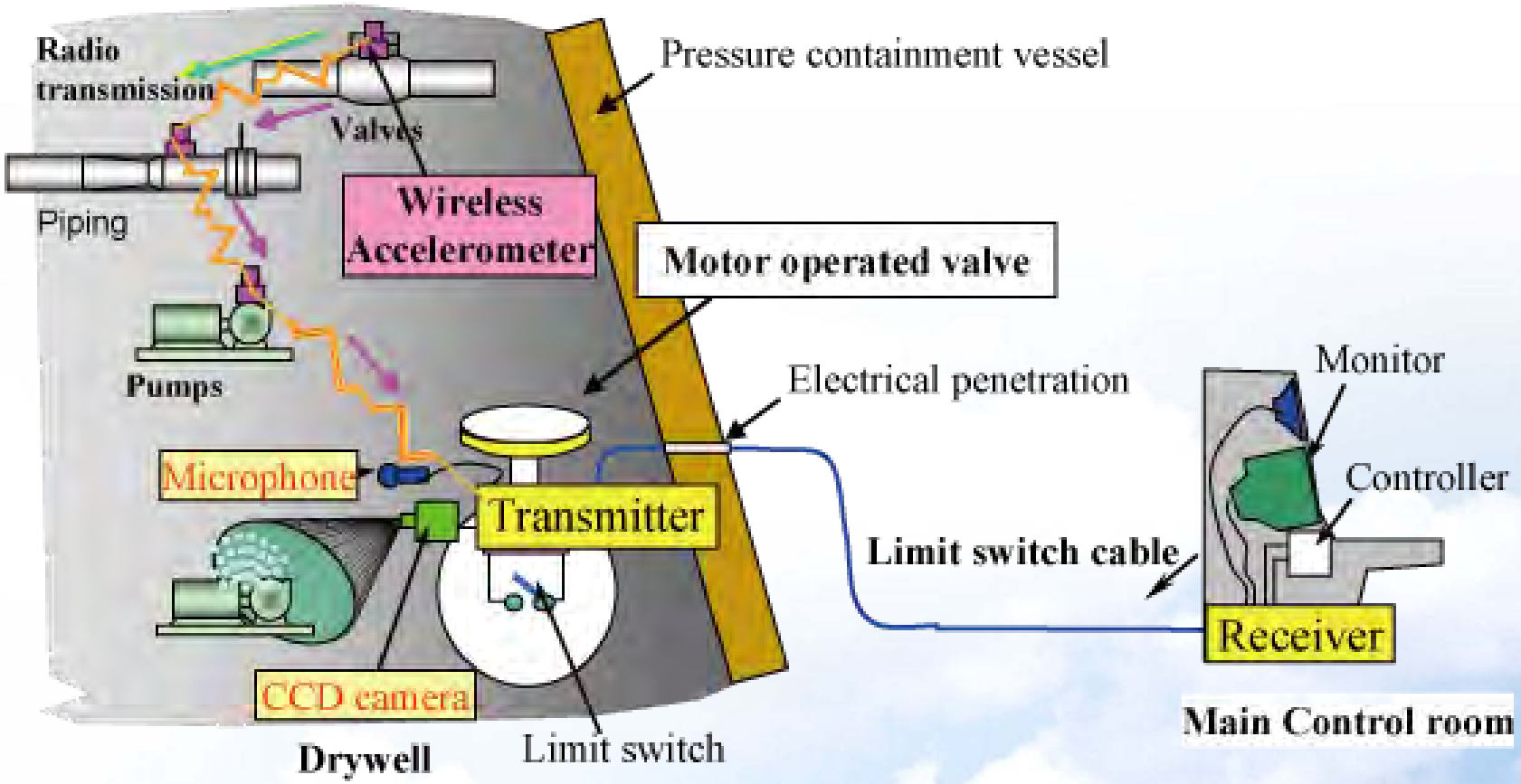


Wireless Equipment Monitoring System (Safety Related)



WSNs for Equipment Monitoring

- **Equipment condition monitoring in NPPs**



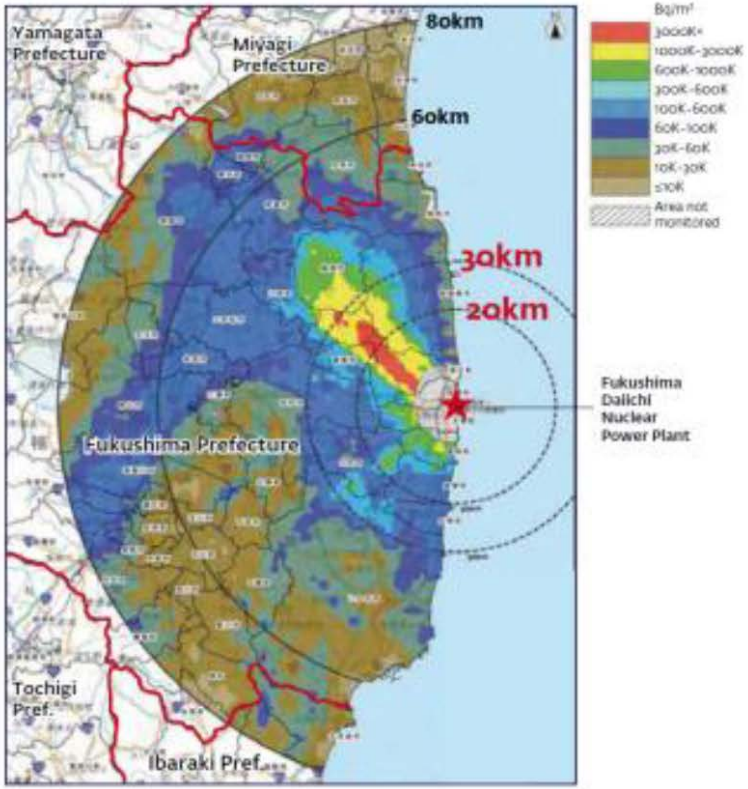
Source: Google image, http://www.jsm.or.jp/ejam/Vol.2.No.1/NT/22/EJAM2-1NT22-Fig.7_Condition_monitoring_of_equipment_in_PCV(2).png

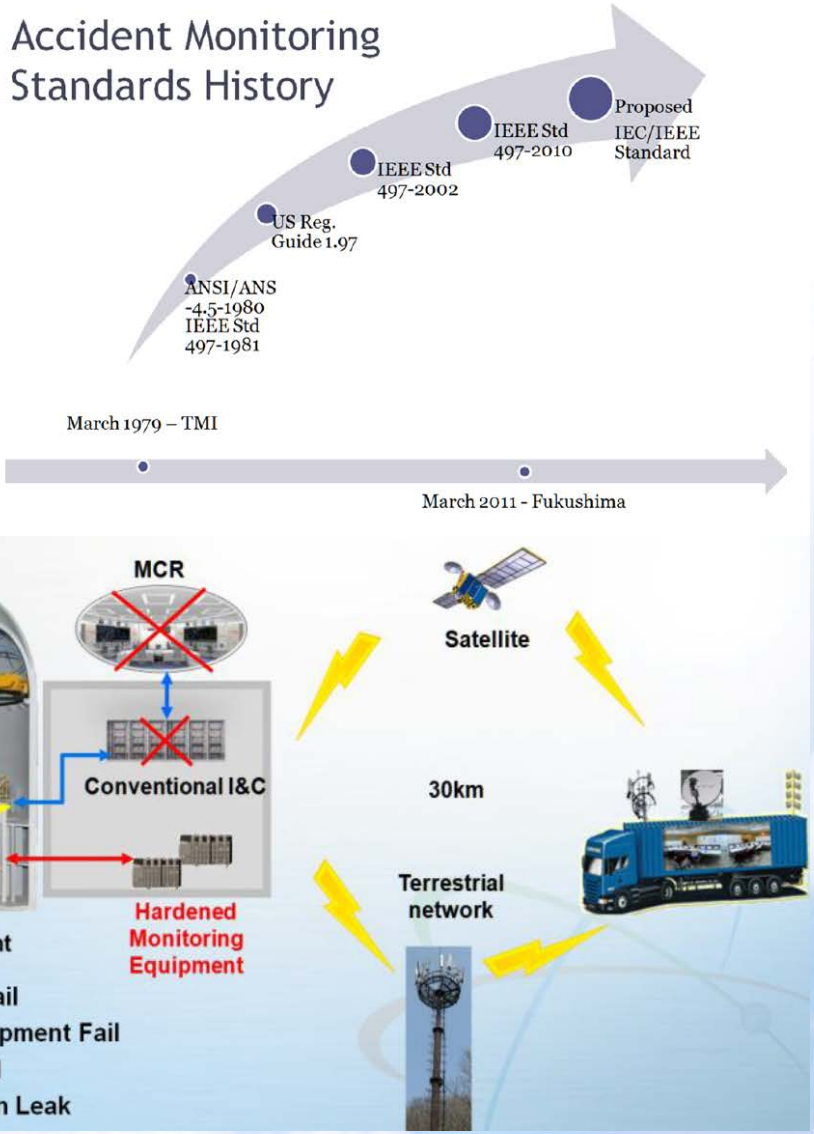
WSNs for Equipment Monitoring

- **Additional sensor measurements can be acquired**
  - In a cost-effective way
  - Provide redundancy and/or diversity
  - Protect a monitoring system against physical mishaps
- **Measurements from wireless sensors**
  - Validate the wired sensor readings
  - Serve as a back-up unit
  - Provide an alternative ways if the wired channel fails
- **WSN can help optimize maintenance**
  - Reduce plant down time
  - Reduce radiation exposure
  - Improve plant economy, safety and availability

Radiation Level Monitoring

- **Wireless technologies**
- **Monitoring technologies**

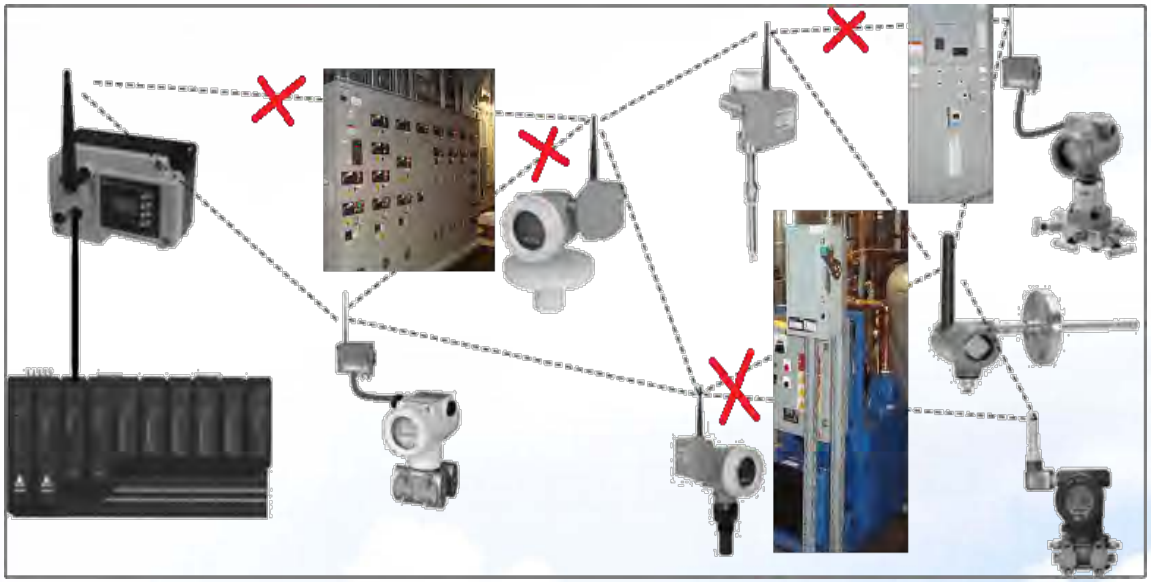


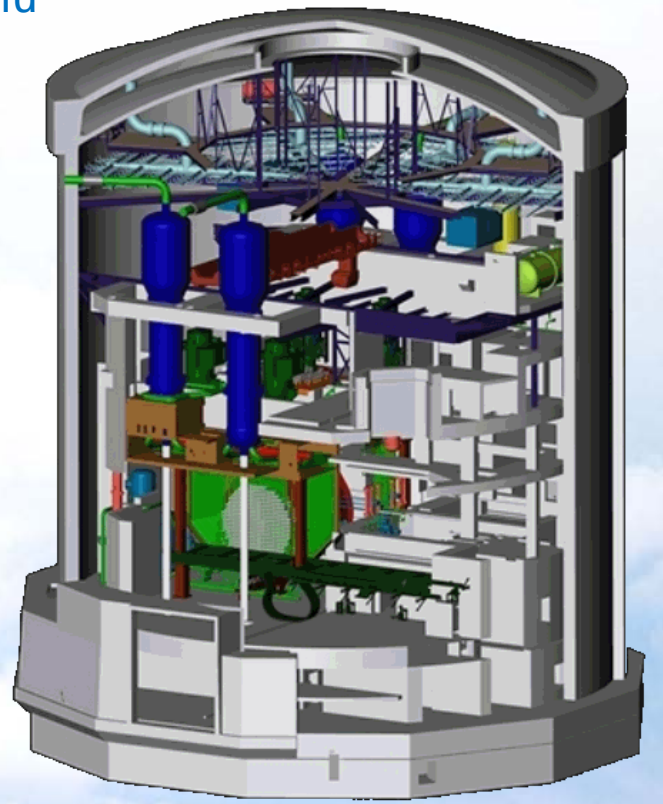


Post-accident and Environment Monitoring

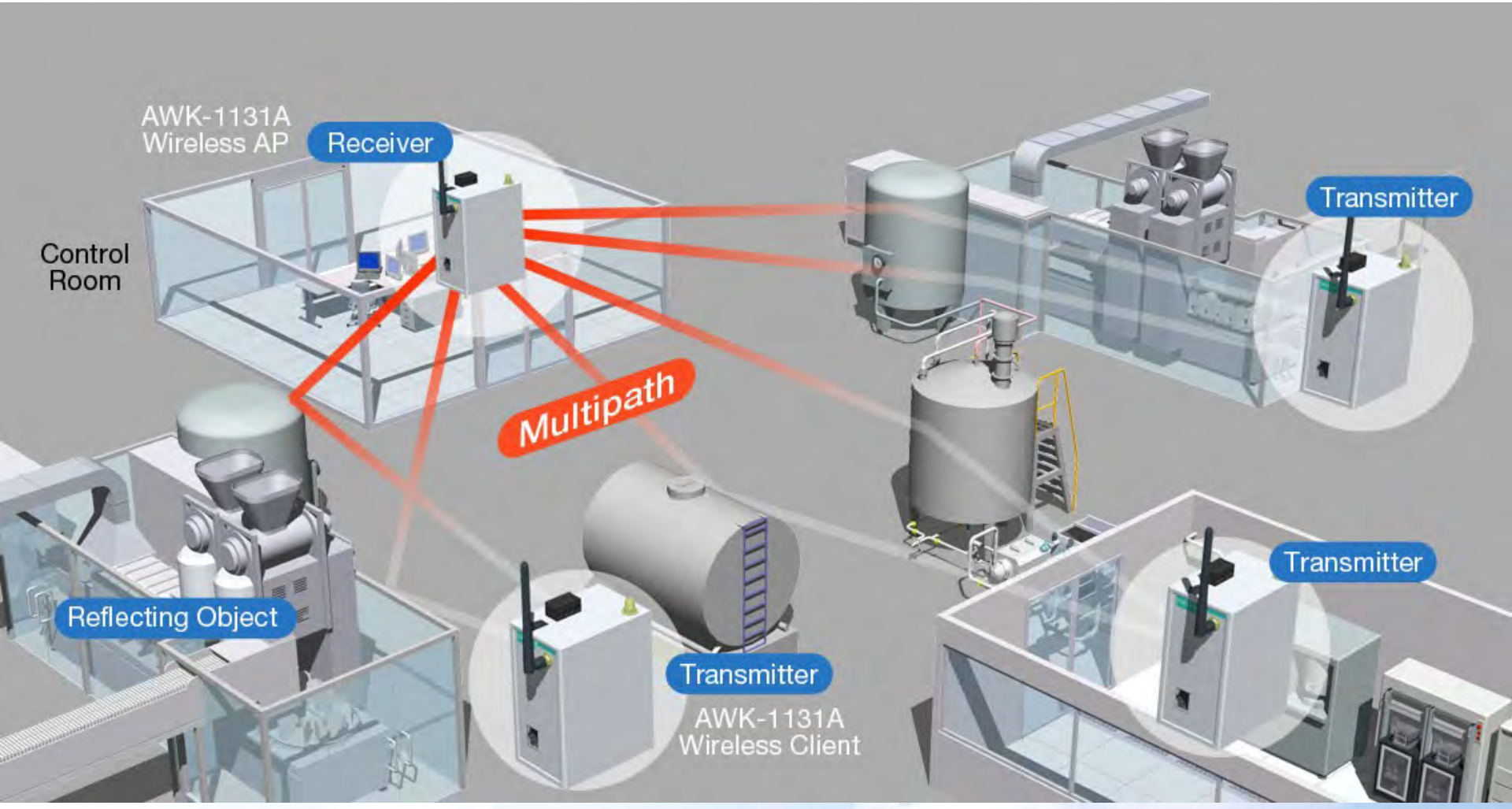
WSNs used for Equipment Monitoring

- **Issues**
  - Performance of WSNs in an NPP environment
    - Harsh EMI environment.
    - Complex geometrics.
    - Packed with equipment and large concrete and steel structures.





Multipath Problems in Wireless Sensor Networks

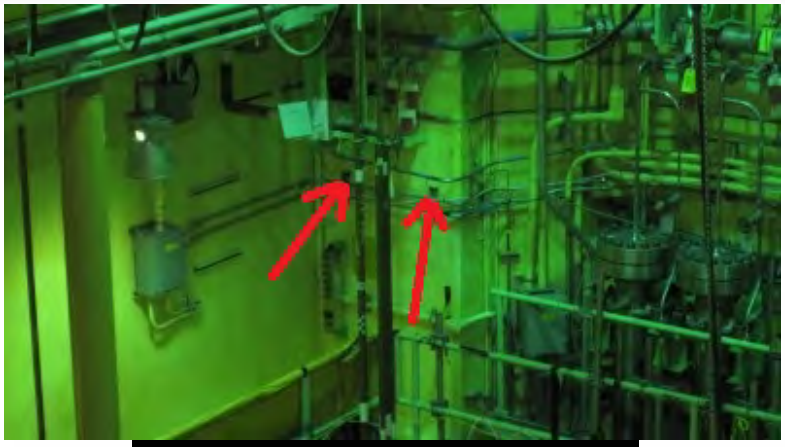


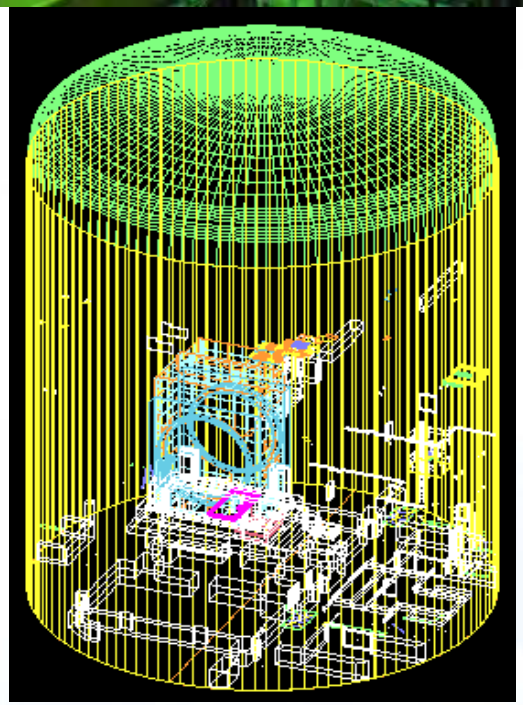
www.moxa.com/newsletter/connection/2014/07/feat_01.htm

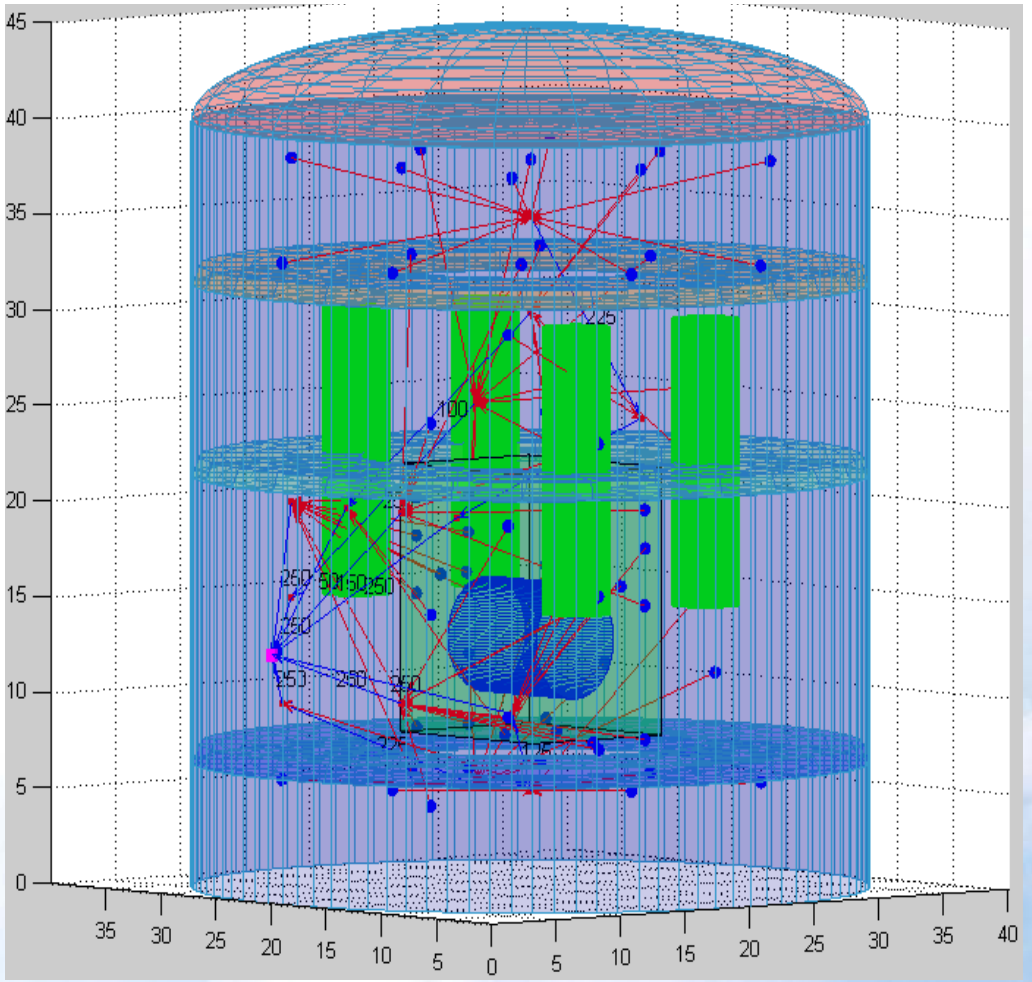
WSNs System Design Requirements

- **Characterization of EM environments in NPP**

WSNs Deployment Strategies in NPPs







Issues to be investigated

- EM interference to safety instruments in the plant
- Interference by the electromagnetic noise from other equipment
- Modulation frequencies used
- Effective signal transmission within the plant
- Radiation damage to electronics in the WSN devices

Exclusion Zones near Safety Instruments

EMI/RFI Impacts on Safety I&C Instruments

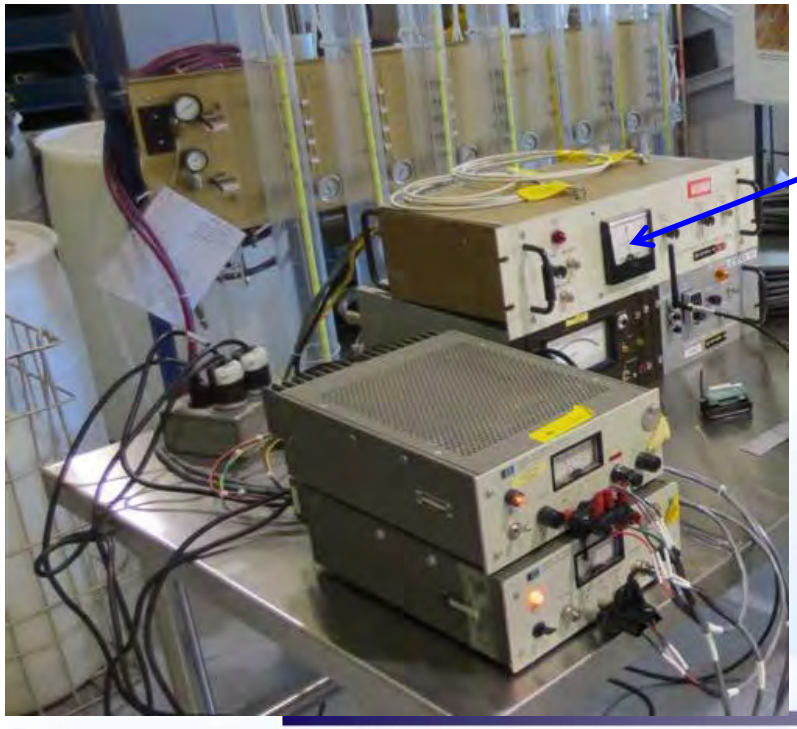
- **EMI/RFI effects depend on the transmit power level**
  - Walkie-talkie and cell phone use higher levels of transmit power
  - WSN devices can operate at a much lower power level
- **The EMI/RFI impacts from WSN modules will be minimal**
  - Several test deployments have lead no issues
  - Experiments have further confirmed such observation

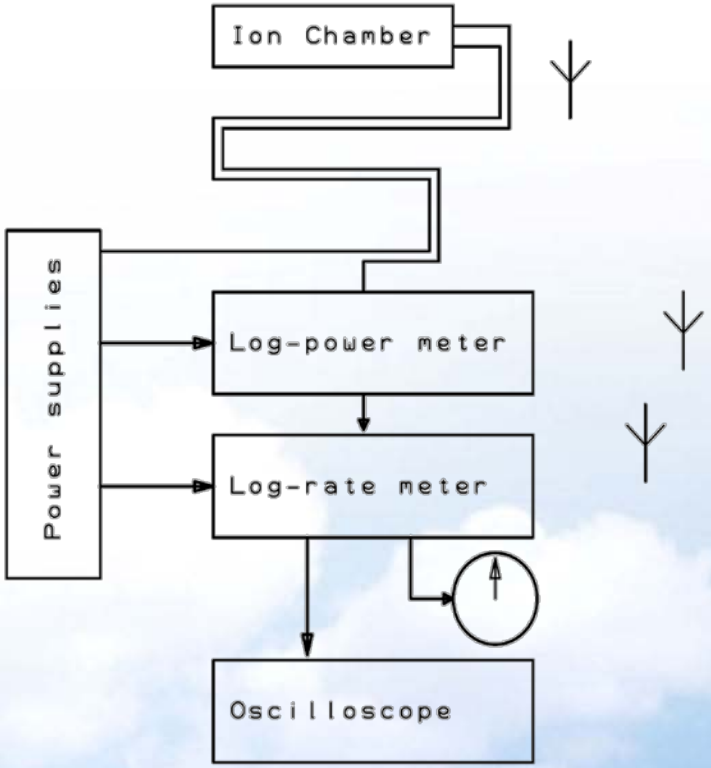
Experimental Results

- **A log-rate meter was selected as a sensitive instrument**
  - Receive the output from a log power meter, which is used to monitor the reactor power
  - Generate the derivative of the log power output
  - This derivative is a natural indicator of how fast the power is increasing
  - Several log rate meter trips have been reported due to EMI/RFI

Systems Used in the Tests

- A fission chamber
- Power supplies
- A log power meter
- A log rate meter
- An oscilloscope



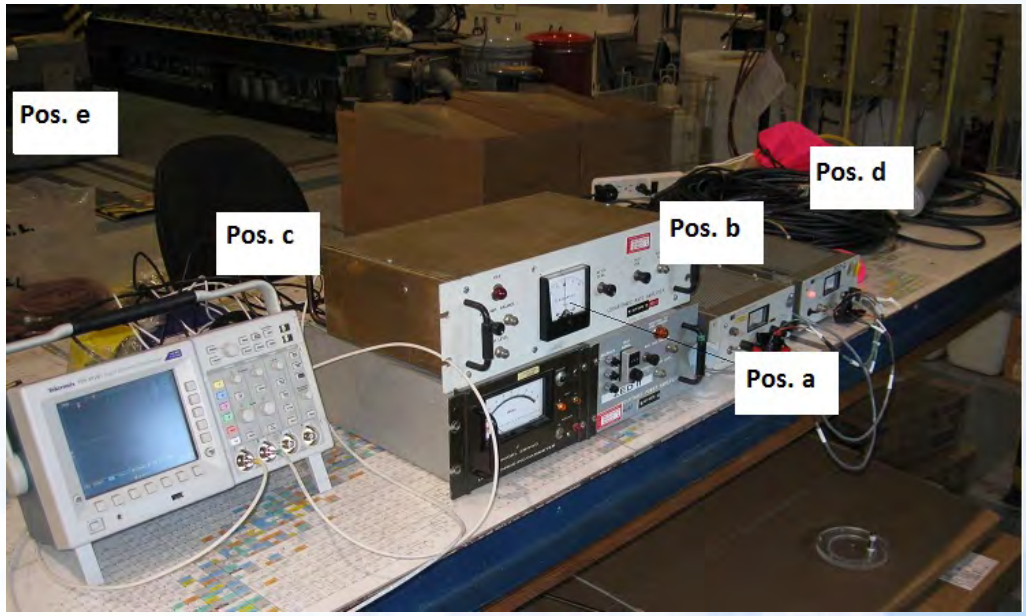


Wireless Devices Used in the Tests

- Dev. 1. The WSN modules, using ZigBee protocol.
- Dev. 2. The WNS modules, using CSS modulation
- Dev. 3. Walkie-talkie
- Dev. 4. Cell phone

Test Layout

- **Locations of the devices**
  - Pos. a. Front of the log-rate meter
  - Pos. b. Side of the log power meter
  - Pos. c. Back of the meters
  - Pos. d. Near the ion chamber and the cables (wound-up beside the instruments)
  - Pos. e. Near the ion chamber and the cables (extended to the full length)



Variation of EMI/RFI with Distance

- **Test equipment used**
  - The same log rate meter
  - The same walkie-talkie
  - ZigBee compliant Memesic IRIS module, with transmit power set to17 dBm (50 mW)

IRIS modules

Walkie-talkie

IRIS

Results Comparison

Comparisons of the EMI/RFI impacts of wireless devices on log-rate meter

Wireless Device	Positions				
	Pos. a	Pos. b	Pos. c	Pos. d	Pos. e
Dev. 1	None	None	None	None	None
Dev. 2	None	None	None	None	None
Dev. 3	Strong	Strong	Very Strong	Weak	None
Dev. 4	Very Weak	Very Weak	Weak	None	None

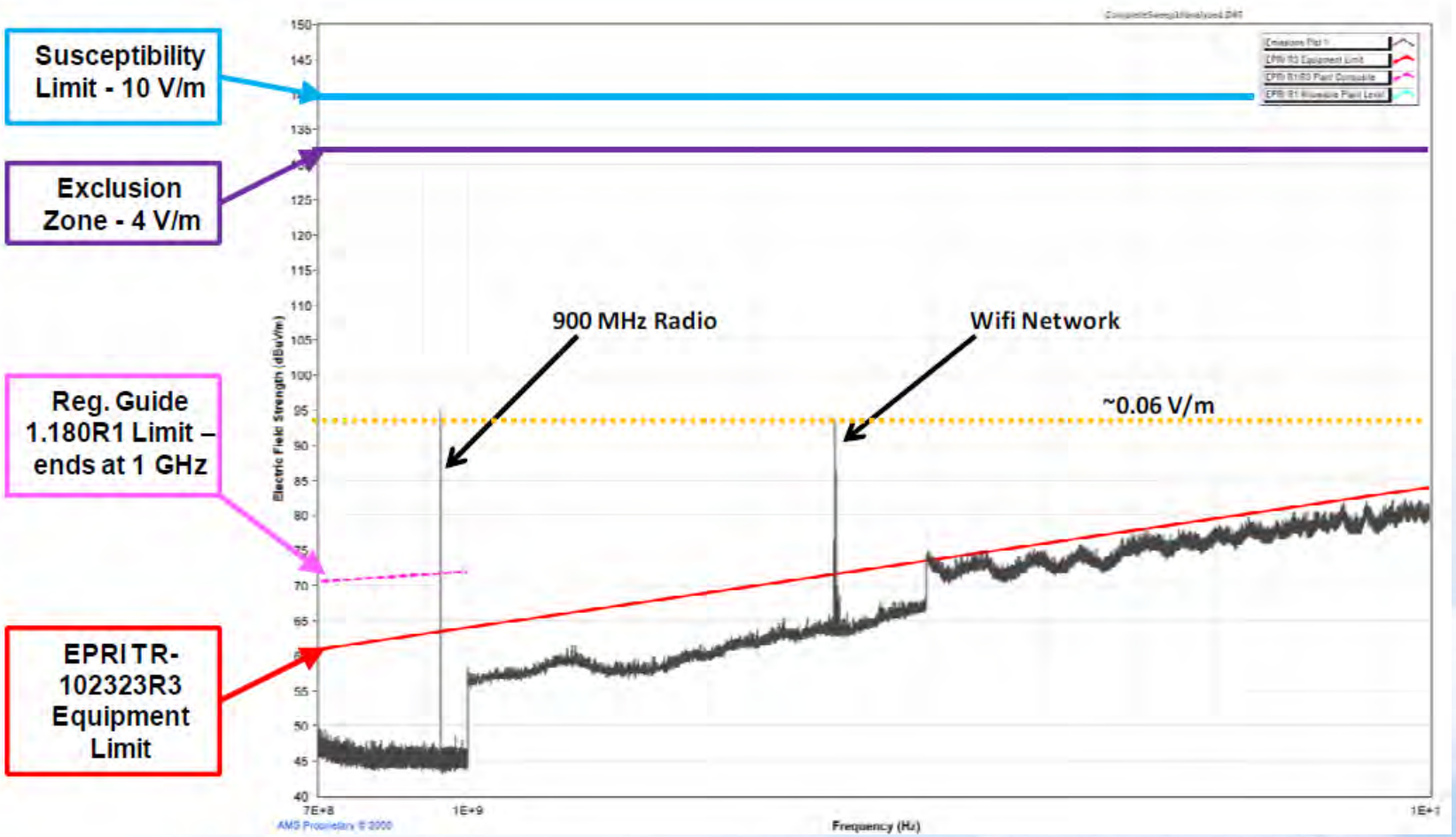
Dev. 1 WS nodes; Dev. 2, Chirp based WS node; Dev. 3, Walkie-talkie; and Dev. 4 cellphone

Results of Comparison

Comparisons of the EMI/RFI impacts of IRIS module and walkie-talkie on log-rate meter at various distances

Distance in inches	Rate change (%/s)	
	Walkie-talkie	WSN module
2	14	0
4	10	0
6	8	0
8	2	0
12	1	0

Limits


Susceptibility Limit - 10 V/m
Exclusion Zone - 4 V/m
Reg. Guide 1.180R1 Limit – ends at 1 GHz
EPRI TR-102323R3 Equipment Limit
900 MHz Radio
Wifi Network
~0.06 V/m
Electric Field Strength (dBuV/m)
Frequency (Hz)
7E+8
1E+9
1E+1

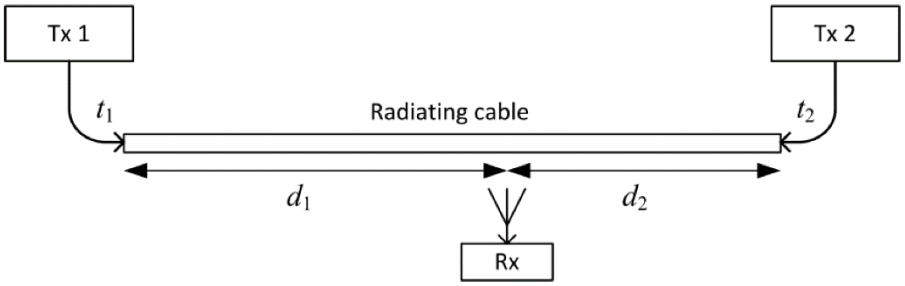
Regulatory aspects

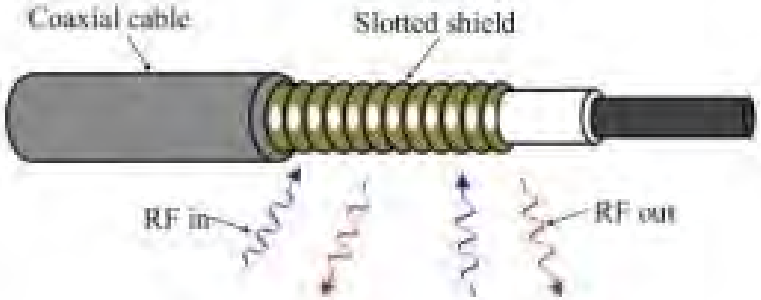
- Several nuclear regulatory bodies have provided guideline to address concerns with EMI/RFI form the WSN devices on the safety system instruments
- US NRC Regulatory Guide 1.180 has
  - identified EMI/RFI as environmental conditions that can affect the performance of safety-related electrical equipment.
  - recommended EM operating envelopes for I&C systems in NPPs.
- Based on this guideline, a wireless system can be used if the EM emission remains within the operating envelope.

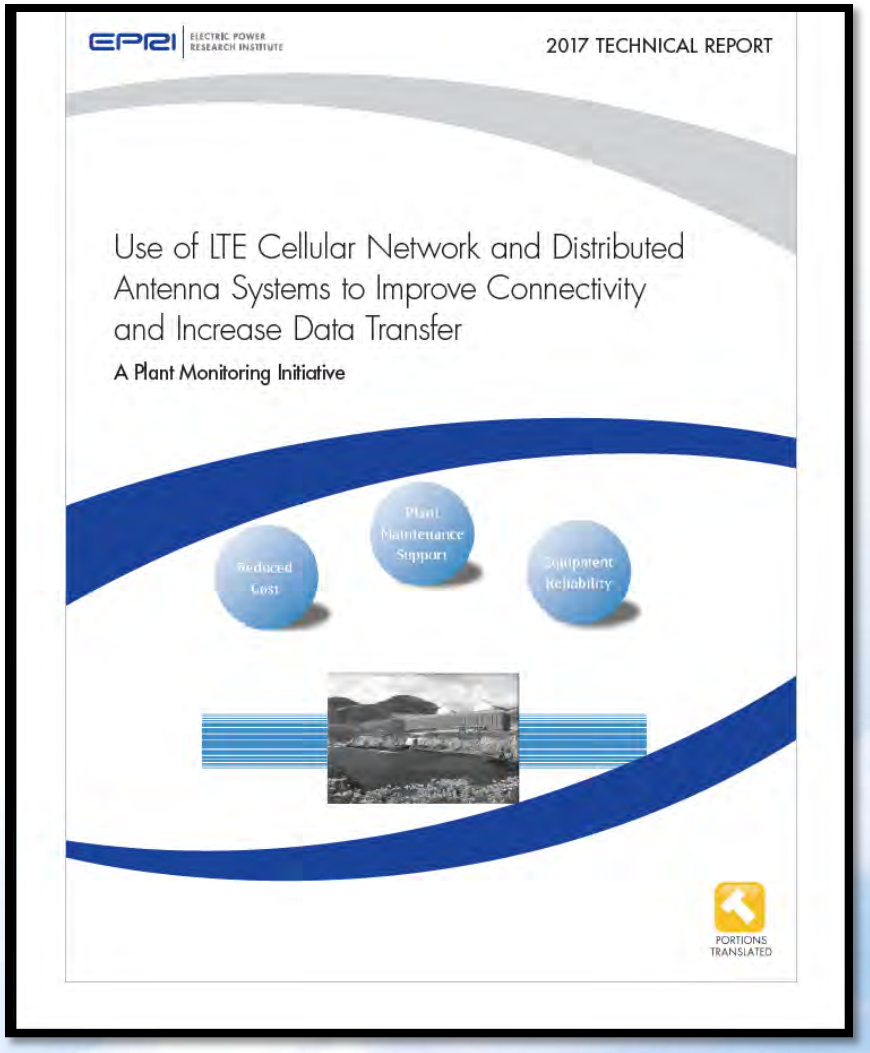
Regulatory aspects

- walkie-talkie radios, which typically use much higher transmission power, and operate at MHz frequency bands
- WSNs devices operate at much lower power level, and in the GHz frequency band
- WSN nodes can be safely placed
- There is a strong evidence that a modern WSN system can perform in a NPP, while satisfying the regulatory guidelines.
- However, all relevant regulatory aspects must be taken in the consideration for designing a WSN for a NPP

Distributed distributed antenna system: leaky cable







Signal strength test for different frequencies

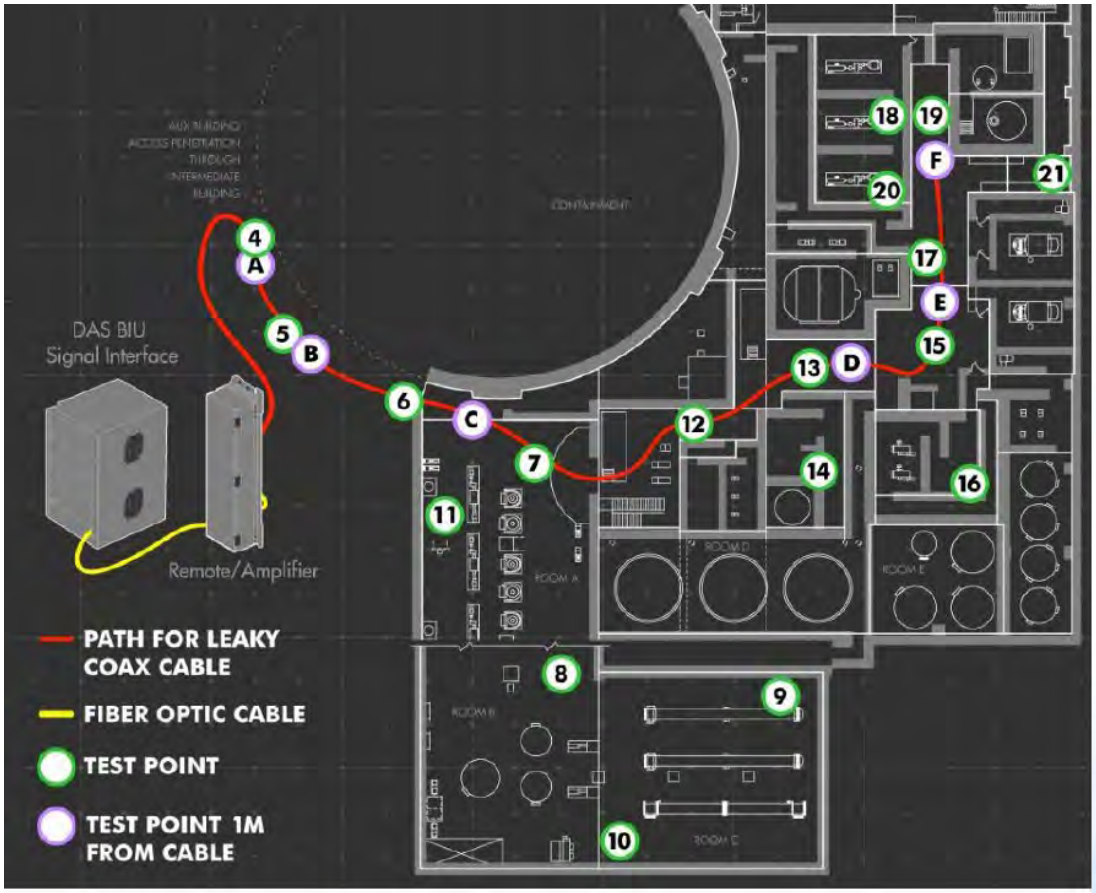


Figure 3-1
Test points collected in the Crystal River auxiliary building

Crystal River Nuclear Power Plant

Signal strengths at different frequencies

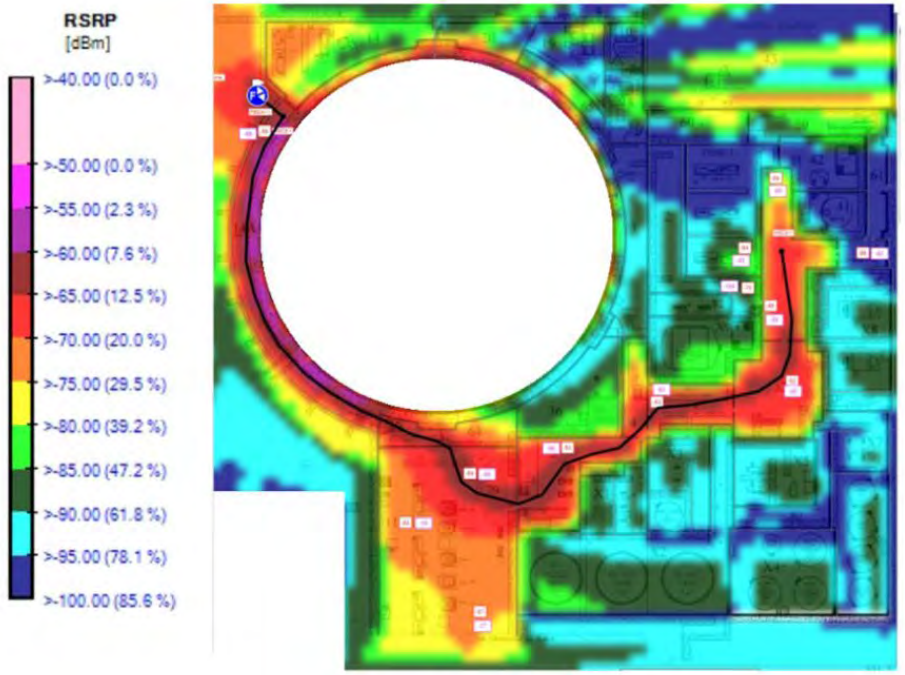


Figure 3-2
RSRP at 730 MHz in auxiliary building

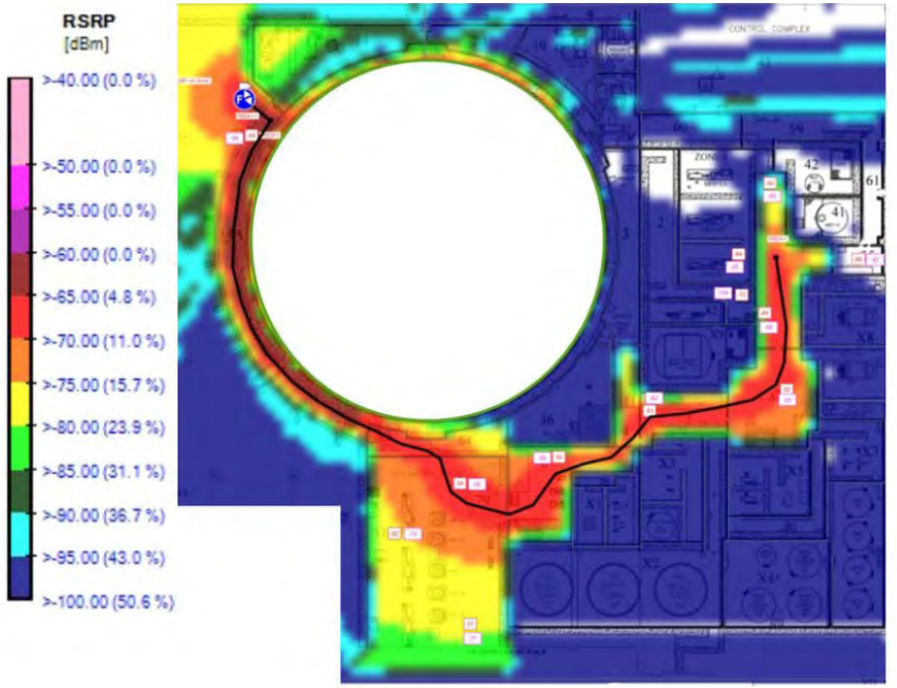


Figure 3-3
RSRP at 2130 MHz in auxiliary building

Reference Signal Received Power (RSRP) under different frequencies

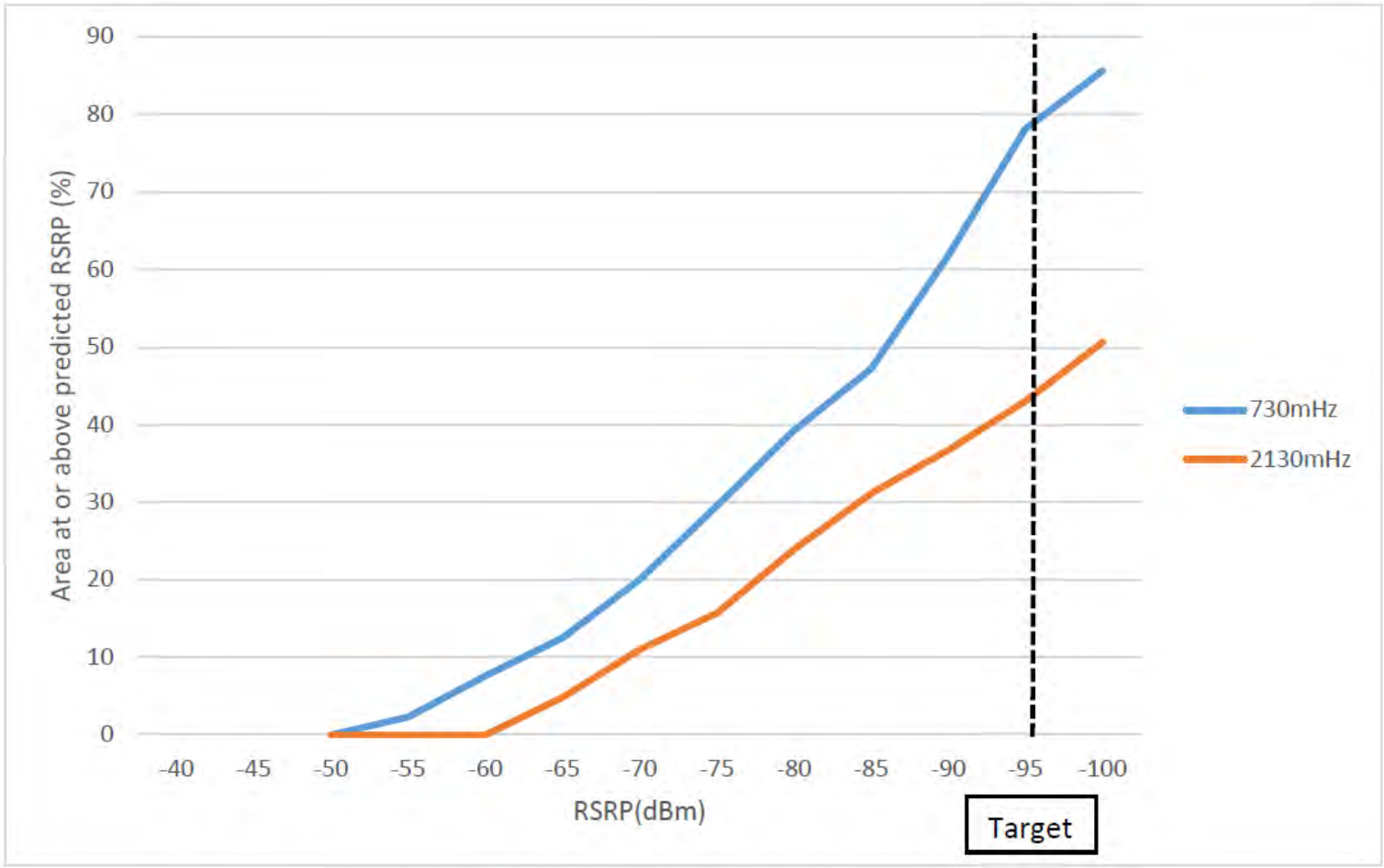
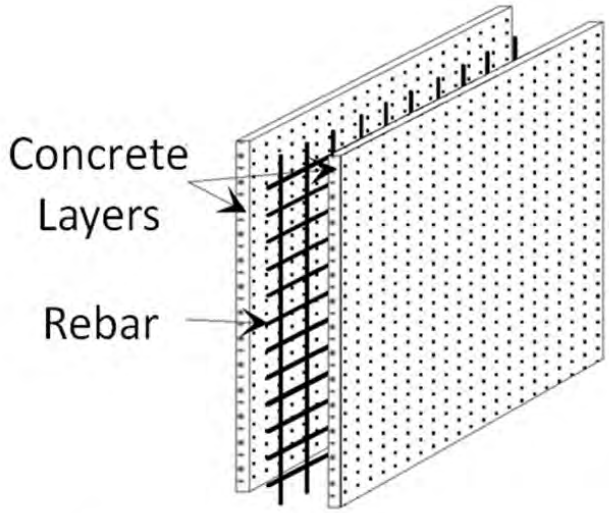


Figure 3-4
Comparison of RSRP coverage for both 730-MHz and 2130-MHz frequencies

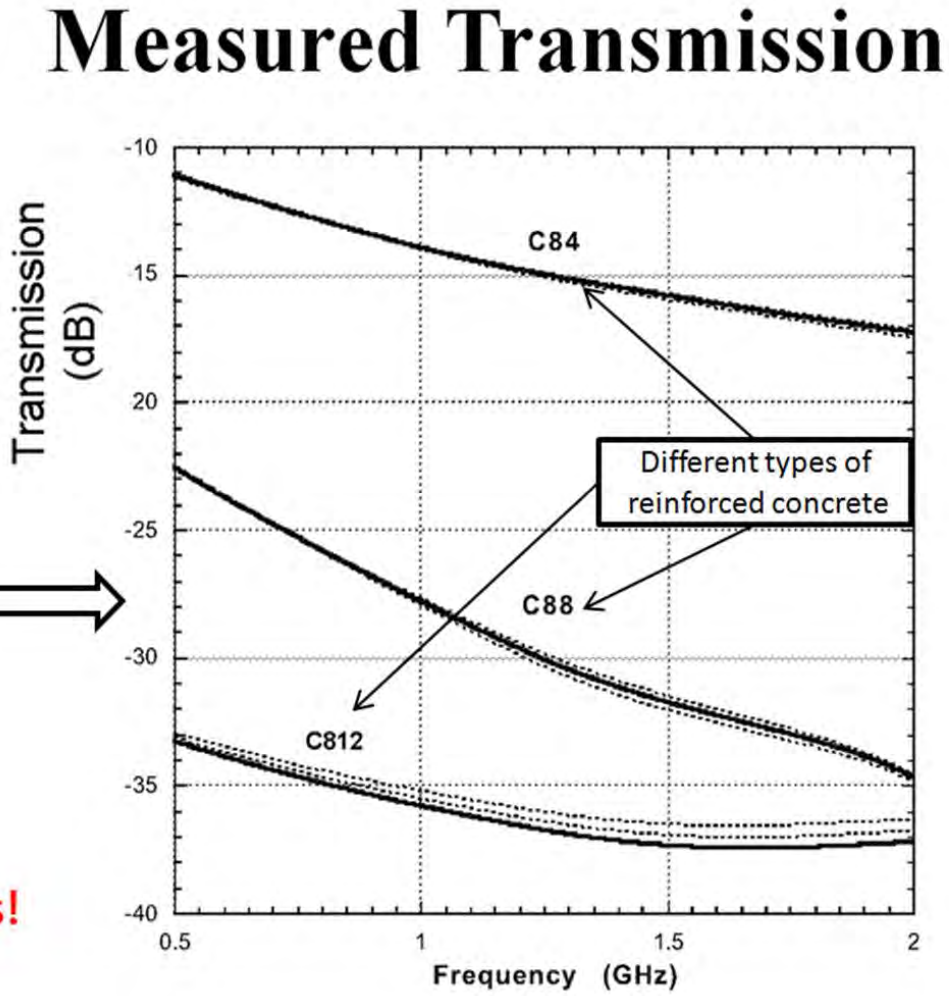
Wall Penetration capability of wireless signals at different frequencies.



Concrete Example

Trend is clear: More dB's penetrate at 0.312 GHz (i.e., 312 MHz) compared to 2 GHz.

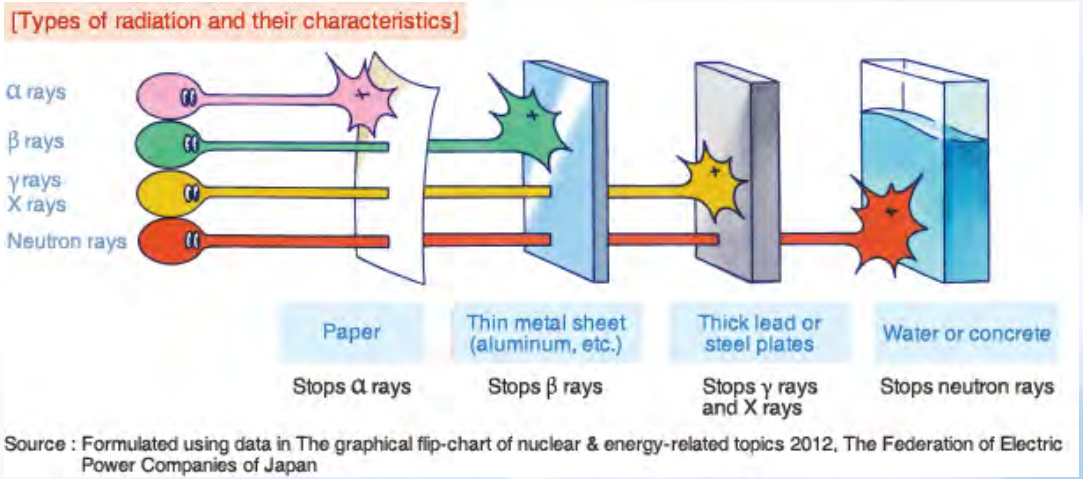
Each 3 dB drop = a 50% power loss!



https://blog.tel-tron.com/2010/06/03/why-312-mhz-kicks-butt-for-senior-living-emergency-call-systems/

Radiation Damage to Electronics

- **Electronic components on board WSN nodes must be able to withstand ionizing radiation**
  - Radiation resistance is one essential requirement for WSN to be used in an NPP
- **Radiation resistance of the WSN node needs to be designed with consideration to**
  - The type of radiation (alpha, beta, gamma rays, neutron)
  - Normal conditions
  - Accident conditions



Source : Formulated using data in The graphical flip-chart of nuclear & energy-related topics 2012, The Federation of Electric Power Companies of Japan

Image source: http://hamaoka.chuden.jp/english/resource/radioactivity/aspect_img_03.jpg

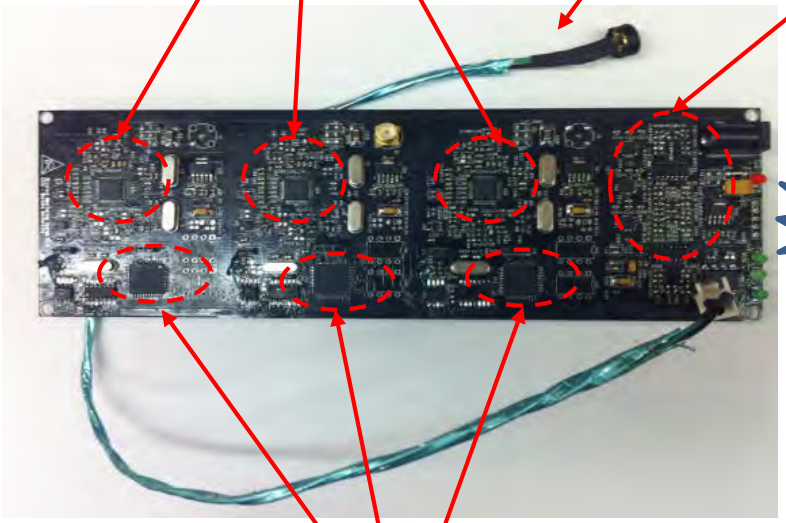
Wireless Monitoring System

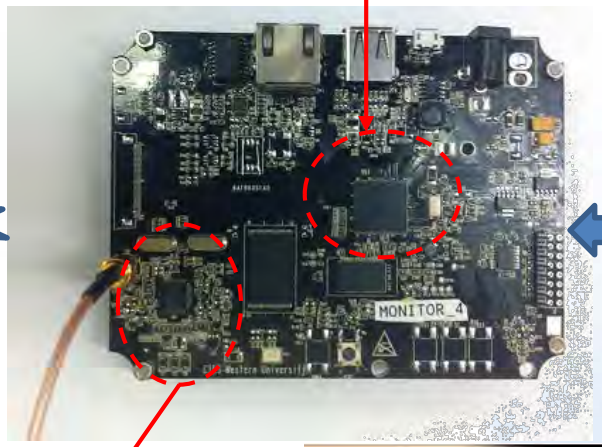
RF Circuits

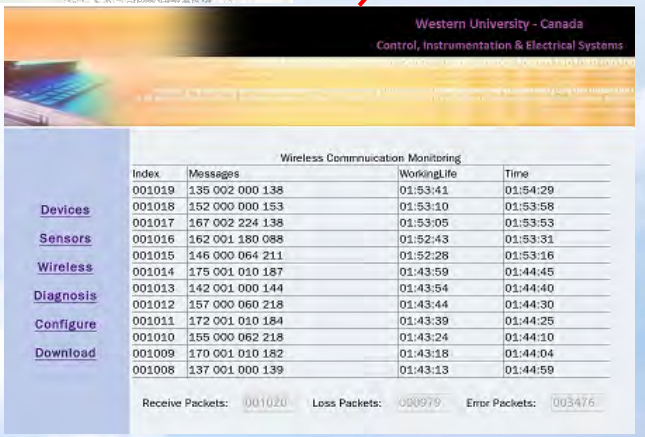
Analog-Digital

Humidity Sensor

Microprocessor



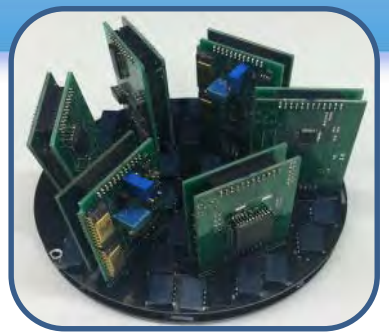




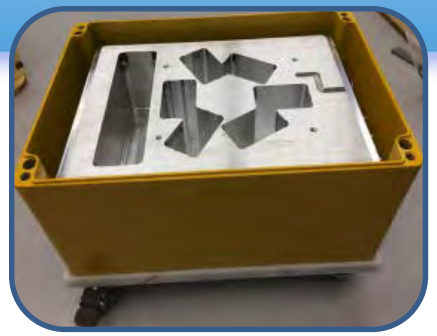
Microcontroller

RF Circuits

A Wireless devices for high level of radiation



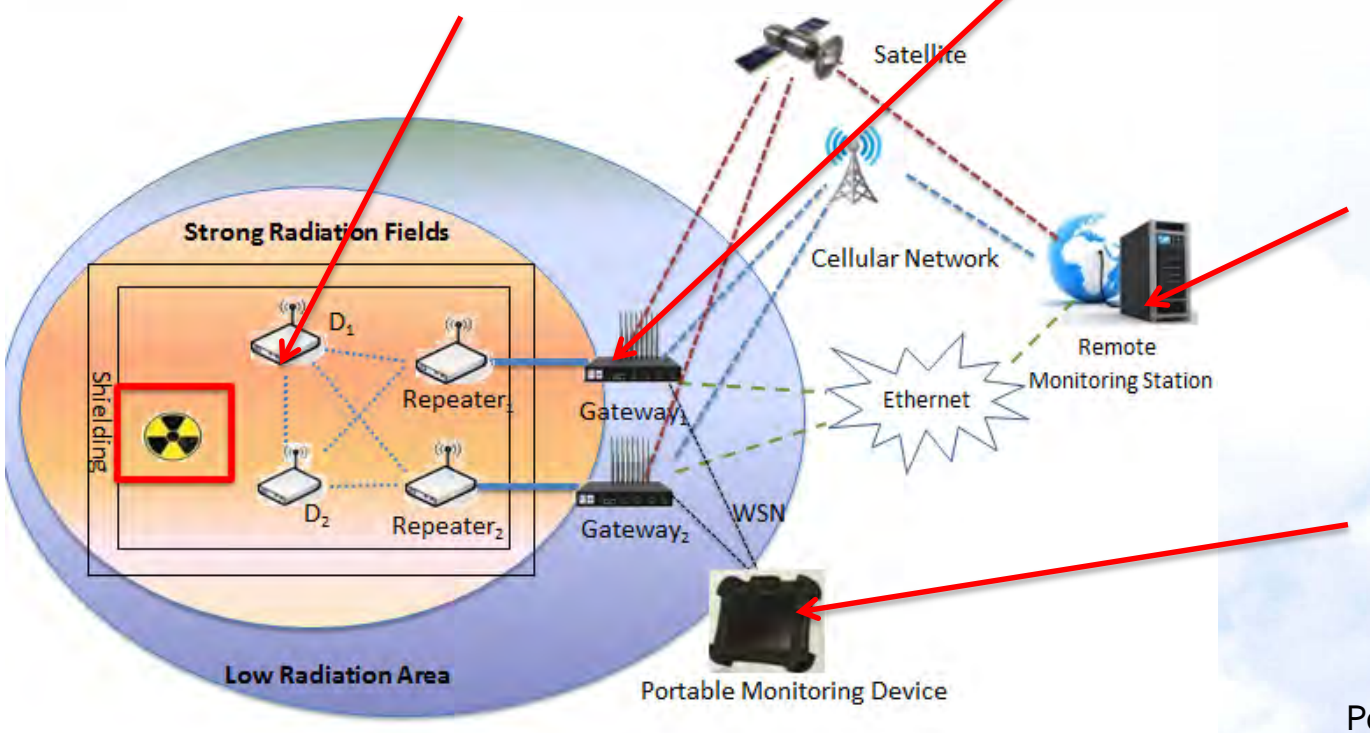
Measurement and Transmission Unit



Shielding Protection

Gateway

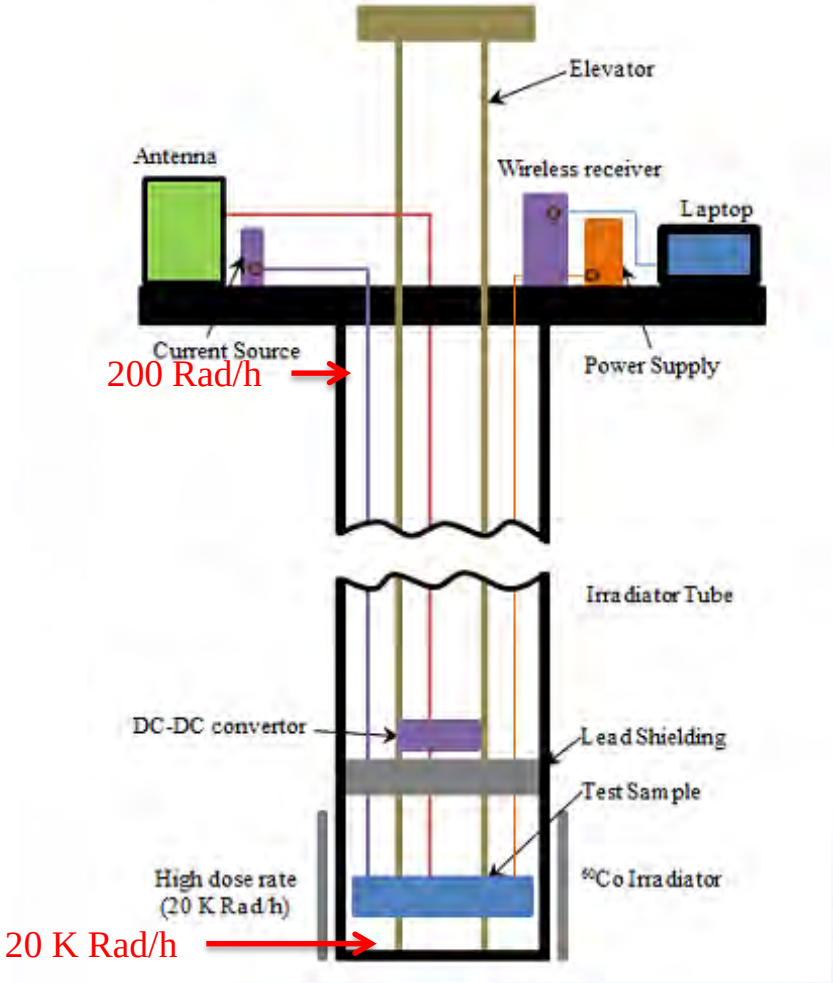
Gateway Protection



Remote Monitoring Station

Portable Monitoring Device

Experimental Approaches

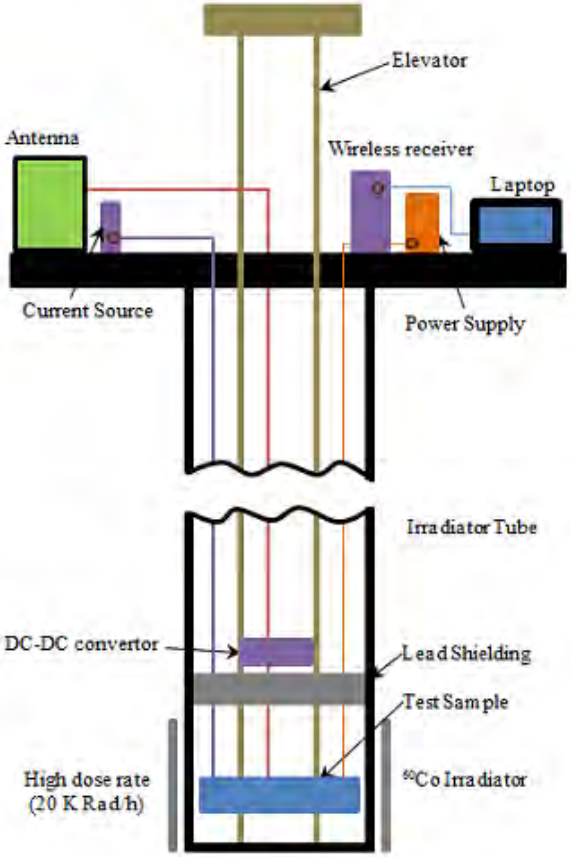


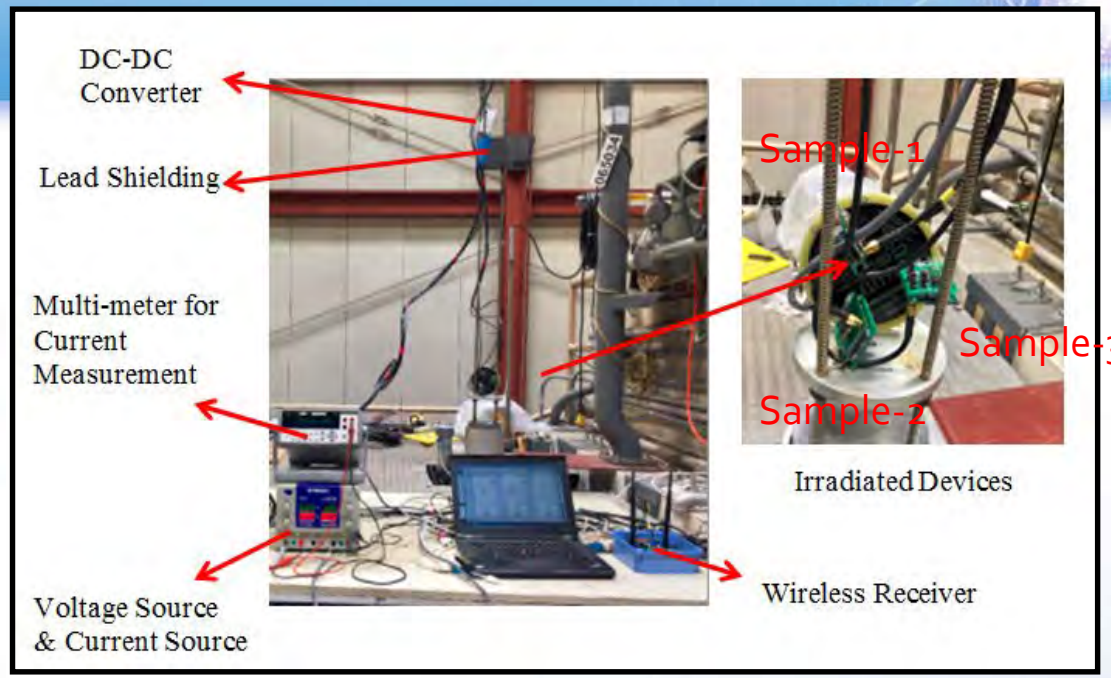
- **Radiation Resistance**
  - The lifespan defined that each unit has a functional failure under the condition of dose rate.
- **Communication Performance**
  - Error packet rate, loss packet rate, etc.
- **Wireless Signal quality**
  - Frequency shift, RSSI, etc.

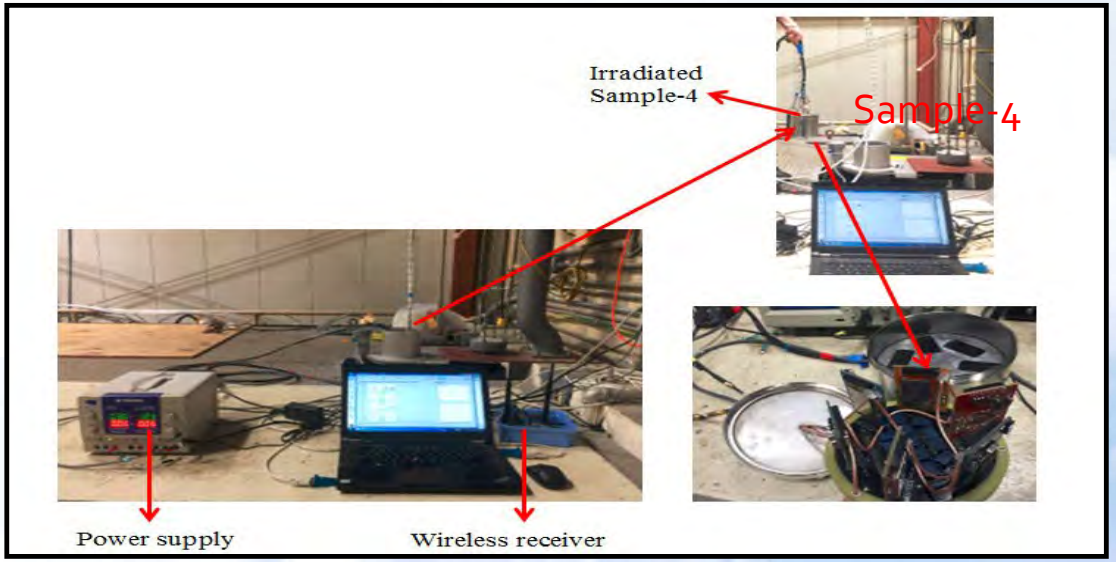
Irradiated Samples

Type	Parameter	Sample-1	Sample-2	Sample-3	Sample-4
Wireless parameter	Frequency	915 MHz	433 MHz	433 MHz	433MHz & 915MHz
Semiconductor technology	Analog signal processing circuit	Bipolar	CMOS, BiCMOS	BiFET, BiCMOS	Redundant design
	Analog-to-digit converter	Bipolar	CMOS	LCCMOS	
	Microcontroller	CMOS	CMOS	CMOS	
	Wireless transceiver	Bipolar	CMOS	CMOS	

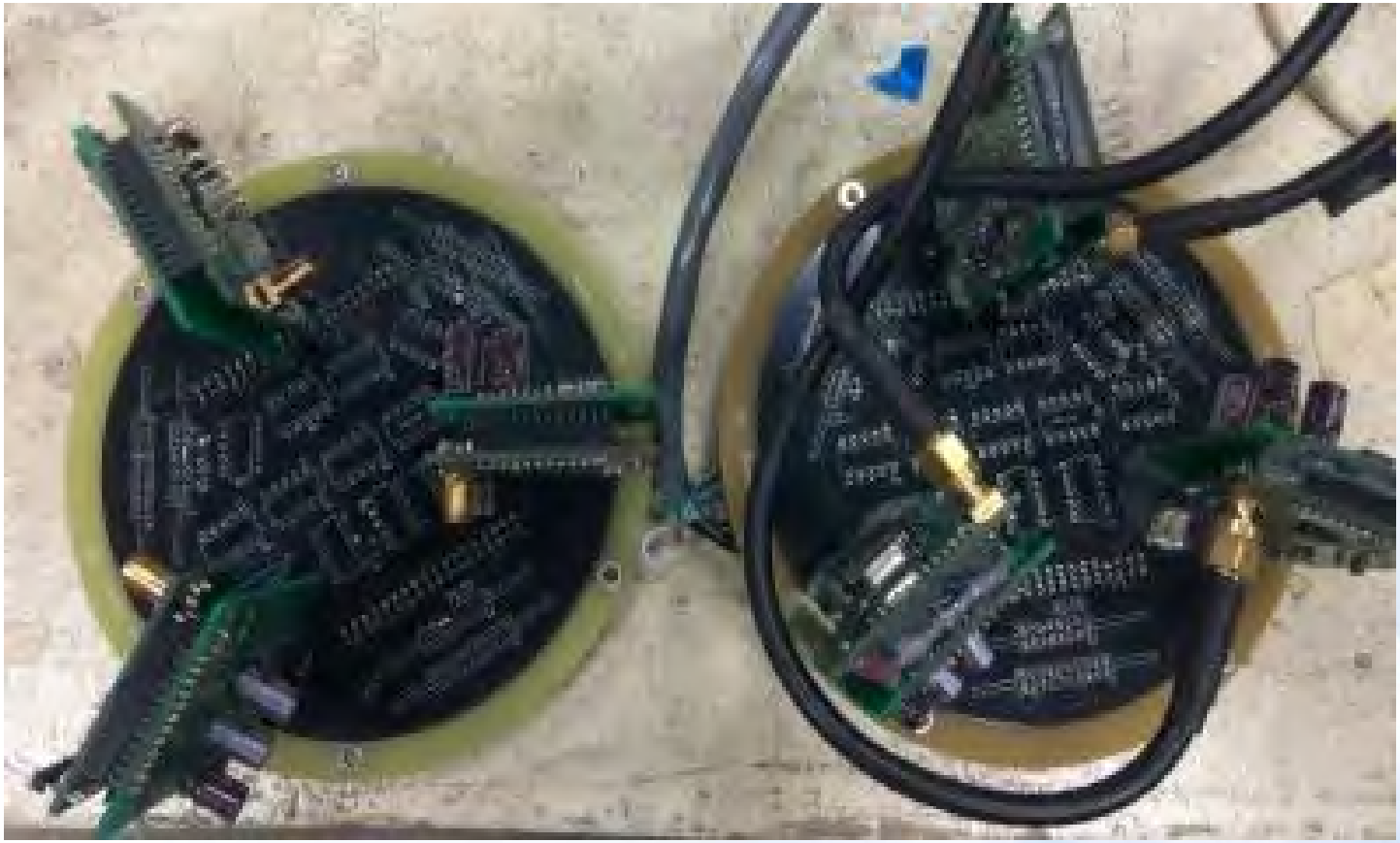
Experimental Setup







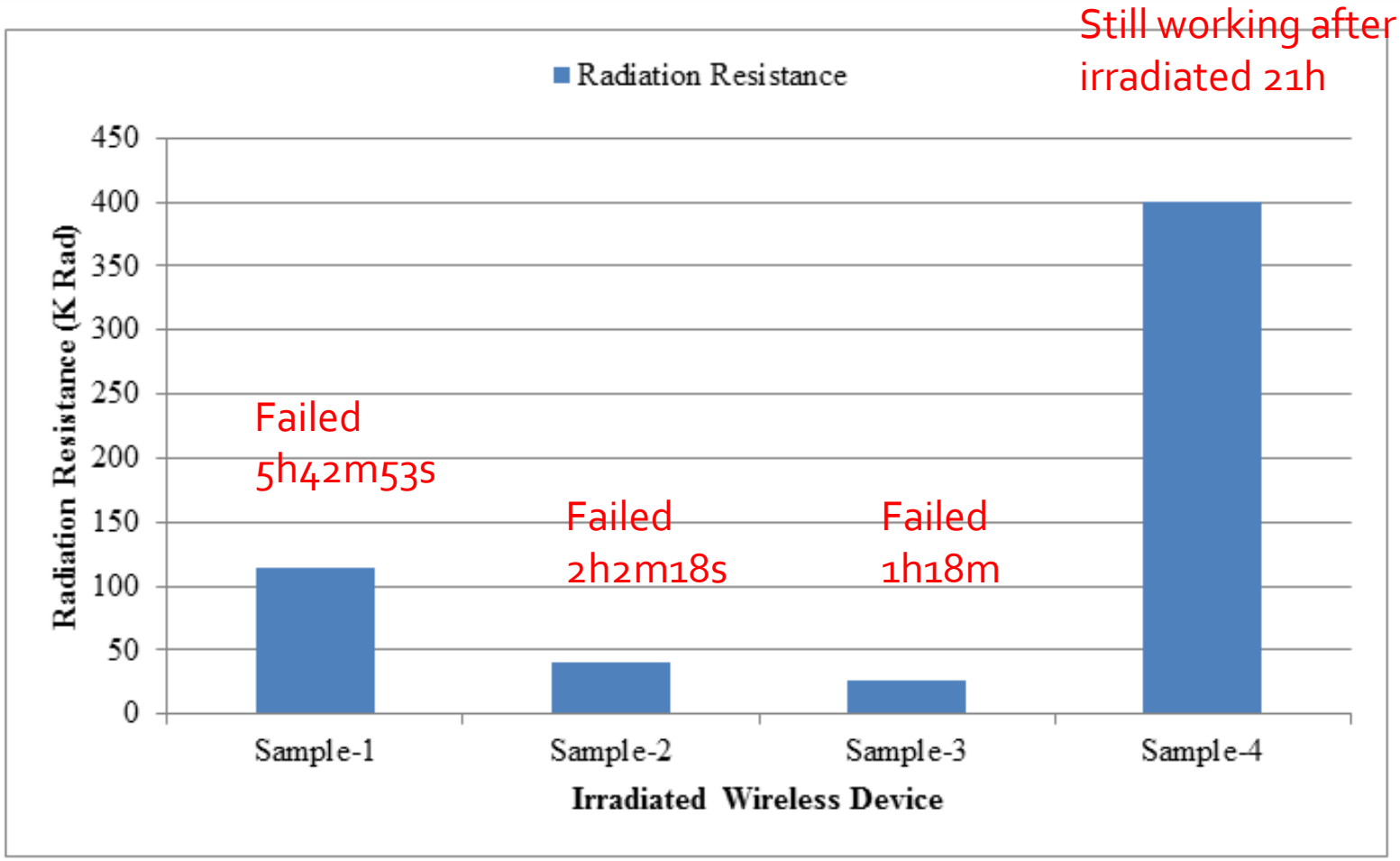
Experimental Results



Before-irradiated

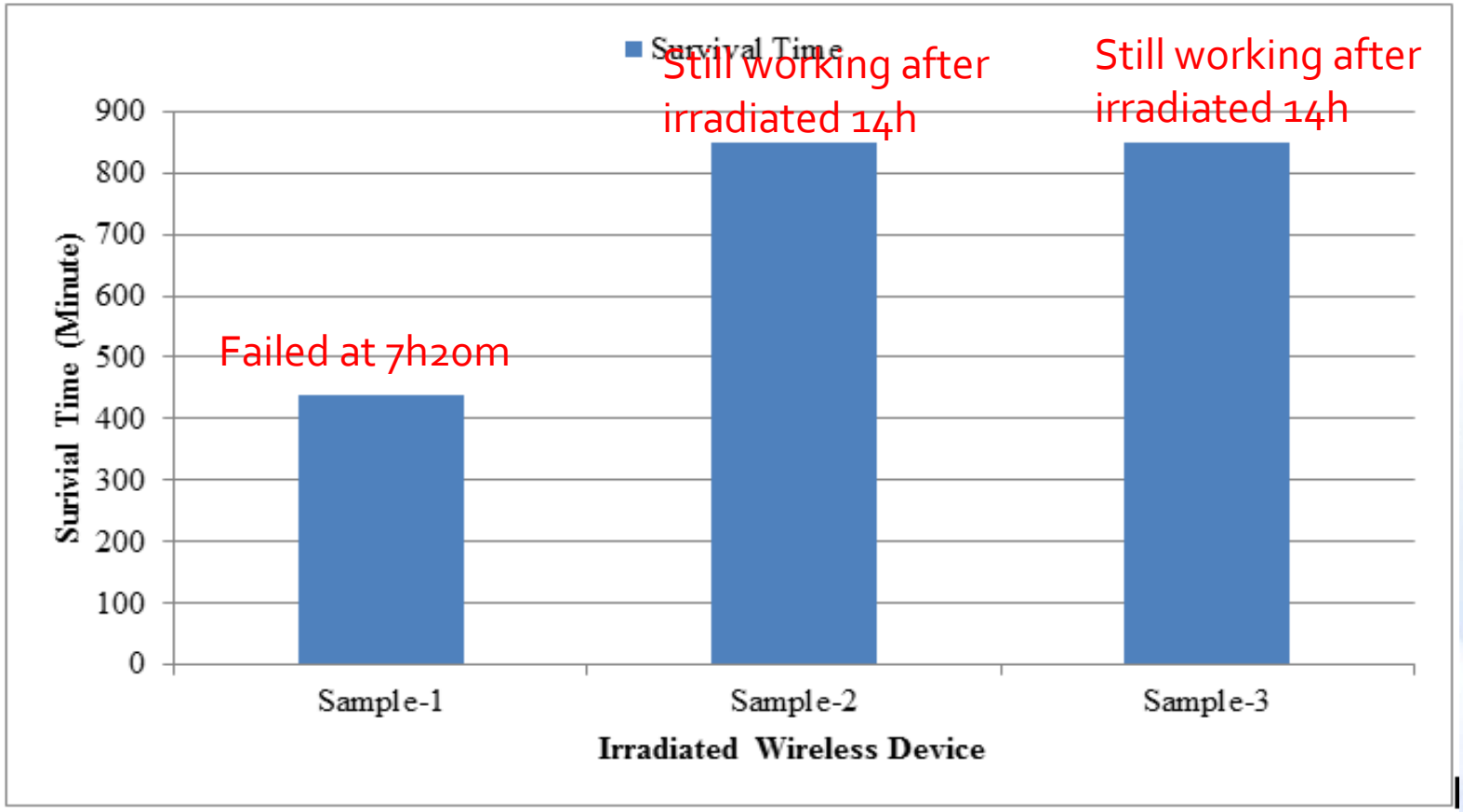
After-irradiated for 20 hours

Experimental Results (Radiation Resistance)



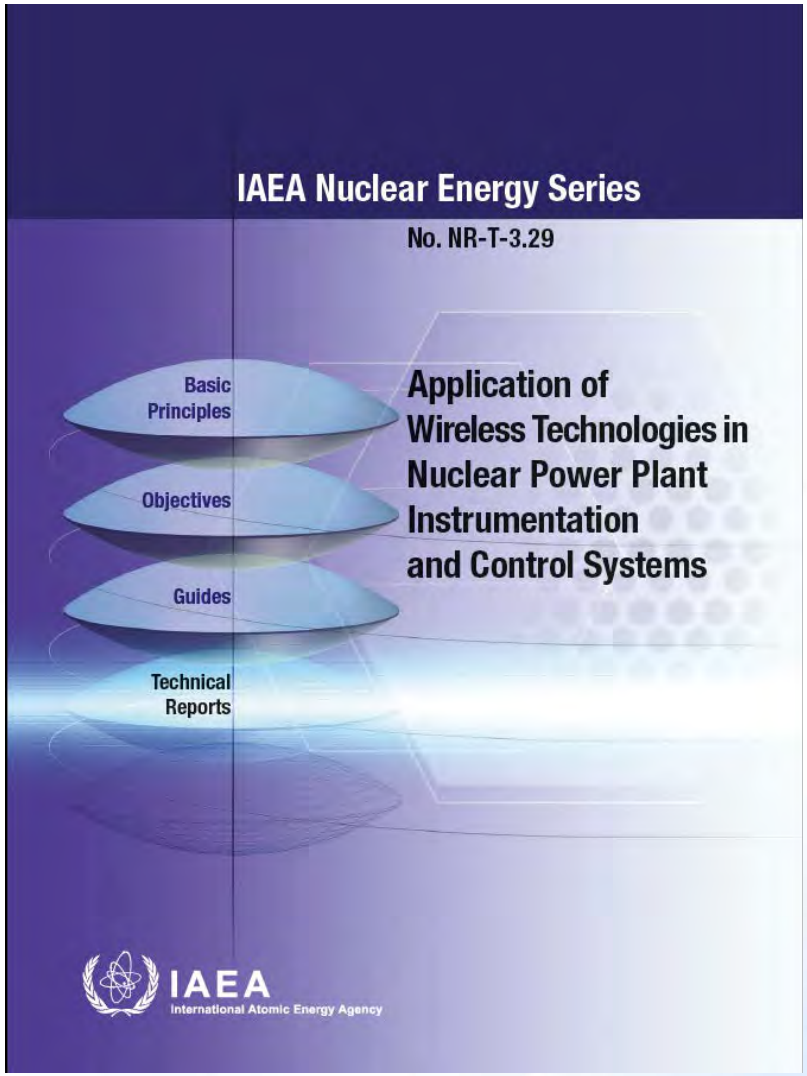
Comparison of radiation resistances of wireless devices under a high dose rate condition (20 K Rad/h)

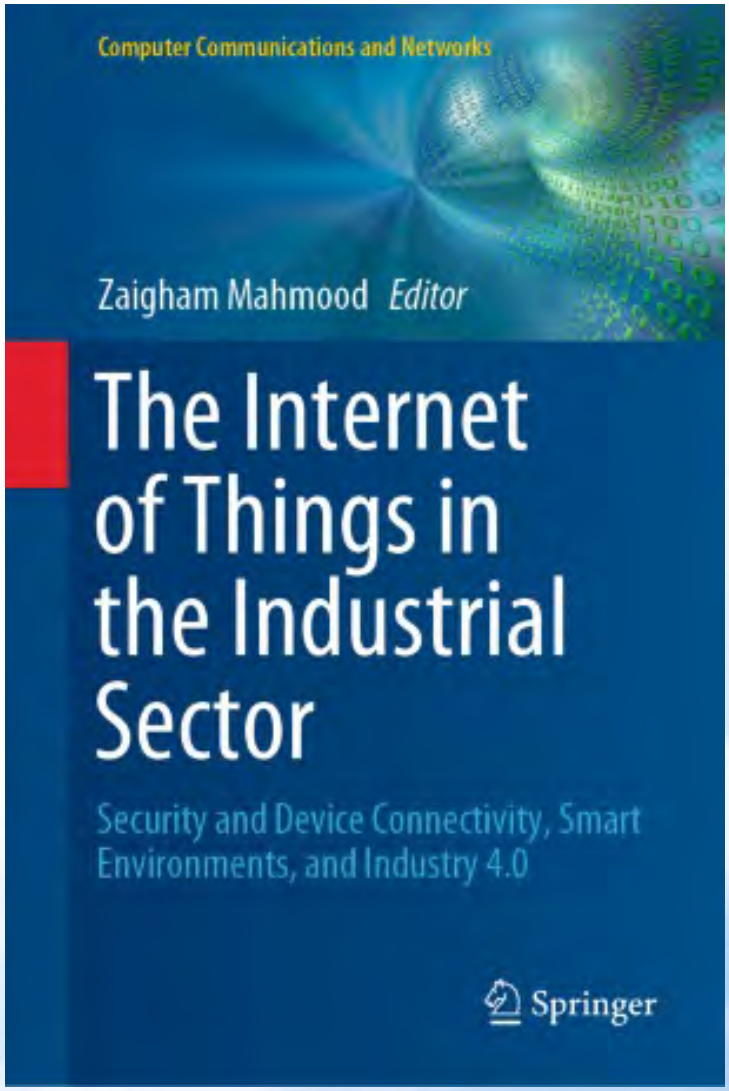
Experimental Results (Radiation Resistance)



Comparison of radiation resistances of wireless devices under a low dose rate condition (200 Rad/h)

Many Resources are available





Conclusions

- WSNs in NPPs has attracted significant interests for NPP applications.
- A WSN system can offer several benefits to the monitoring applications in a NPP.
- Several challenges need to addressed.
- Distributed antenna (leaky cable) seem to be an effective way to connect many devices together.
- Many wireless (such as WiFi based) systems have been installed in nuclear facilities.

Thank you for your attention!

감사합니다