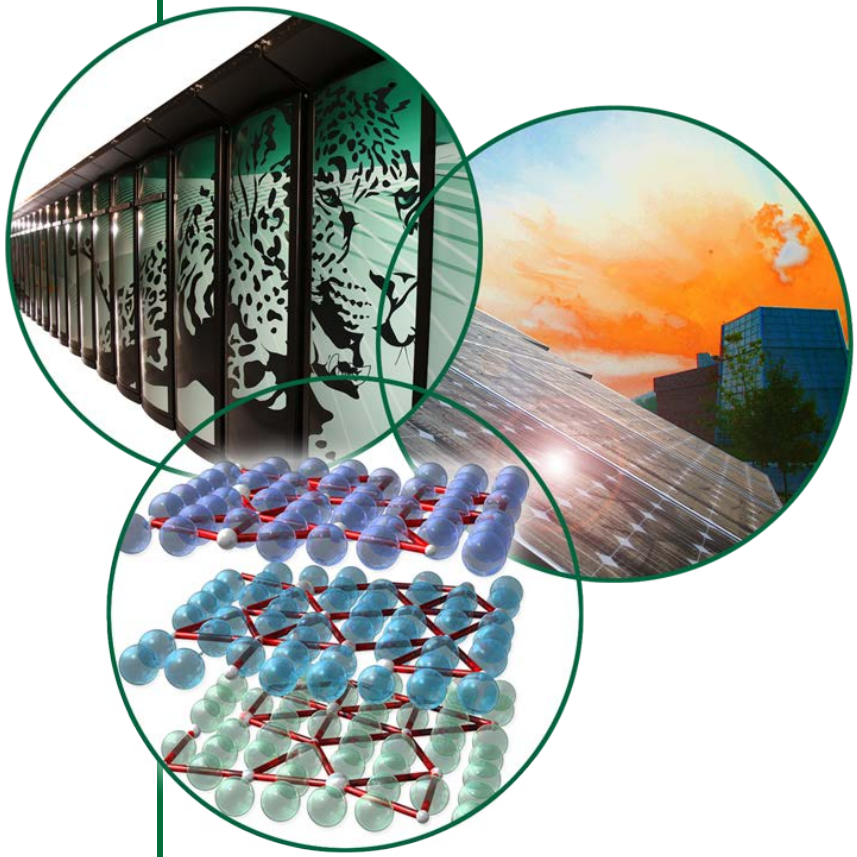
Industrial Wireless Sensor Networks

Stephen Smith
Teja Kuruganti
Wayne Manges
Tim McIntyre



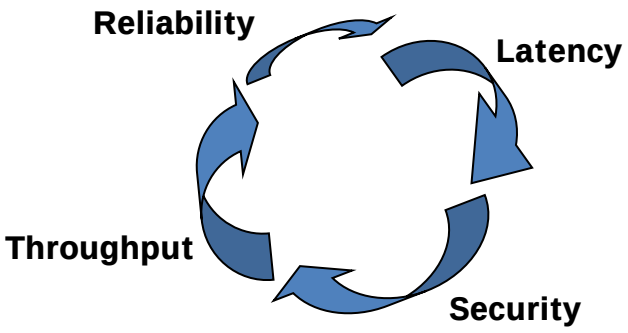
U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Wireless Industrial Sensor Networks

Wireless Enables Ubiquitous Sensing

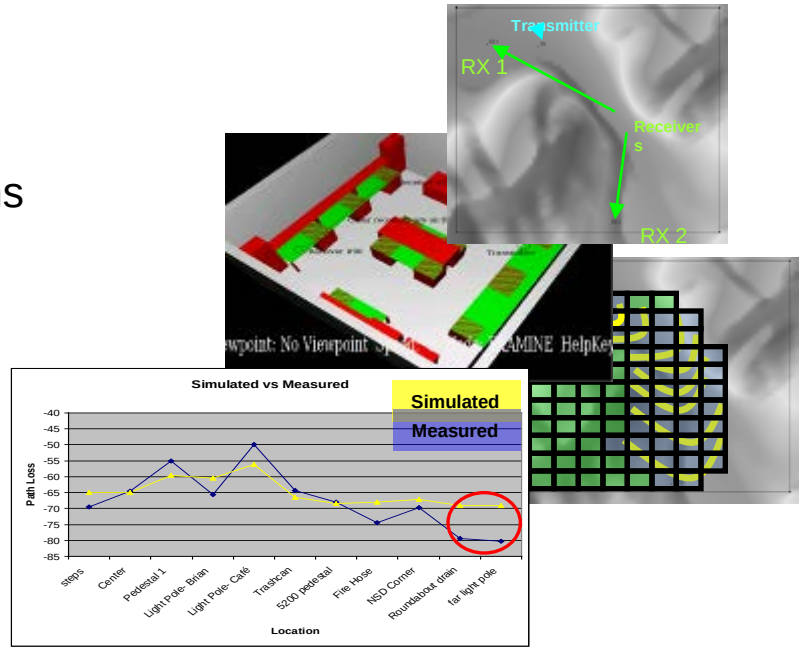
- National Research Council – “advanced wireless sensors” identified as a critical research need.
- President’s Committee of Advisors on Science and Technology – “wireless sensors can improve efficiency by 10% and cut emissions by more than 25%”
- Industrial Wireless Workshop – trade throughput for reliability
- DOE Industrial Wireless Program

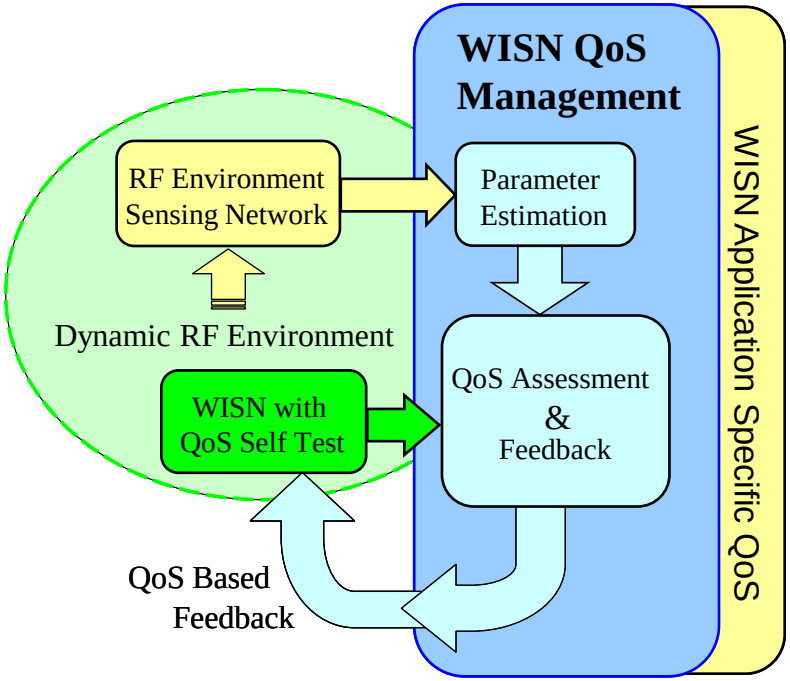


- The four parameters are non-orthogonal
- Deployment demands performance
- Understanding environment is the key
- Wireless – radio, packaging, antenna
- Industrial – harsh, fault tolerant, safety related, cost
- Sensor – filters, sampling, sensitivity, interferers, controls
- Networks – real-time, latency, throughput, security, integrity, vertical integration

“Engineered” vs. “Can you hear me now?!!”

- RF channel is dynamic and time-varying
- Fast site-specific radio channel path-loss data for use in wireless network simulations
- Robust channel models can be created
- Characterize common environmental elements among data centers



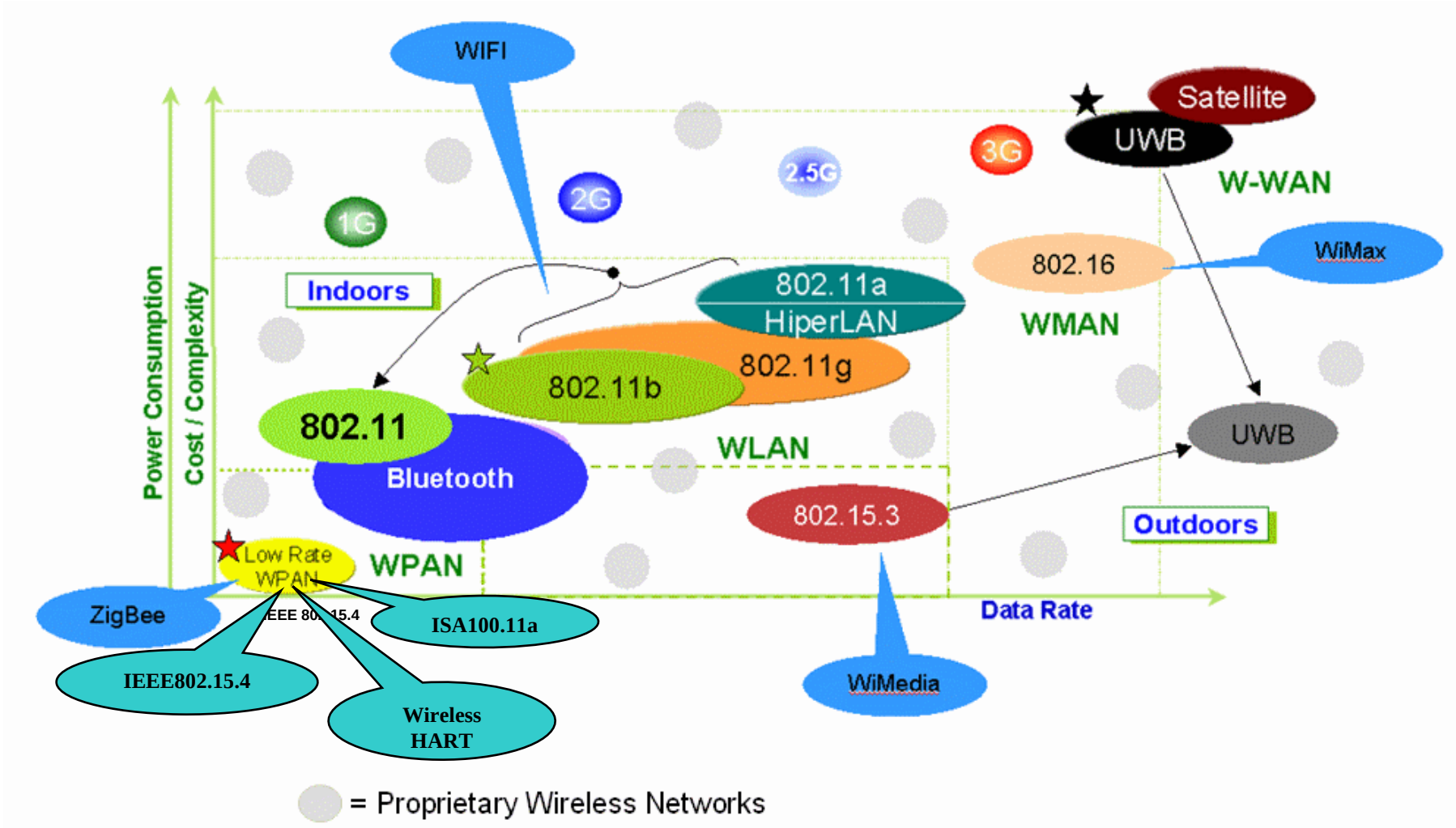


- Closed-loop control requires deterministic quality of service
- Robust channel models will help develop novel estimation techniques for stable controls

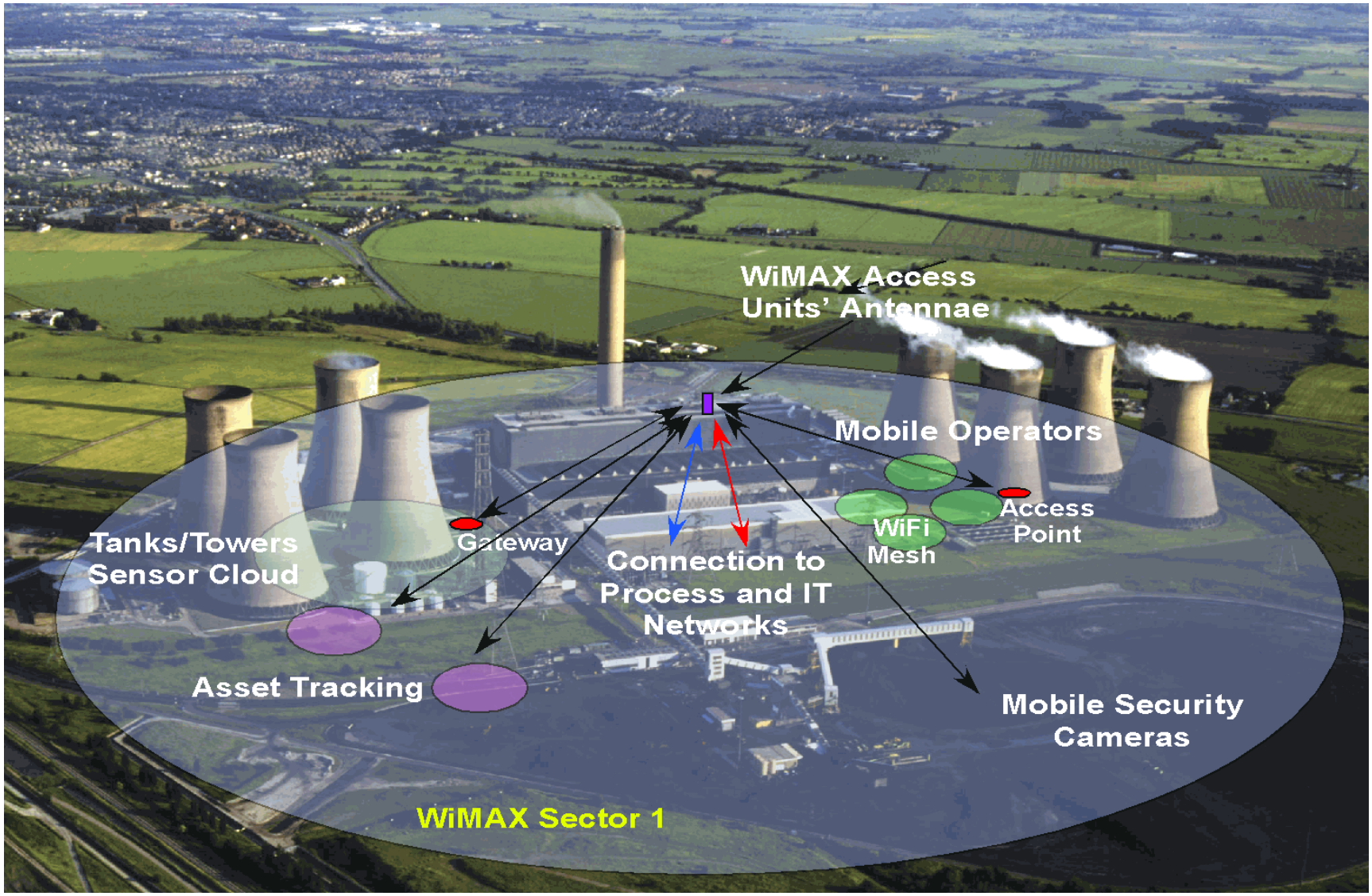
Thrust Areas for Advanced Wireless Communications R&D at ORNL

- **Robust communication systems** – improving the robustness and reliability of communication systems by developing advanced signal processing techniques in the areas of spread-spectrum modulation, space-time coding, iterative error-correcting decoding, interference cancellation, bandwidth-efficient modulation, and rapid synchronization
- **Cognitive communications** – allows communications mode to adapt based on local knowledge of the environment and adequate decision-making processes
- **Ubiquitous wireless sensor/actuator networks** – enables a pervasive and ubiquitous communications (monitoring and control) presence by addressing key issues like self organization, seamless integration, security, scalability, mobility, and energy constraints
- **Bio-inspired communications** – building micro- and nano-scale communication systems that take advantage of the computational and organizational strategies used by biological organisms to solve complex problems in real time

The Wireless Landscape

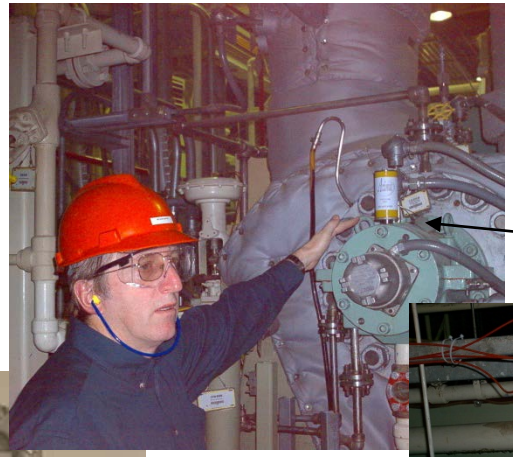


Industrial Wireless: A Network of Networks

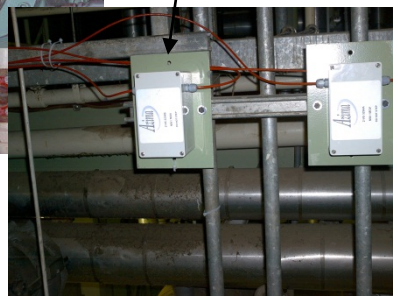


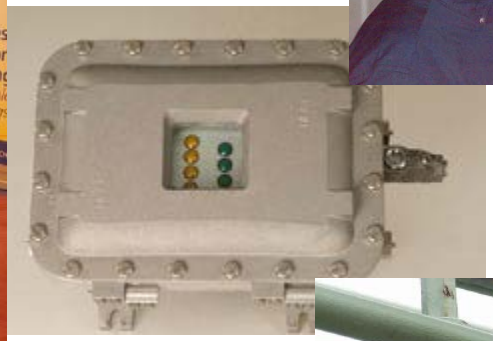
Co-resident Wireless Systems

Early Adopters – Blazing the Wireless Trail!



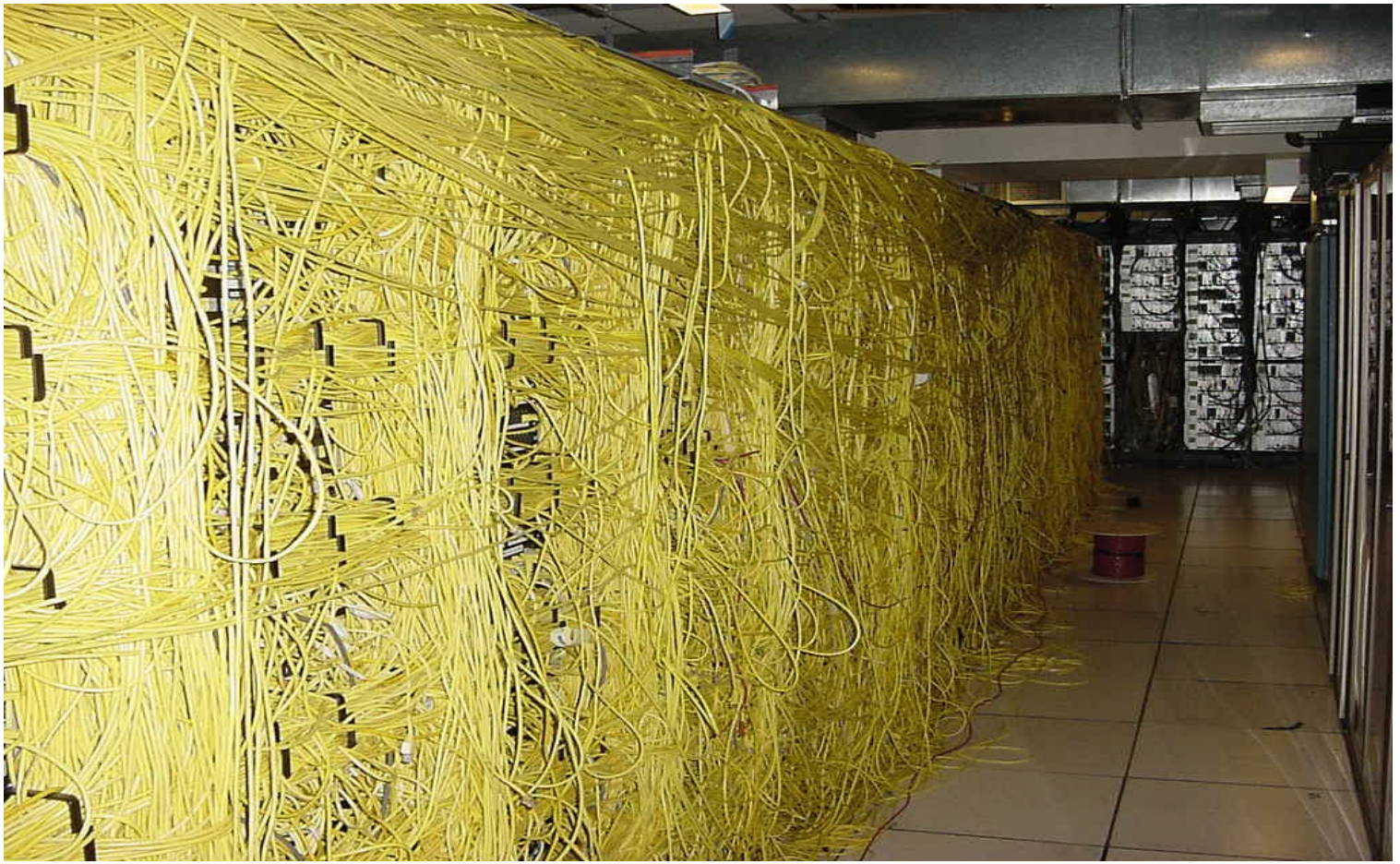
Wireless Vibration Sensor





Why Develop a Global Industrial Wireless Standard?

Because I always know where my signals are going!



Why Develop a Global Industrial Wireless Standard?

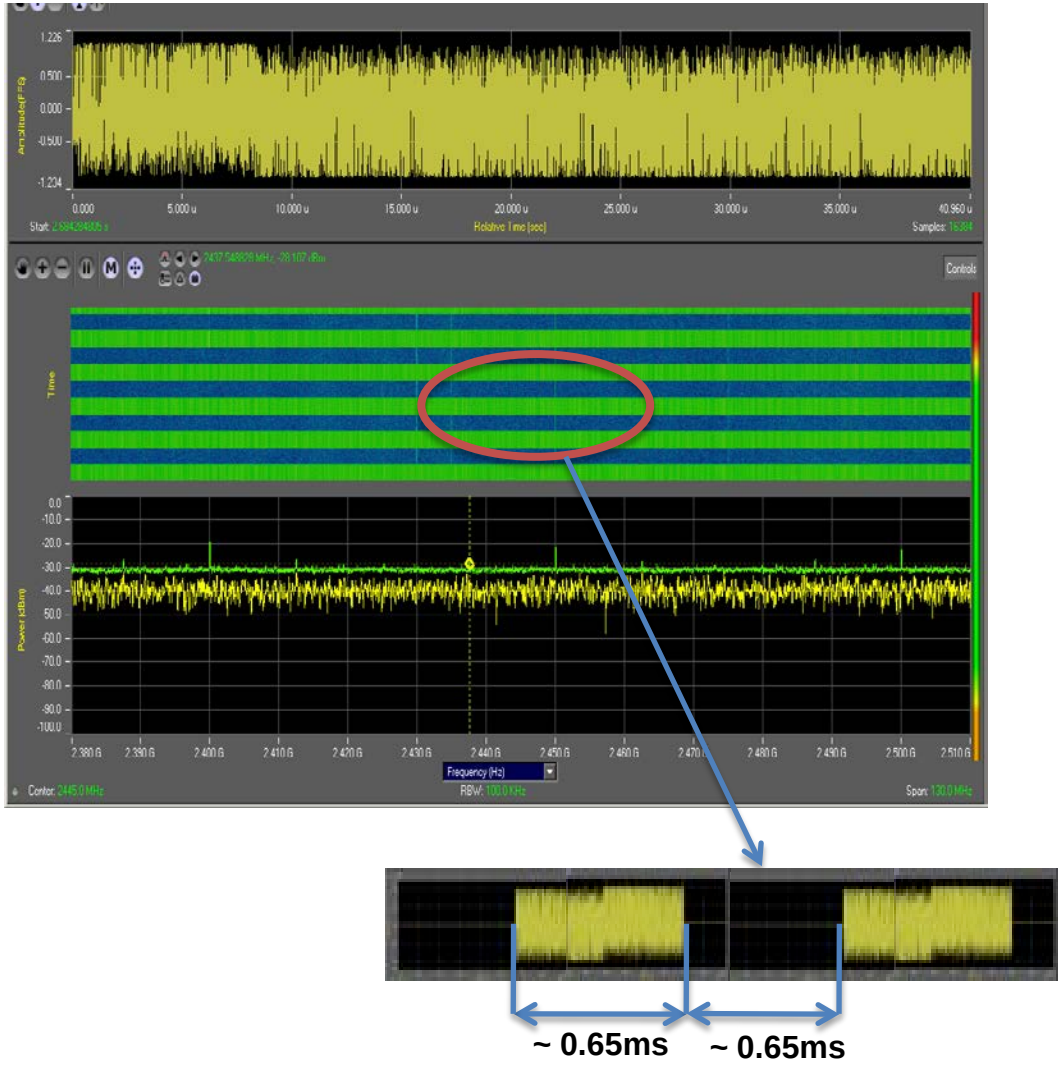
Because somebody will always invent an adapter!

What is ISA100?

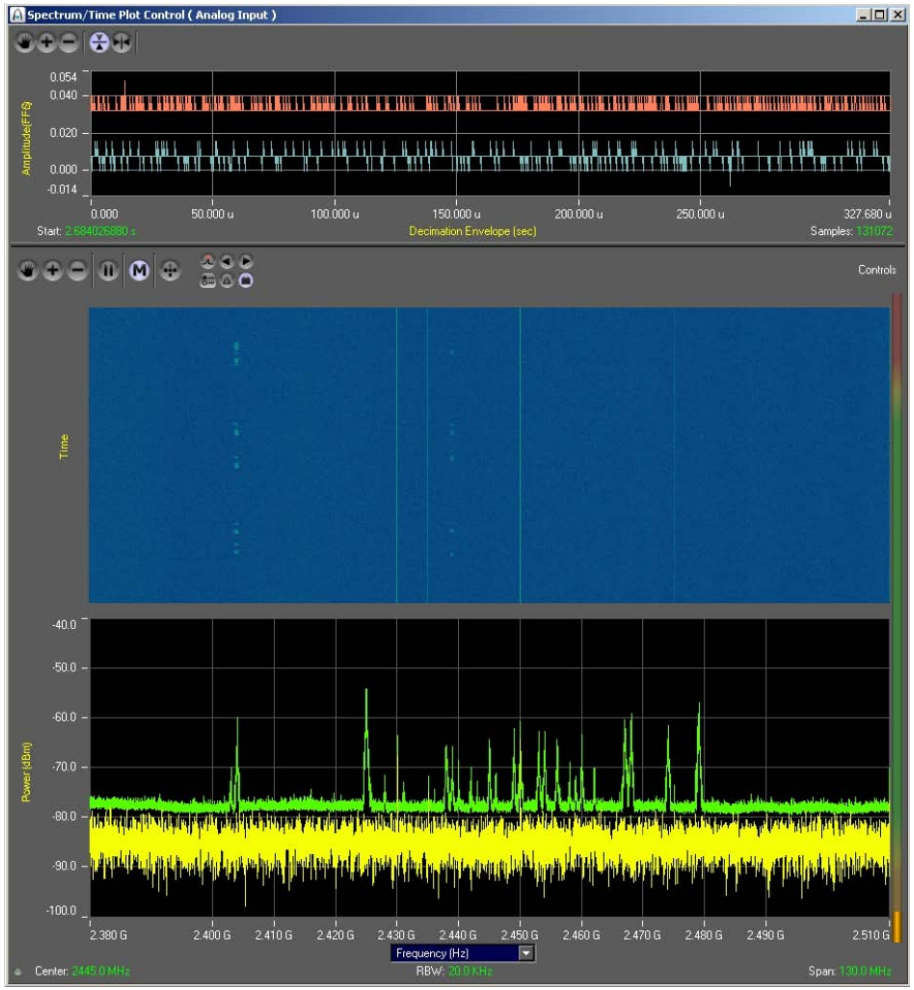
Family of standards designed from the ground up for many industrial wireless applications

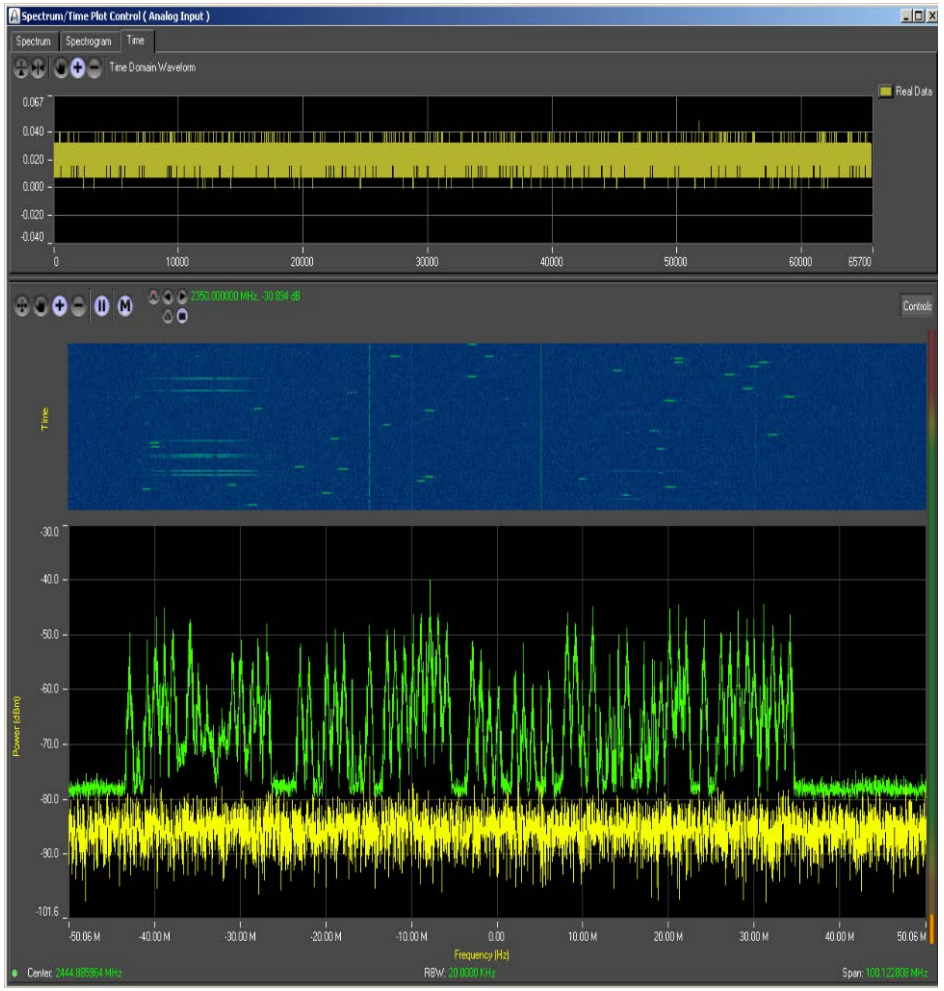
ISA100 Family of Standards:
One-Stop Standardization Designed to Accommodate all Your Plant Needs

Interference: Broadband high- powered

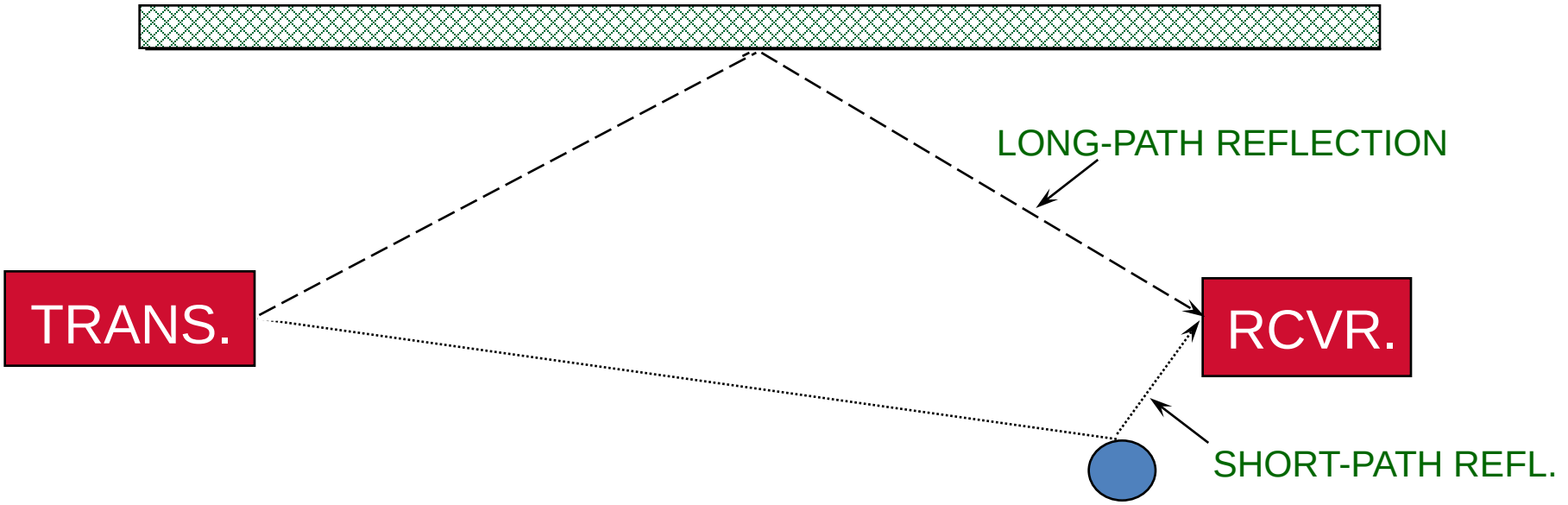


More interference: ambient channel noise





Multipath Interference

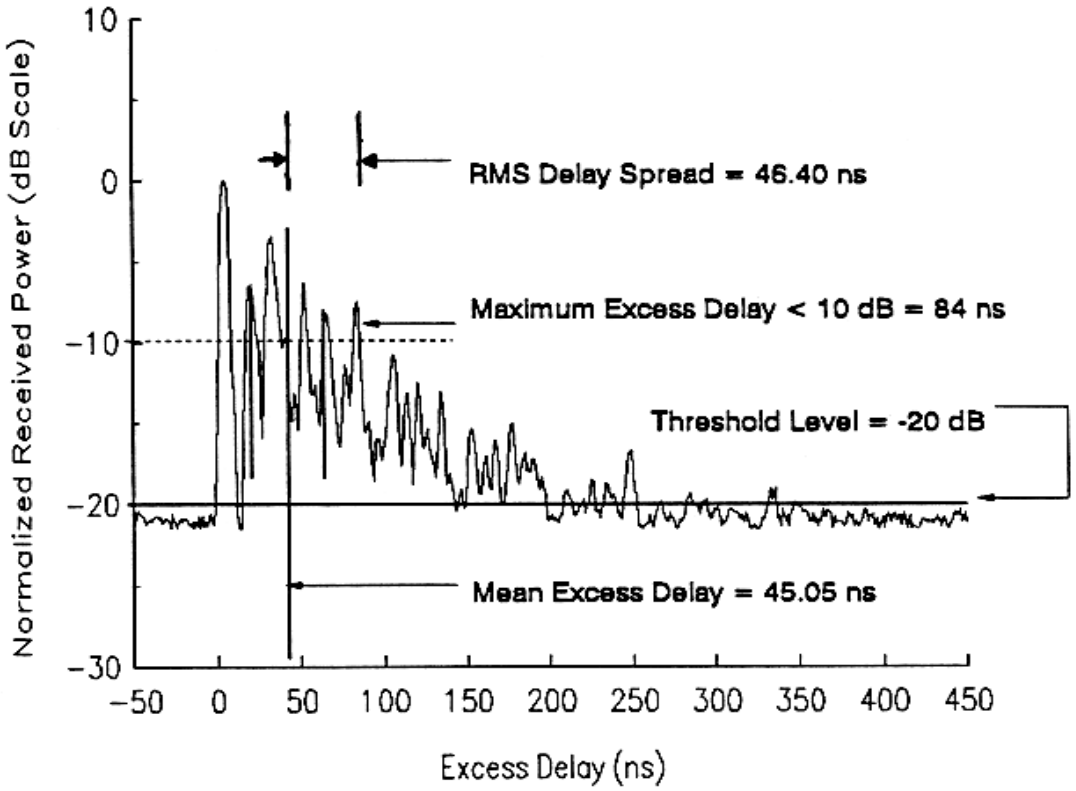


Differential delays are approx. 1 ns per foot

Short-path delays (indoors) are typically $< 0.1\mu s$

HSS Spread-spectrum modulation can largely cancel long-path effects

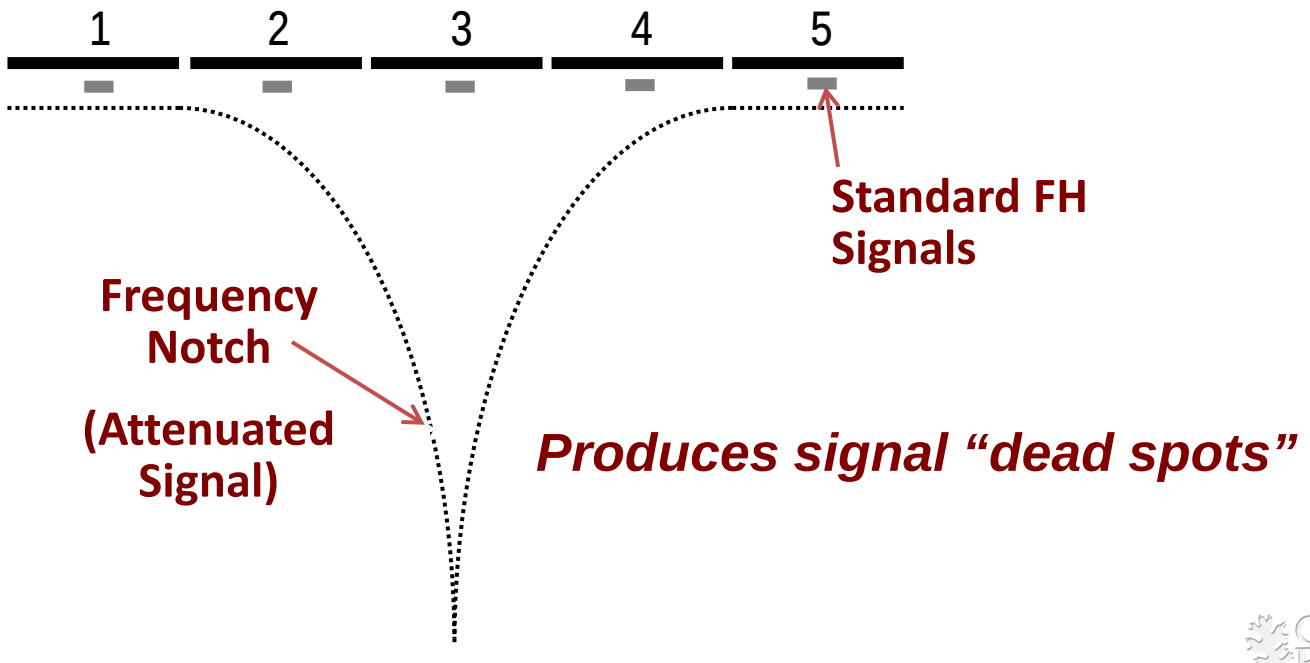
Time-Domain Representation



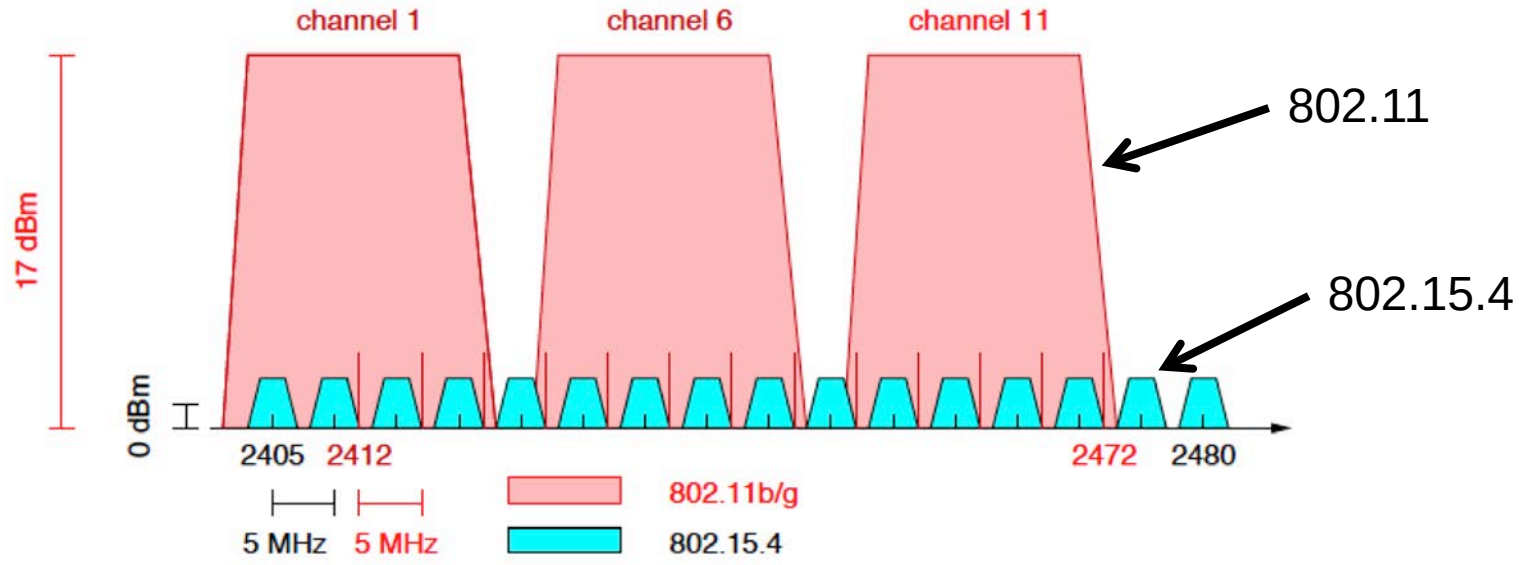
Typical indoor (large room) multipath delay profile.

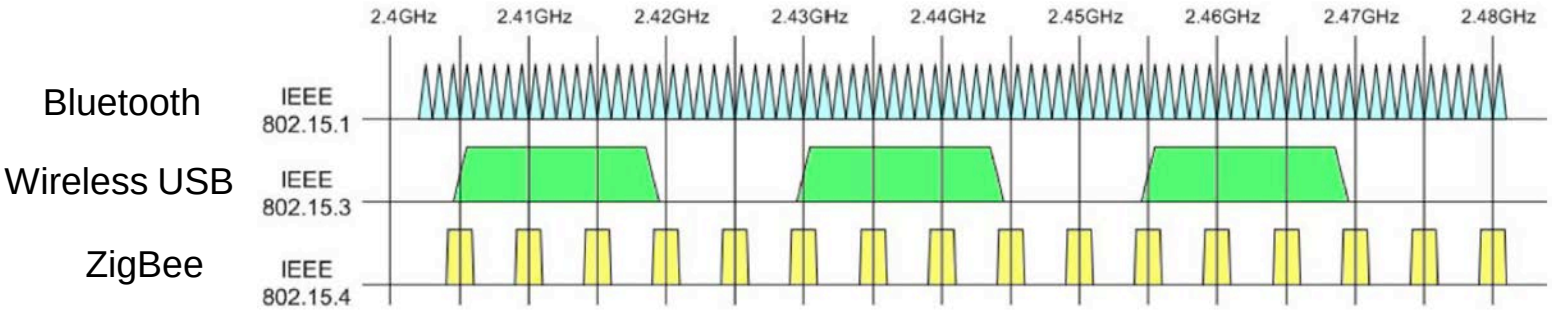
Frequency-Domain Effect of Multipath

Vector cancellations due to multiple paths (some out-of-phase) result in signal "notches" at specific frequencies as determined by dimensions of RF-reflective environment.



Close-Up on 2.45-GHz ISM Band



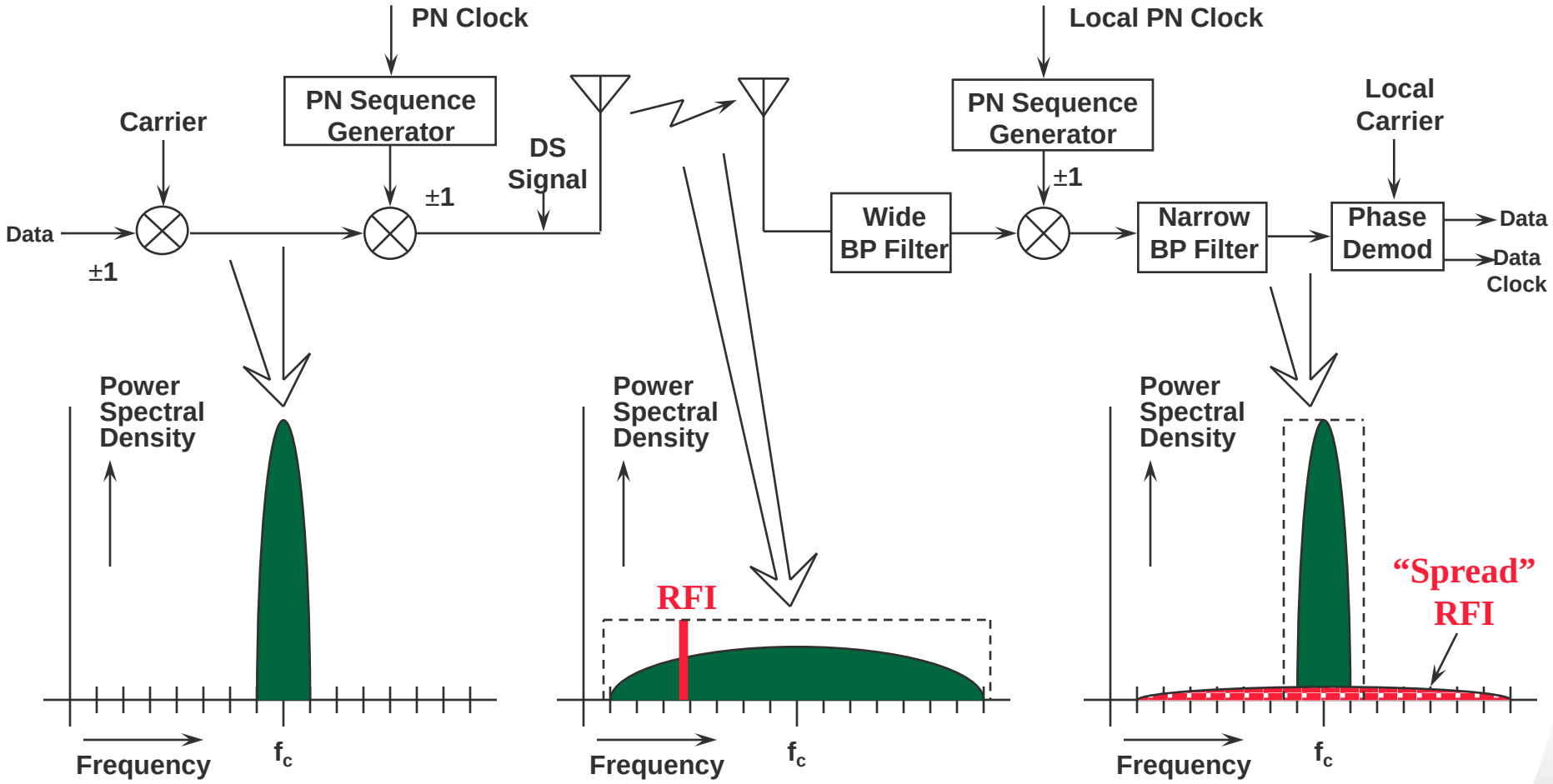


802.15.4-compliant devices must yield to 802.11 traffic, while real candidate industrial and SG technologies may not.

ORNL's Solution: Hybrid Spread Spectrum

- **Novel, adaptive technique (U.S. Patents 7,092,440; 7,656,931; 7,660,338).**
- **HSS: a synergistic, programmable combination of DS, FH, and TH.**
- **Advantages:**
  - **Adaptive Hybrid Spread-Spectrum (HSS) modulation format *combines* DSSS and frequency/time hopping in a multi-dimensional, orthogonal signaling scheme.**
  - **Capable of excellent LPI, LPD & security properties (programmable).**
  - **Adaptive, robust protocol for high QoS applications.**
  - **Can be operated in burst mode for very low power drain.**
  - **Superior resistance to multipath and jamming (high process gain).**
  - **Easily deployed with modern chip technology.**
  - **Compliant with existing government rules for license-free ISM bands.**
  - **Ideally implemented via modern FPGA-based electronics, ASICs, and software-defined radio (SDR) techniques.**

DIRECT-SEQUENCE SPREAD-SPECTRUM SIGNALS

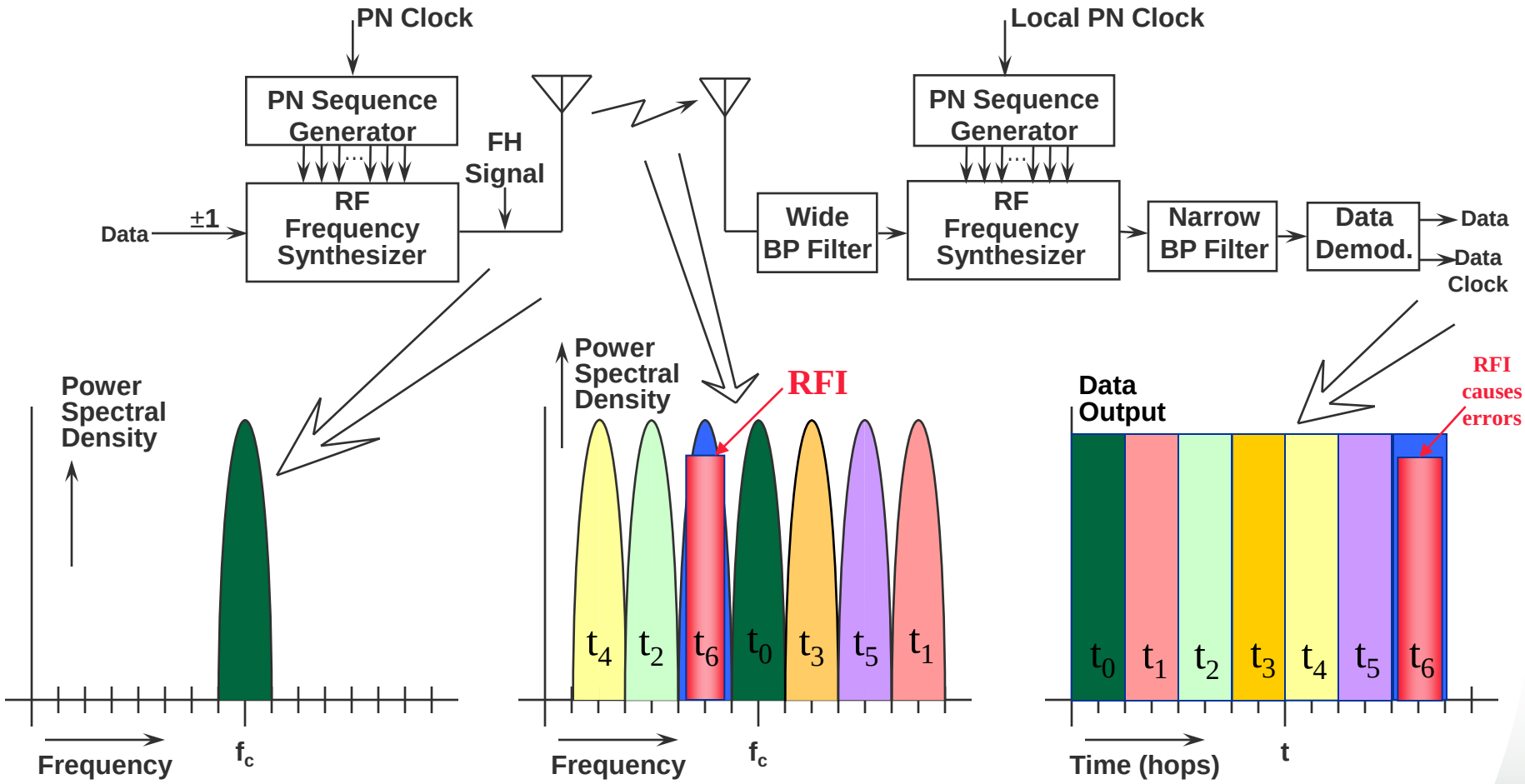


Narrow spectrum at output of modulator before spreading

Spectrum has wider bandwidth and lower power density after spreading with PN sequence (PN Rate >> Data Rate)

Original narrowband, high power density spectrum is restored if local PN sequence is same as and lined up with received PN sequence

FREQUENCY-HOPPING SPREAD-SPECTRUM

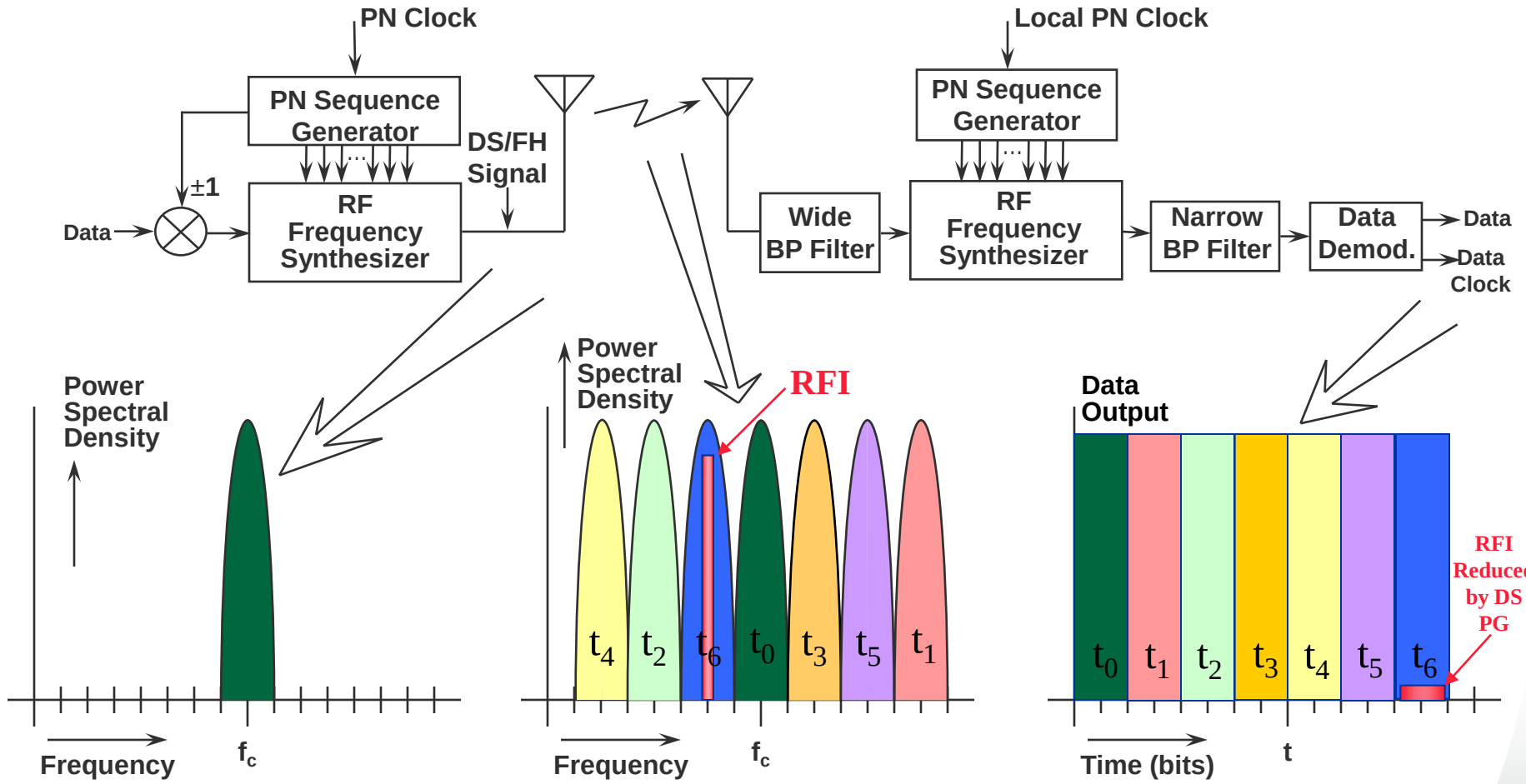


Narrow spectrum at output of modulator while hopping

Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate << Data Rate for standard FHSS)

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

HYBRID SPREAD-SPECTRUM (DS/SFH)

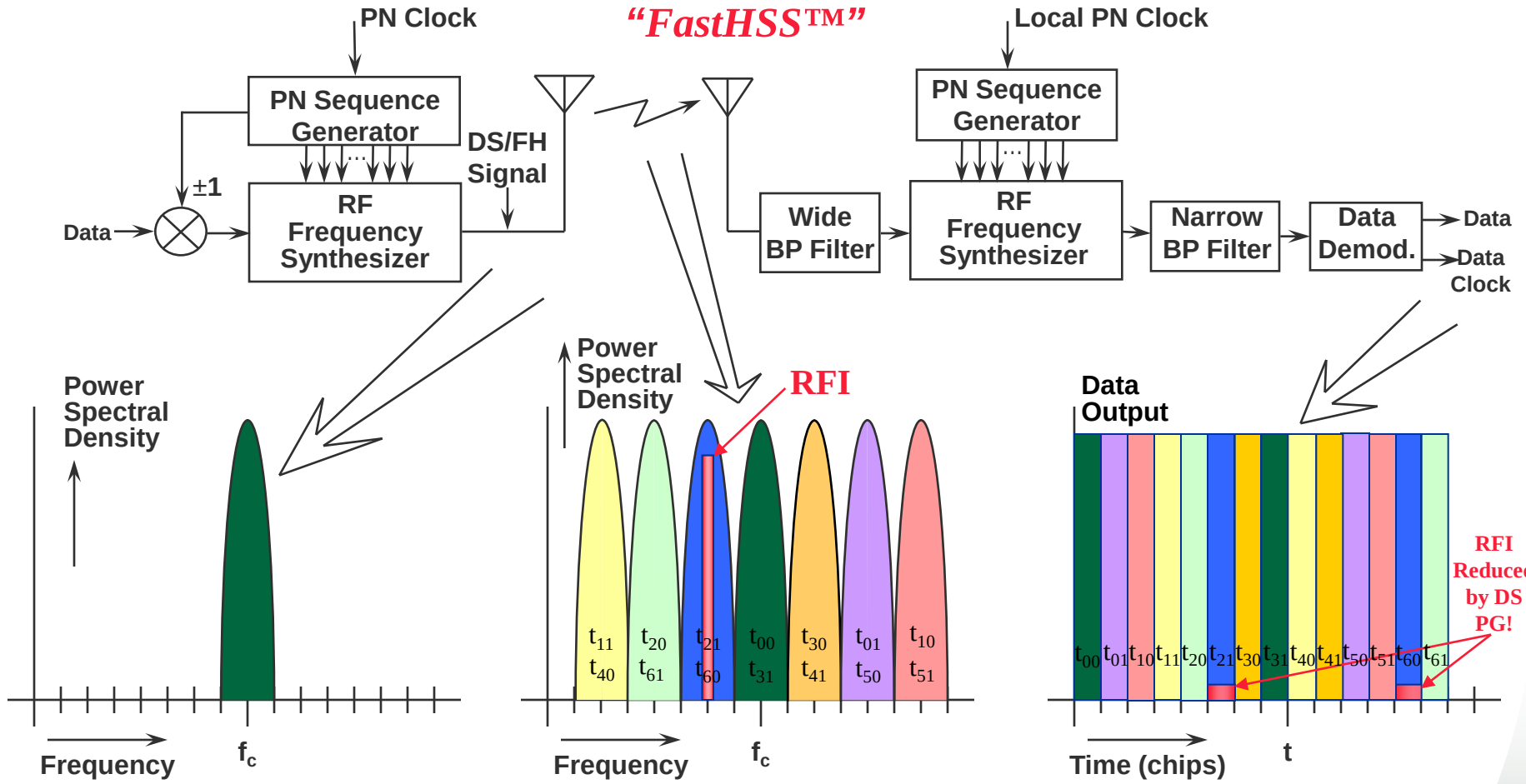


DS (wide) spectrum at output of modulator while hopping

Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate << Data Rate for standard HSS; >> for FastHSS™)

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

FAST HYBRID SPREAD-SPECTRUM (DS/FFH)



DS (wide) spectrum at output of modulator while hopping

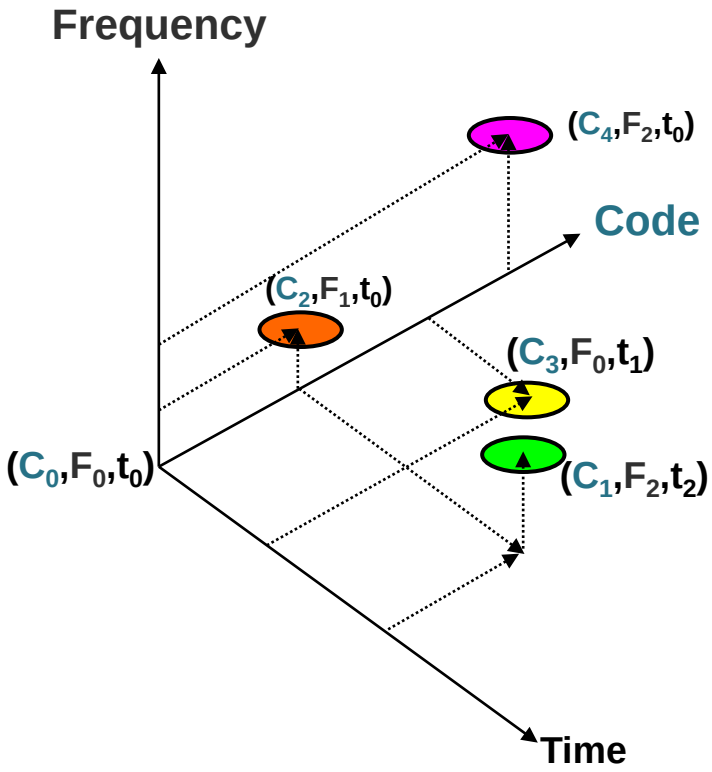
Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate >> Data Rate for FastHSS™; e.g., as above, 2 hops per bit).

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

$$G_{p(FH/DS)\ dB} = G_{p(FH)\ dB} + G_{p(DS)dB} = 10 \log (\text{no. of hopping channels}) + 10 \log (BW_{DS}/R_{info})$$

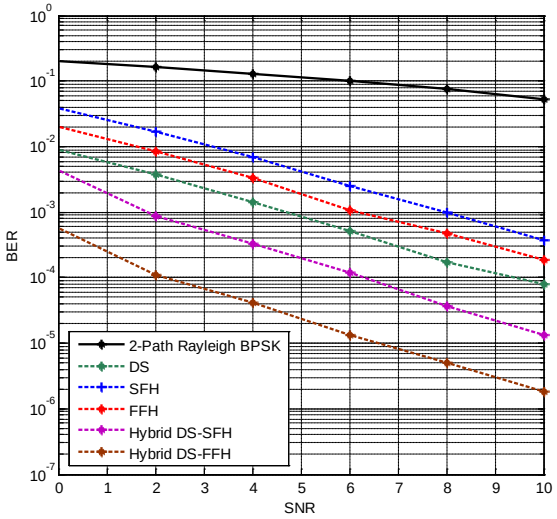
HSS is a Multidimensional Signal

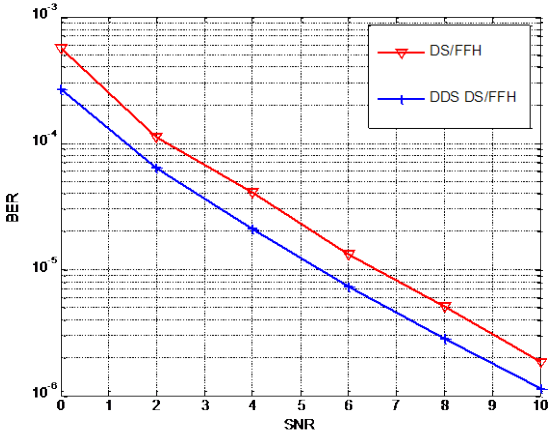
- **HSS can be defined in 3 axes (code, frequency, and time).**
  - **Each dimension is orthogonal with the others.**
  - **Permissible signal spaces along an axis may also be ~ orthogonal.**
    - **Codes**
    - **Frequencies**
    - **Time slots**
- **Easily adaptable to exploit many degrees of freedom to meet system requirements.**
- **Some signal overlaps may be orthogonal.**

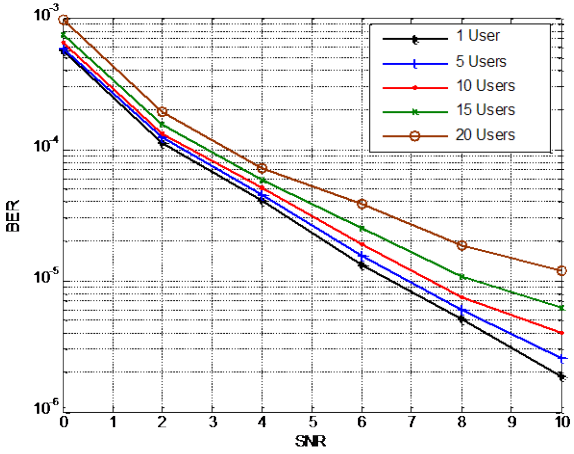


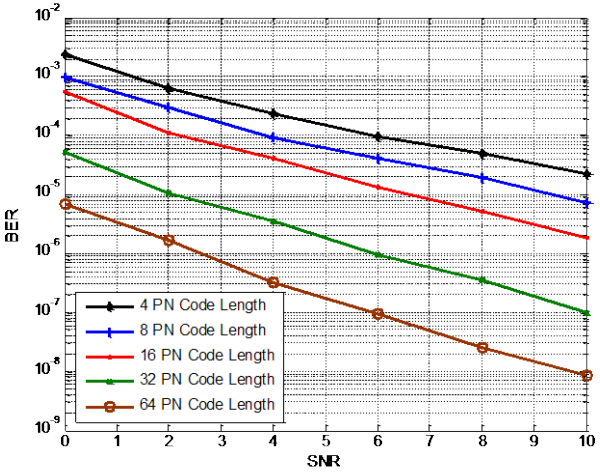
Simulation confirms the performance

More Results published in upcoming IEEE MILCOM and IEEE CQR

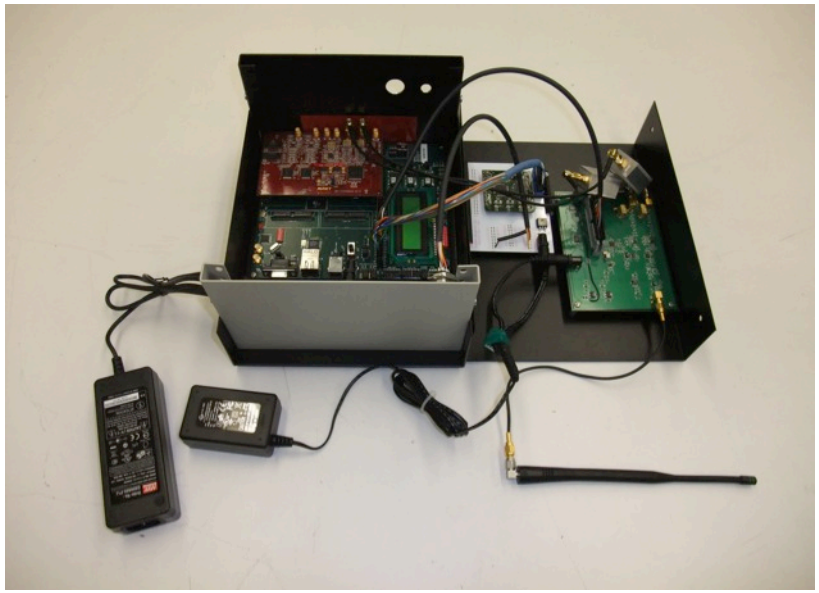




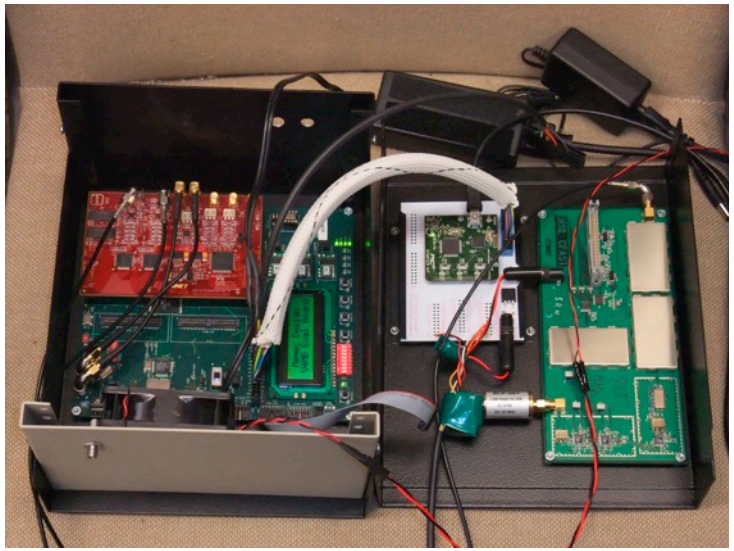




HSS System Hardware Prototypes



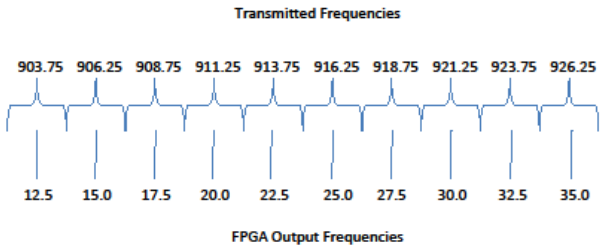
Transmitter



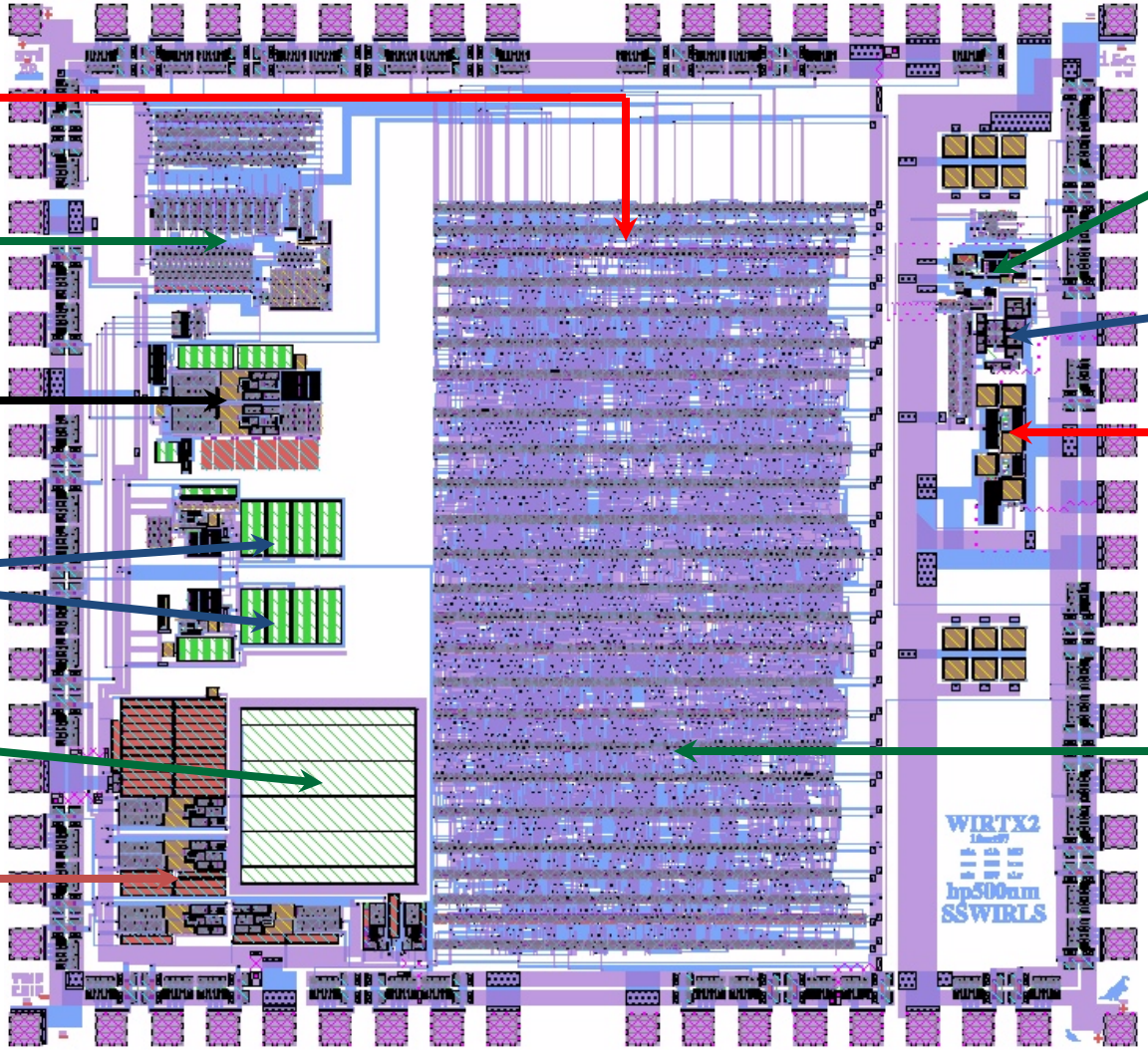
Receiver

Channel Frequencies

Using 891.25 MHz Local Oscillator



Advanced Wireless Telesensor Chip



Spread-Spectrum Gen.

ADC

Voltage Ref.

Temp. Sensors

Optical Detector

Optical Data Interface

Size:
3.3 mm sq.

VCO/PLL

Mixer

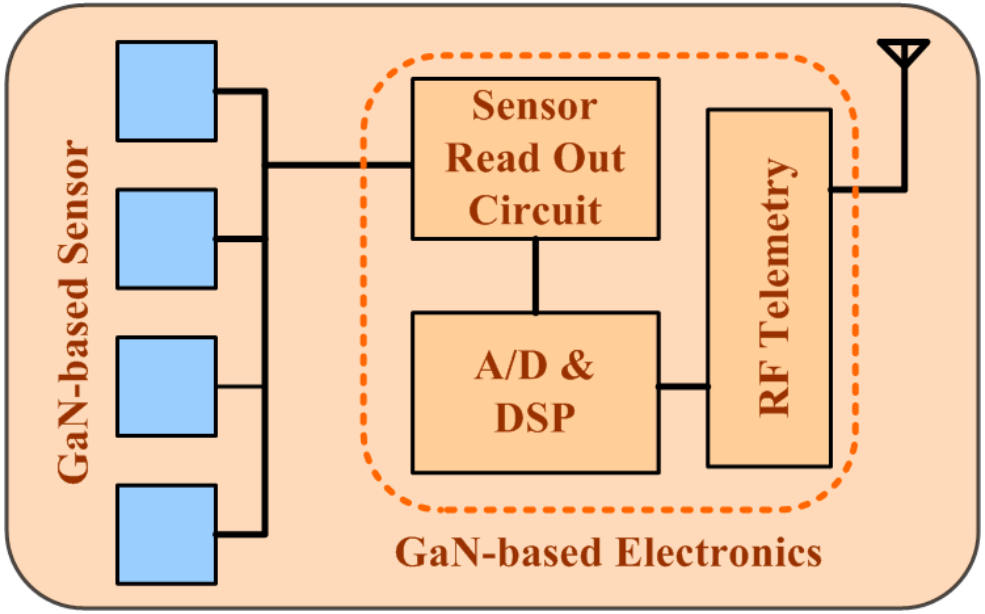
RF Amp

Control Logic *(+IEEE 1451)*

Process:
0.5-µ H-P

High-Temperature Sensors

- Wireless sensors capable of working in extreme environments can significantly improve the efficiency and performance of industrial processes by facilitating better monitoring and control.
- Example applications: fossil plants, steam turbines, jet engines.
- SAW devices are also potentially useful at high temps.



Comparison of WBG materials with Si

Property	Si	SiC	GaN
Suitability for High Power Application	Medium	High	High
Suitability for High Frequencies	Low	Medium	High
HEMT structure	No	No	Yes
Suitability of High Temperature Application	No	Yes	Yes
Low Cost Substrate	Yes	No	Yes

GaN Material Superiority

GaN is an attractive material for high-power electronics due to its:

- wide bandgap ➔ for high temperature operation
- high breakdown field ➔ for large blocking voltage applications &
- high saturated electron velocity ➔ for high frequency performance

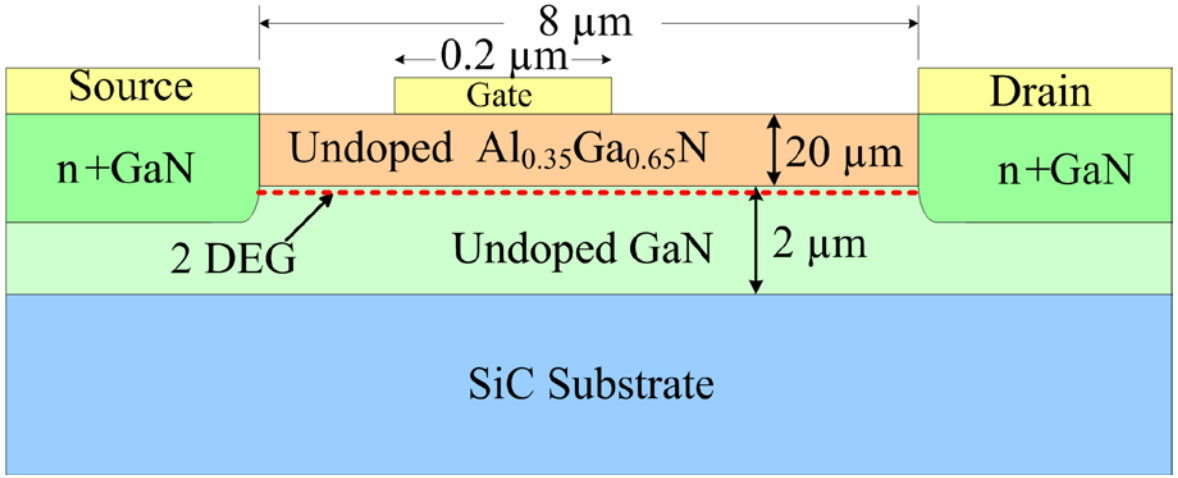
Material	μ	ε	E_g	BFM Ratio	JFM Ratio	T_{max} (°C)
Si	1300	11.4	1.1	1.0	1.0	300
SiC	260	9.7	2.9	3.1	60	600
GaN	**1500**	**9.5**	**3.4**	24.6	80	700

Baliga figure-of-merit: $BFM = \varepsilon \mu E_G^3$

Johnson's figure-of-merit: $JFM = \frac{E_C . v_s}{2\pi}$

Ref.: *Umesh K. Mishra, et al, "AlGaN/GaN HEMTs—An overview of Device Operation and Applications". June 2002*

GaN Device Structure



- **AlGaN/GaN HEMT investigated in this work was primarily developed for power applications and was grown on a SiC substrate for high temperature operation.**
- **The source and drain contacts are ohmic, whereas gate is Schottky barrier with gold as the gate metal.**
- **Due to bandgap difference between AlGaN and GaN a potential well is formed in the GaN layer at the interface.**
- **Spontaneous and piezoelectric polarization exist in the heterointerface because of the lattice mismatch between AlGaN and GaN. These polarized charges are confined in the potential well, forming a 2-D electron gas.**

Many Potential Wireless Applications

- Personnel Tracking/Locating
- Human Safety Management
- Material Tracking
- Product Tracking
- Field Operator Efficiency
- Field Maintenance Efficiency
- Plant Security
- Business Performance Measures
- Incremental Process Measures
- Extended Plant Visibility (Video)
- Tank Gauging Redundancy
- Access Control
- Intrusion Detection
- Safety Event Monitoring
- Leak Detection
- Equipment Measurements
- Product Measurements
- Inferential Measurements
- Hand-held HMI
- Key Performance Measurement
- Mobile Asset Management
- Evacuation Management

Thanks for your attention!

Questions?