Intelligent Wireless Sensor Networks for System Health Monitoring

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ARC Intelligent Wireless Sensor Network Project

- **Wireless Sensor Network (WSN) Development**
  - WSN technology based on IEEE 802.15.4 Personal Area Network (PAN) and ZigBee Protocol allows creation of ad-hoc sensor networks that integrate sensors for specific health monitoring functions
  - IEEE 1451 provides framework for a Family of Smart Transducer Interface Standards using embedded meta-information for dynamic configuration and management
  - Fault tolerance provided through mesh network and module redundancy
  - System on a Chip (SoC) technology allows low-cost implementation with robust performance at minimal power consumption, mass and volume.
- **Demonstration Software Integration**
  - A custom software application program recognizes sensor modules upon PAN association, populating a data display with sensor ata values, PAN and node status information and time stamps using meta-information compliant with IEEE 1451.4 Transducer Electronic Datasheet (TEDS)
    - ARCBees measure temperature, pressure, humidity, force, acceleration, vibration and strain
- **Development and Flight Instrumentation (DFI) for Launch Vehicles**
  - Apply the WSN technology and intelligent sensor software to health monitoring of a launch vehicle payload shroud, supporting ancillary data collection for flight tests.
  - Start by applying technology in the lab and mature from TRL 5 to TRL 8 for use in flight.
    - RF Compatibility and Susceptibility
    - Association and failover reliability and speed

Intelligent Wireless Sensor Network (WSN) Project Sponsors and Contributors

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  - Daniel Winterhalter, NESC Chief Scientist
- The Project received support from the Discovery and Systems Health (DaSH) Technical Area of the Intelligent Systems Division
  - Ann Patterson-Hine, Technical Area Lead
- The ARC WSN project leveraged SBIR Phase 2 funded work at Stennis Space Center as its technology base
  - Fernando Figueroa, SSC-UA20
  - Ray Wang, President, Mobitrum Corp.
- ARC WSN Team:
  - Rick Alena
  - Mark Foster
  - Thom Stone
  - Jeff Becker
  - John Ossenfort
  - Jarren Baldwin
  - Ray Gilstrap
  - Pete Wilson

Key Advantages of Wireless Sensor Networks (WSN)

- Wireless Sensor Network (WSN) technology allows sensors to be placed in locations difficult to reach using cables
  - This includes internal structural elements and pressure interfaces
- WSN technology scales up well to allow construction of sensor arrays
  - Can support thousands of sensors at sustainable data rates over 100 Kbps
- Wireless systems in general are subject to different common mode failure mechanisms than wired systems
  - Specific fault mode is structural failure or environmental conditions affecting cable or connector reliability
  - Hybrid systems (wired and wireless) can provide a greater level of reliability than either one alone

Working Definition for Intelligent WSNs

Intelligence is defined as the capability for supporting dynamic ad-hoc self-configuring real-time sensor networks able to adapt to faults while maintaining measurement accuracy and temporal integrity.

- Wireless Networks use ad-hoc Personal Area Network (PAN) technology based on the IEEE 802.14.5 standard allowing creation of dynamic PANs
- The Wireless Sensor Module (WSM) incorporates the functions of the Transducers, Transducer Interface Module and Wireless Network Interface as defined in IEEE 1451
- WSMs provide information processing at the Point of Measurement (POM)
- Unique identity and descriptive meta-information is embedded into WSMs mechanisms for information exchange based on IEEE 1451 Standards
- Applications programs instantiate PANs and WSMs during run-time, identifying modules and sensors by unique identity and reading sensor values directly as accurate time-stamped engineering units
- Applications produce complex sensor network displays using only information available through the network, reflecting actual network configuration at all times, despite faults and deliberate changes in the network and modules.

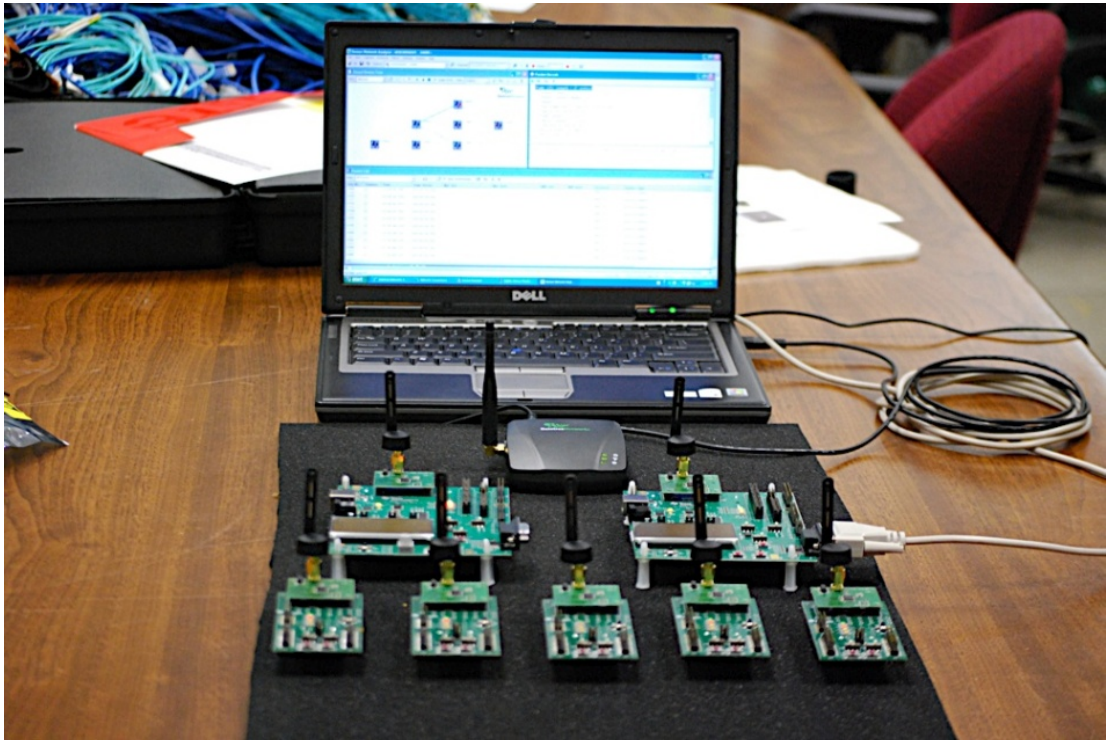
Potential Benefits

- Intelligent WSMs provide unique high-level identities and configuration information to the application software eliminating the need to provide such information as configuration files, databases or software variables.
  - The application software is NEVER out of configuration
  - This improves sensor calibration and tracking processes, reducing operational cost
- Applications poll the sensor network and discover sensor modules creating sensor display applets as modules associate with the network in real-time
  - This can significantly reduce software development cost and effort - particularly for updating the software after changing the sensor complement.
- Point of Measurement (POM) capability provides high-level descriptions of modules and sensors and conversion to engineering units with global timestamps, eliminating ambiguity for interpreting the data stream
  - Produces accurate readings with temporal integrity despite changing network paths supporting cause and effect diagnostic reasoning.
- Computation at POM allows parametric extraction (i.e. FFT) or threshold detection in the WSM, greatly reducing sensor network bandwidth requirements
  - Increases WSN measurement resolution while maintaining low bandwidth, simplifies application software and lowers network cost

Technical Approach

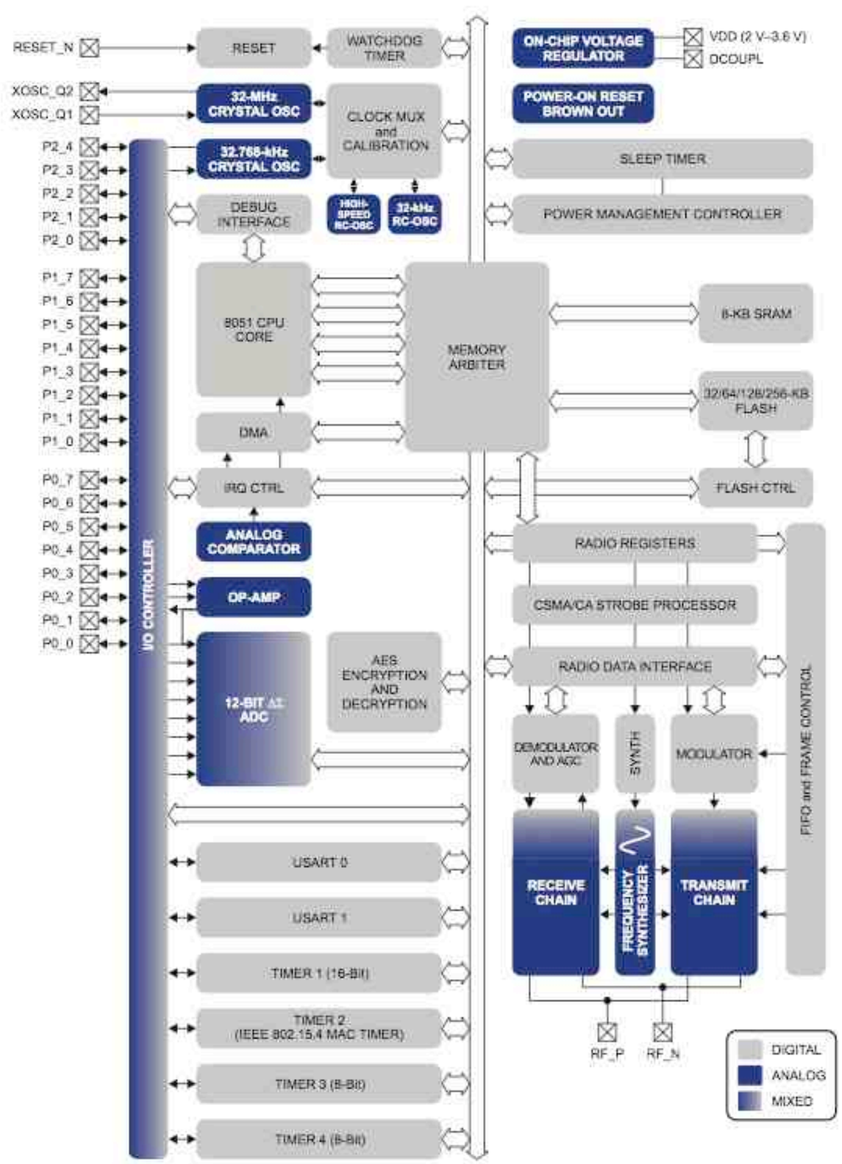
- WSMs are created using System-on-a-Chip (SoC) technology providing low cost, low power and small size (Low SWAP)
- The architecture and information structure is compatible with IEEE 1451 providing a high-level description to the application software using meta-information embedded in each module
  - Use Electronic Data Sheet formats (EDS) for WSM and PAN status (1451.0)
  - Use Tranducer Electronic Data Sheet (TEDS) for describing sensors (1451.4)
- Network Capable Application Processor (NCAP) provides bridge between PAN and TCP/IP network, providing information access and distribution using standard publish/subscribe or equivalent protocols.
- Sensor Applications poll the sensor network through the NCAP discovering sensor modules, reading EDS and TEDS and creating sensor display applets dynamically in real-time
  - Individual sensor displays and graphs
  - Sensor network maps and status displays
- The WSN is characterized for fail-over performance and RF susceptibility and interference in various environments

ZigBee Testbed Components

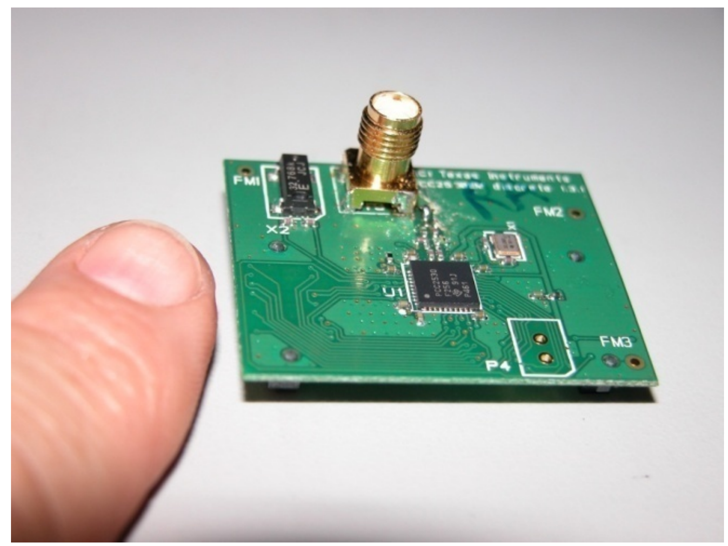


- Coordinator - establishes PAN
- Gateway - connects PAN to TCP/IP data network
- Routers - forward data
- Sensor modules (WSM) - originate sensor data stream

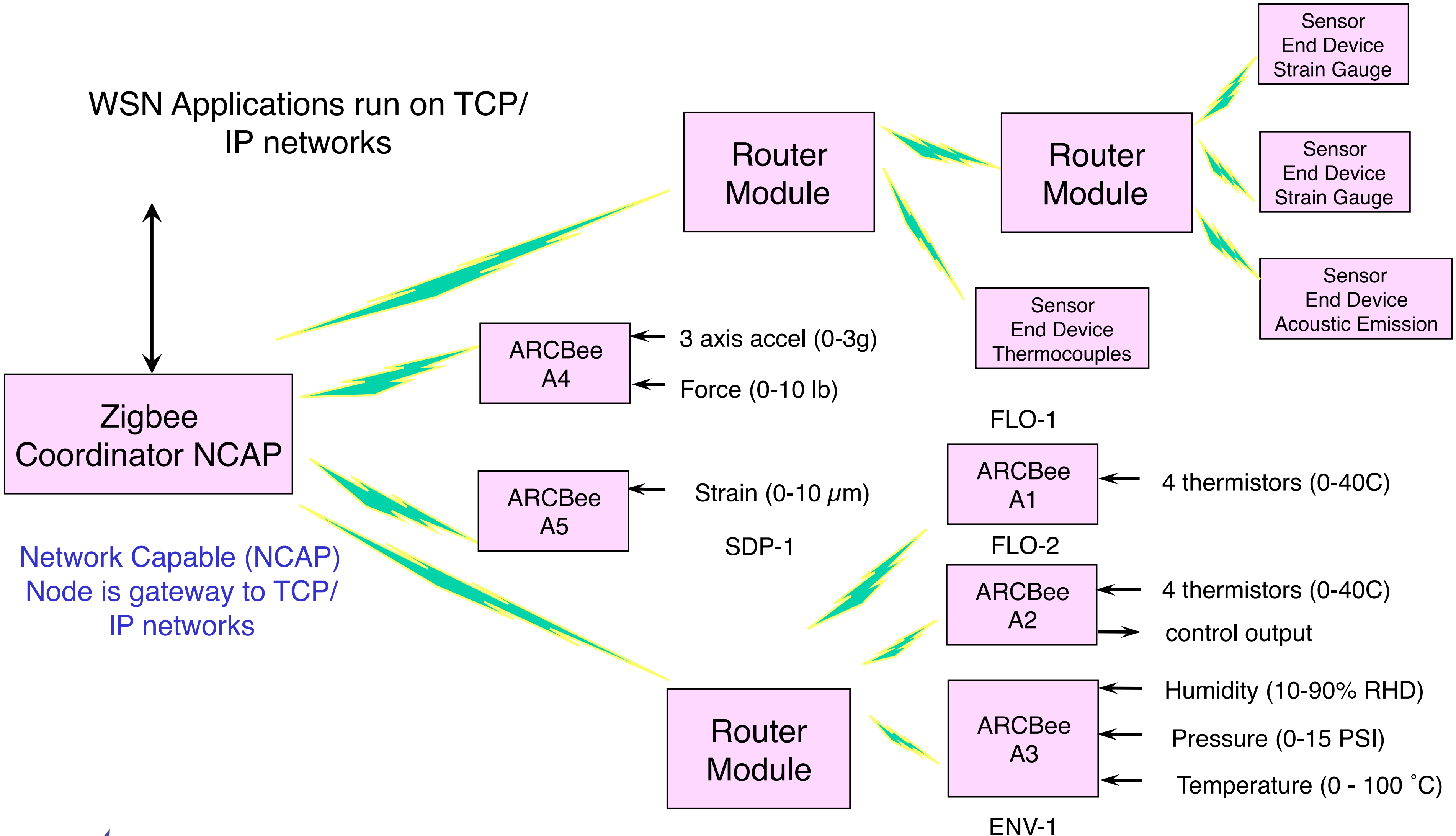
WSM System on a Chip technology



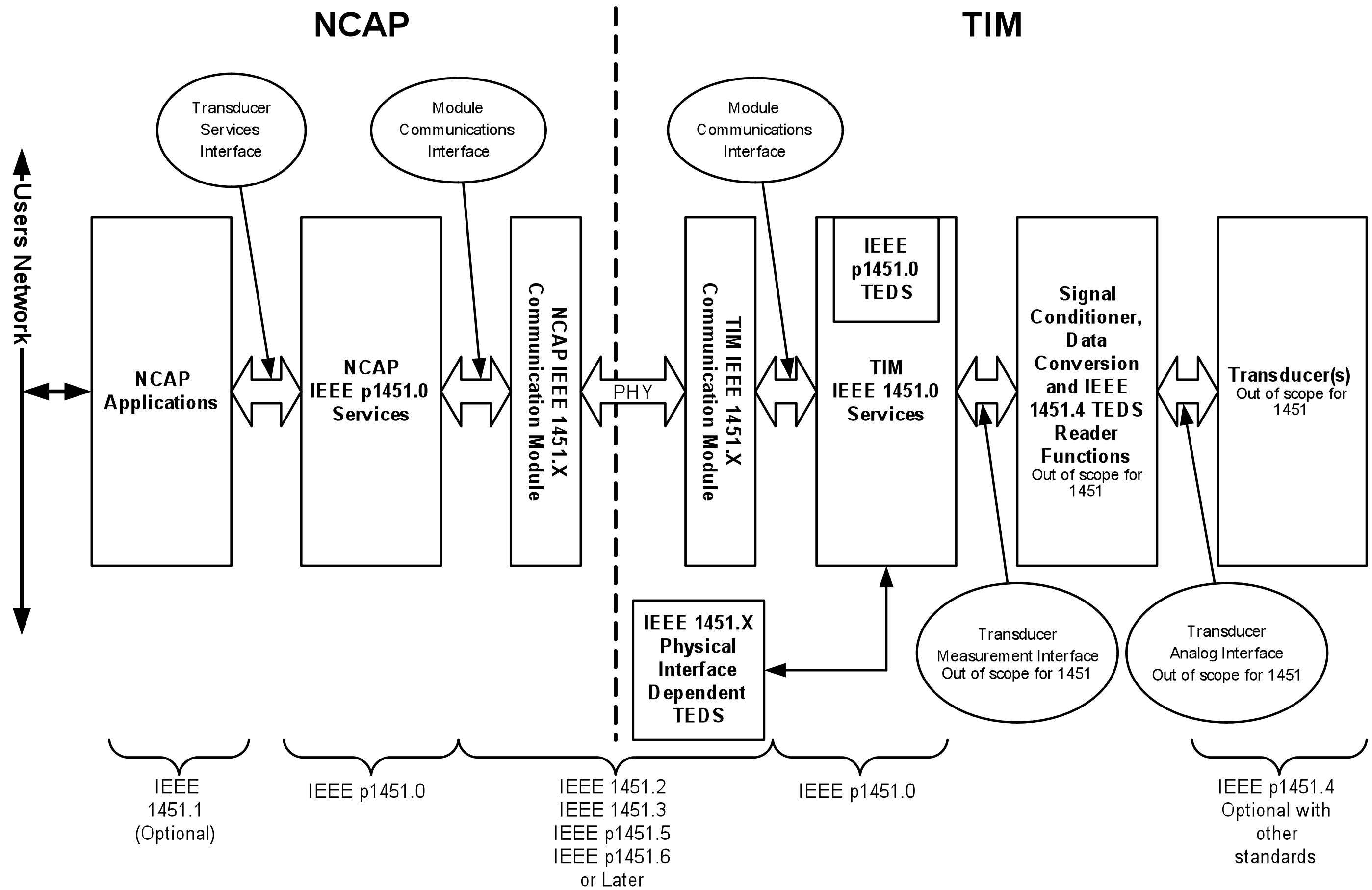
- TI CC2530 single-chip ZigBee solution
- Microcontroller hosting ZigBee Pro Stack
- DRAM and Flash, firmware update
- Timers, USB, serial, digital I/O, encryption
- ADC 12 bit, 8 channel
- 802.15.4 transceiver
- Actual size for complete assembly shown below



Wireless Sensor Network Testbed Demonstration



IEEE 1451 Reference Architectue



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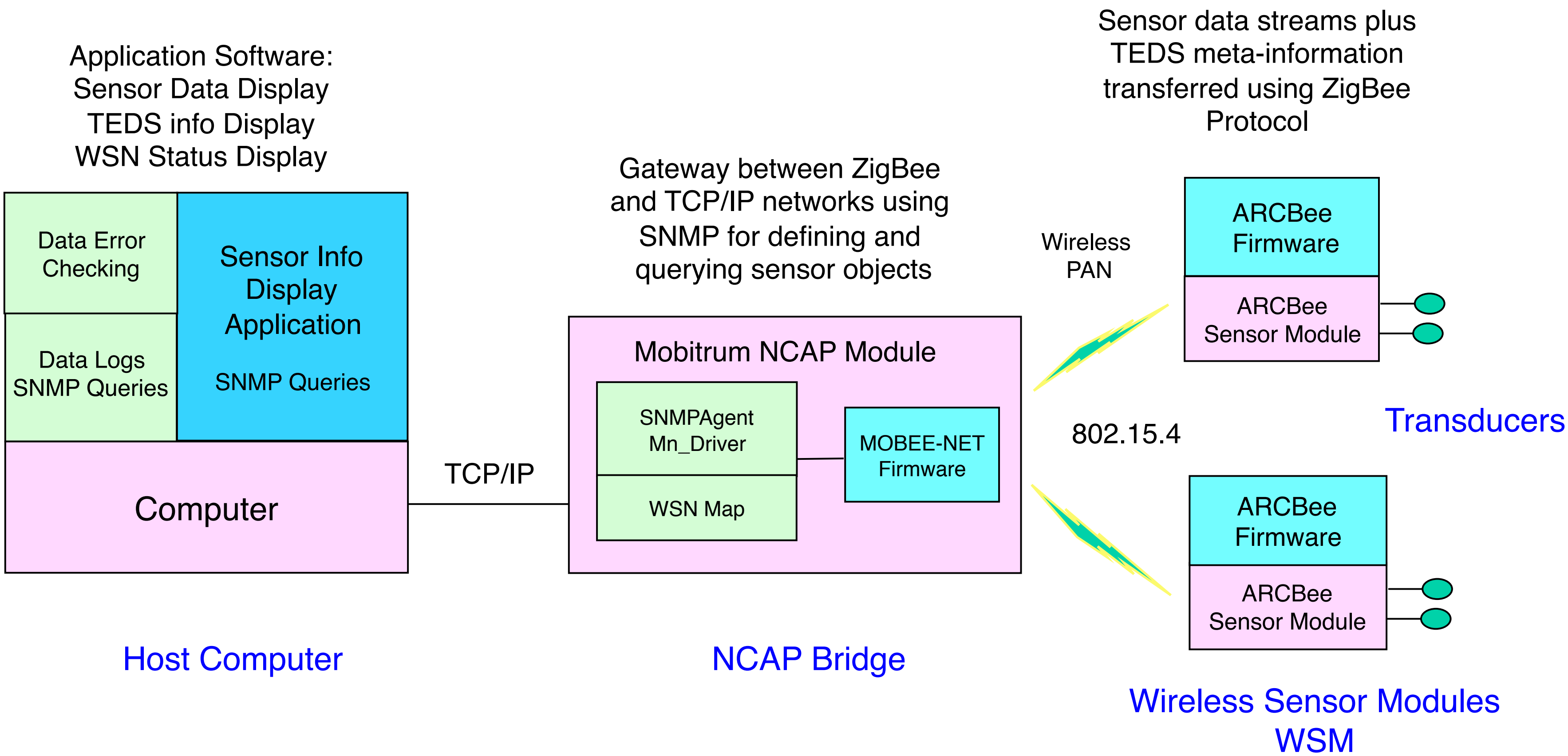
WSN Architecture Diagram

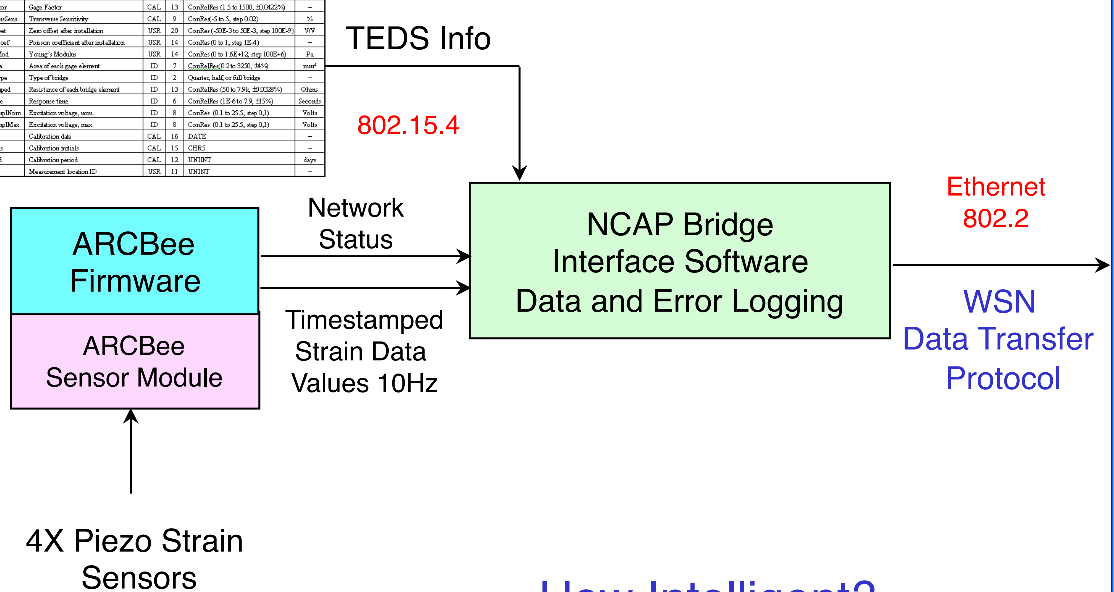


- Smallest architectural unit is the WSM
- Specify PHY as 1451.5 – wireless
- Use POM within WSM for calibration
- NCAP hosts SNMP and data servers
- Applications hosted on TCP/IP network

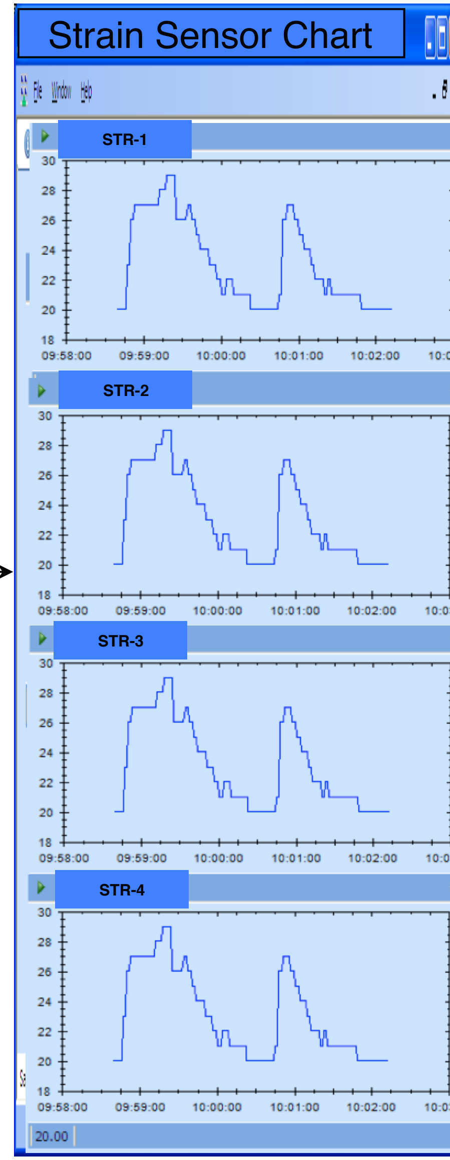
Wireless Intelligent Sensor Network Data Flow Diagram

IEEE 1451
Transducer Electronic Data Sheet
TEDS for strain sensors
In ARCBee Flash Memory

Property	Description	Access	Bits	Data Type (and Range)	Units
TEMPLATE	Template ID		8	Integer (value = 35)	–
%ElecSigType	Transducer electrical signal type	ID	–	Assign = 3, "Bridge Sensor"	–
%MinPhysVal	Negative full-scale strain	CAL	14	ConRes (-0.4 to 0.4, step 50E-6)	strain
%MaxPhysVal	Positive full-scale strain	CAL	14	ConRes (-0.4 to 0.4, step 50E-6)	strain
%MinElecVal	Minimum electrical output	CAL	14	ConRes (-1 to 1, step 125E-6)	V/V
%MaxElecVal	Maximum electrical output	CAL	14	ConRes (-1 to 1, step 125E-6)	V/V
%MapMeth	Mapping method	ID	–	Assign = 6, "Bridge"	–
%GageType	Gage Type	ID	5	Enumeration of gage configurations	–
%GageFactor	Gage Factor	CAL	13	ConRelRes (1.5 to 1500, ±0.0422%)	–
%GageTransSens	Transverse Sensitivity	CAL	9	ConRes(-5 to 5, step 0.02)	%
%GageOffset	Zero offset after installation	USR	20	ConRes (-50E-3 to 50E-3, step 100E-9)	V/V
%PoissonCoef	Poisson coefficient after installation	USR	14	ConRes (0 to 1, step 1E-4)	–
%YoungsMod	Young's Modulus	USR	14	ConRes (0 to 1.6E+12, step 100E+6)	Pa
%GageArea	Area of each gage element	ID	7	ConRelRes(0.2 to 3250, ±4%)	mm²
%BridgeType	Type of bridge	ID	2	Quarter, half, or full bridge	–
%SensorImped	Resistance of each bridge element	ID	13	ConRelRes (50 to 7.9k, ±0.0328%)	Ohms
%RespTime	Response time	ID	6	ConRelRes (1E-6 to 7.9, ±15%)	Seconds
%ExciteAmplNom	Excitation voltage, nom.	ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
%ExciteAmplMax	Excitation voltage, max.	ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
%CalDate	Calibration date	CAL	16	DATE	–
%CalInitials	Calibration initials	CAL	15	CHRS	–
%CalPeriod	Calibration period	CAL	12	UNIINT	days
%MeasID	Measurement location ID	USR	11	UNINT	–



Sensor data streams accessed over TCP/IP sockets providing sensor data stream, TEDS and Network Status



Access	Bits	Data Type (and Range)	Units
	8	Integer (value = 35)	-
ID	-	Assign = 3, "Bridge Sensor"	-
CAL	14	ConRes (-0.4 to 0.4, step 50E-6)	strain
CAL	14	ConRes (-0.4 to 0.4, step 50E-6)	strain
CAL	14	ConRes (-1 to 1, step 125E-6)	V/V
CAL	14	ConRes (-1 to 1, step 125E-6)	V/V
ID	-	Assign = 6, "Bridge"	-
ID	5	Enumeration of gage configurations	-
CAL	13	ConRelRes (1.5 to 1500, ±0.0422%)	-
CAL	9	ConRes(-5 to 5, step 0.02)	%
USR	20	ConRes (-50E-3 to 50E-3, step 100E-9)	V/V
USR	14	ConRes (0 to 1, step 1E-4)	-
USR	14	ConRes (0 to 1.6E+12, step 100E+6)	Pa
ID	7	ConRelRes(0.2 to 3250, ±4%)	mm²
ID	2	Quarter, half, or full bridge	-
ID	13	ConRelRes (50 to 7.9k, ±0.0328%)	Ohms
ID	6	ConRelRes (1E-6 to 7.9, ±15%)	Seconds
ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
CAL	16	DATE	-
CAL	15	CHRS	-
CAL	12	UNIINT	days
USR	11	UNINT	-

Access	Bits	Data Type (and Range)	Units
	8	Integer (value = 35)	-
ID	-	Assign = 3, "Bridge Sensor"	-
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CAL	14	ConRes (-1 to 1, step 125E-6)	V/V
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ID	5	Enumeration of gage configurations	-
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CAL	9	ConRes(-5 to 5, step 0.02)	%
USR	20	ConRes (-50E-3 to 50E-3, step 100E-9)	V/V
USR	14	ConRes (0 to 1, step 1E-4)	-
USR	14	ConRes (0 to 1.6E+12, step 100E+6)	Pa
ID	7	ConRelRes(0.2 to 3250, ±4%)	mm²
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ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
ID	8	ConRes (0.1 to 25.5, step 0,1)	Volts
CAL	16	DATE	-
CAL	15	CHRS	-
CAL	12	UNIINT	days
USR	11	UNINT	-

How Intelligent?

Application program creates and displays sensor information and data values as each sensor module is activated using only the TEDS information to configure the WSN and the application software

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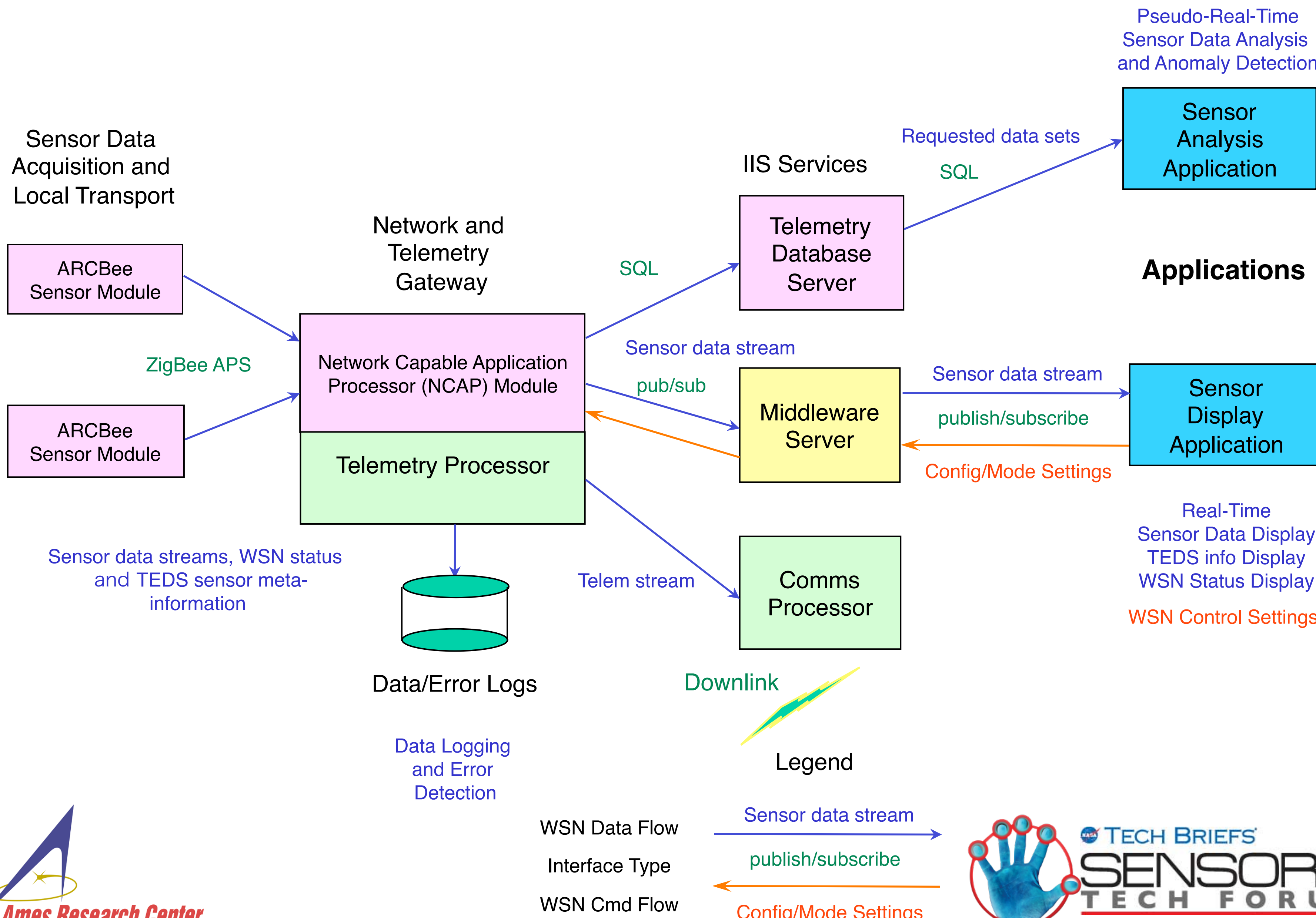
WSN Architecture and Dataflow Diagram



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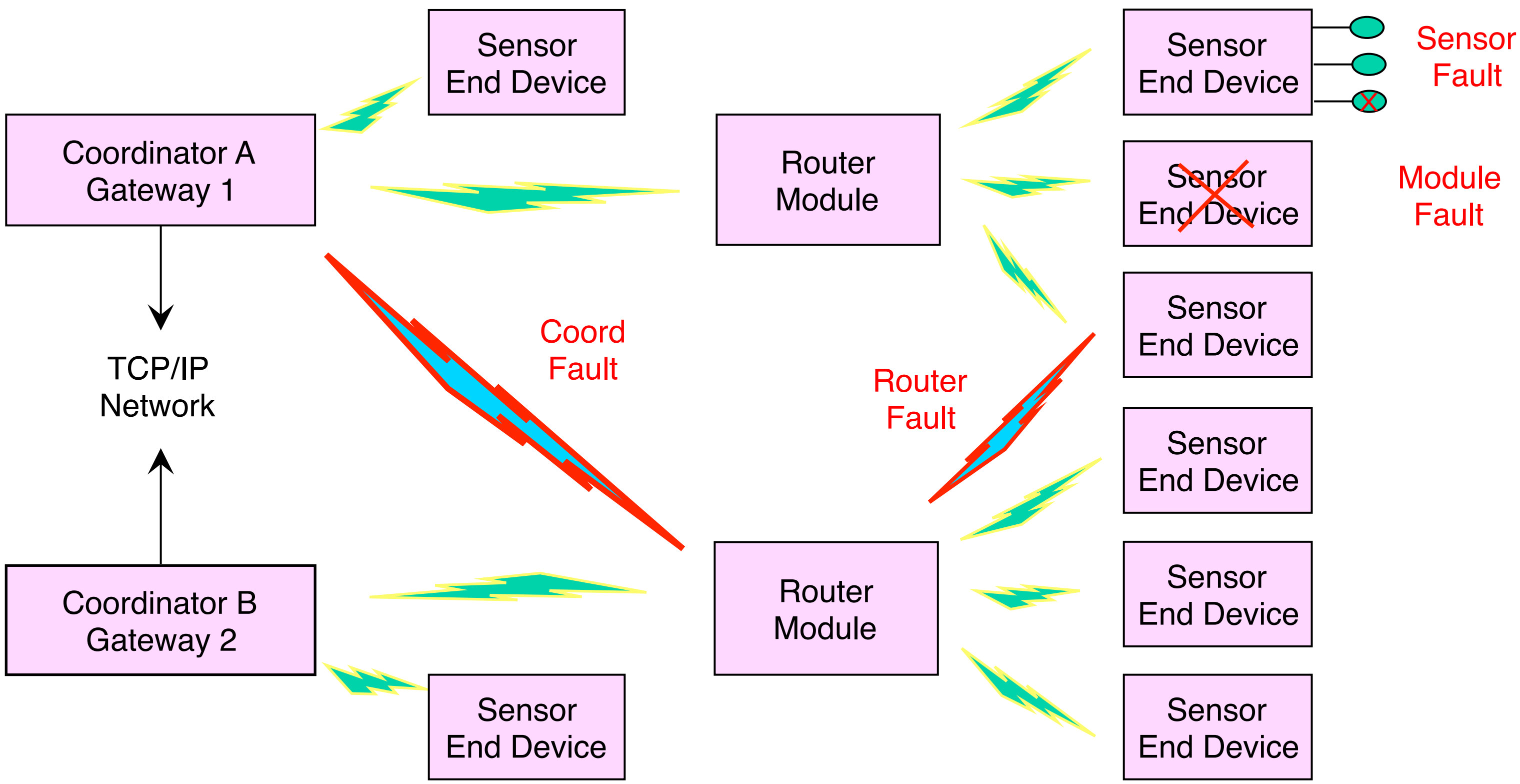
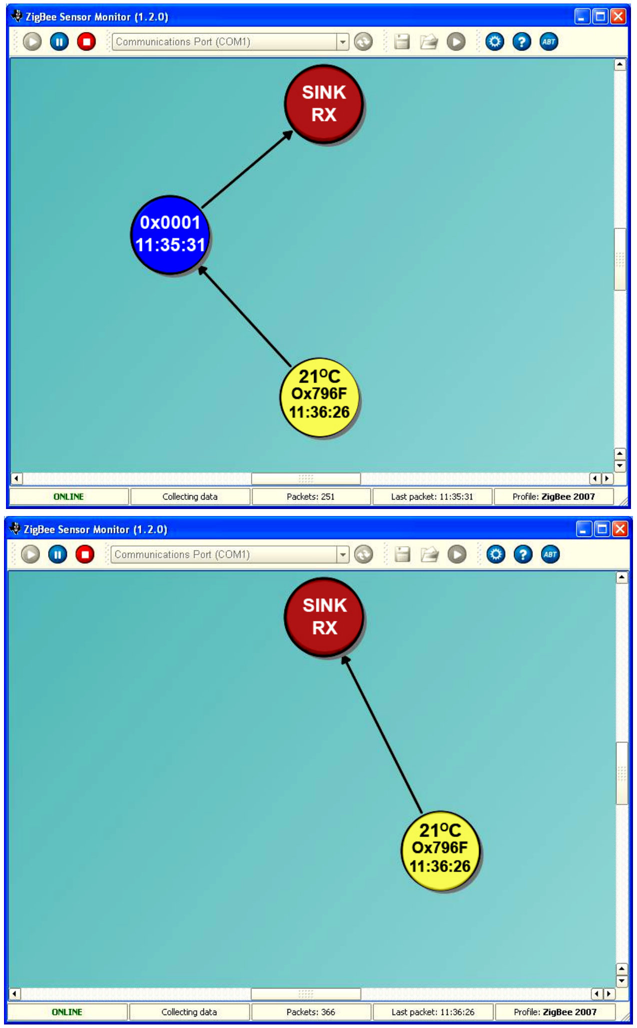
WSN Two-Tier Fault-Tolerant Mesh Network Architecture

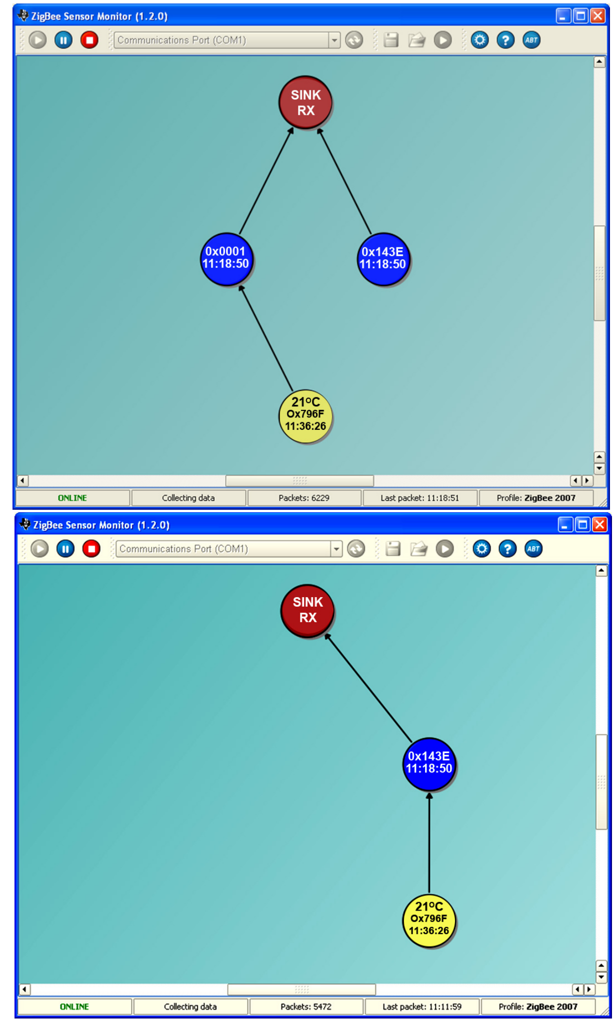


- Redundant sensors in each module cover sensor failures
- Redundant Sensor Modules cover Module failures
- Redundant Routers cover router failures
- Redundant Coordinators/Gateways cover PAN formation faults and Gateway faults

Two-Hop WSN Failover Configuration

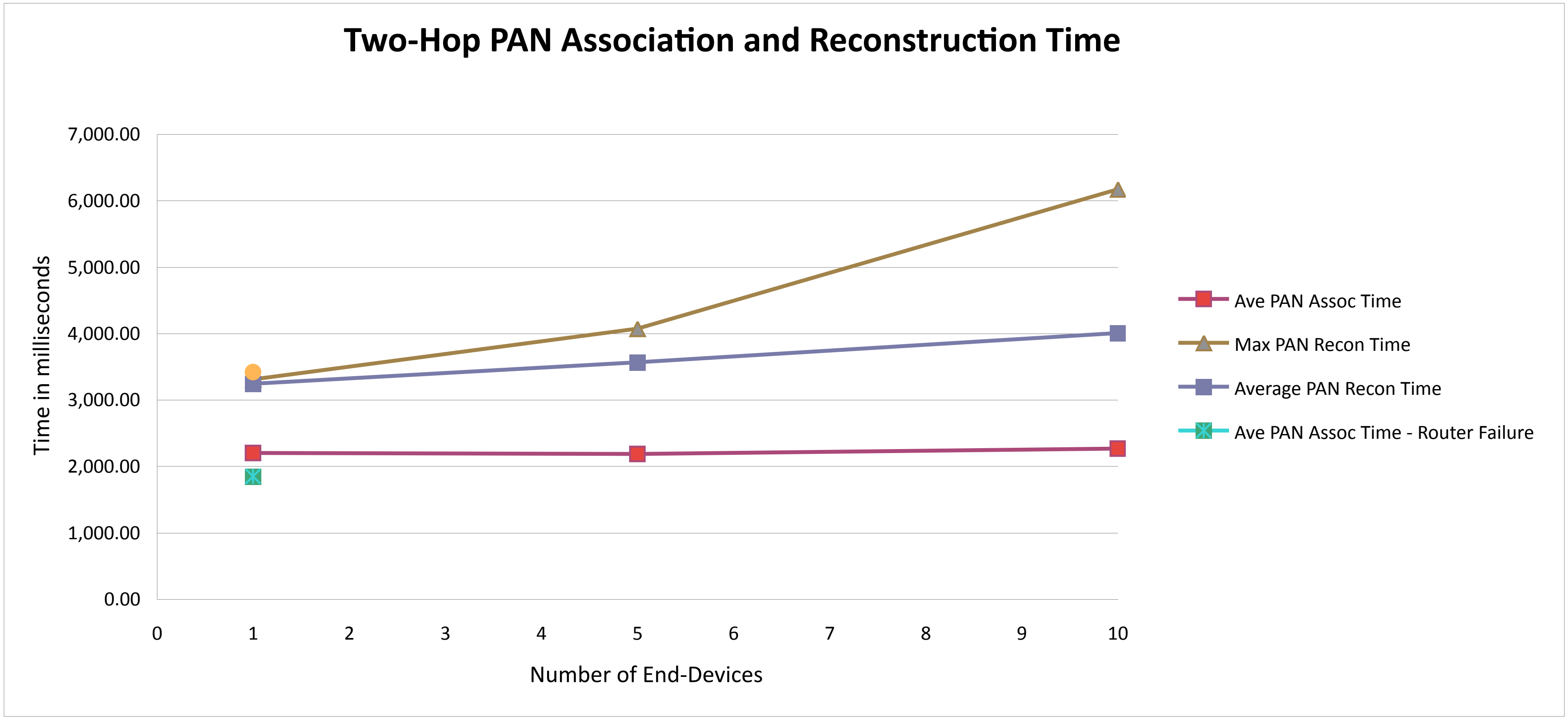


Failover from router



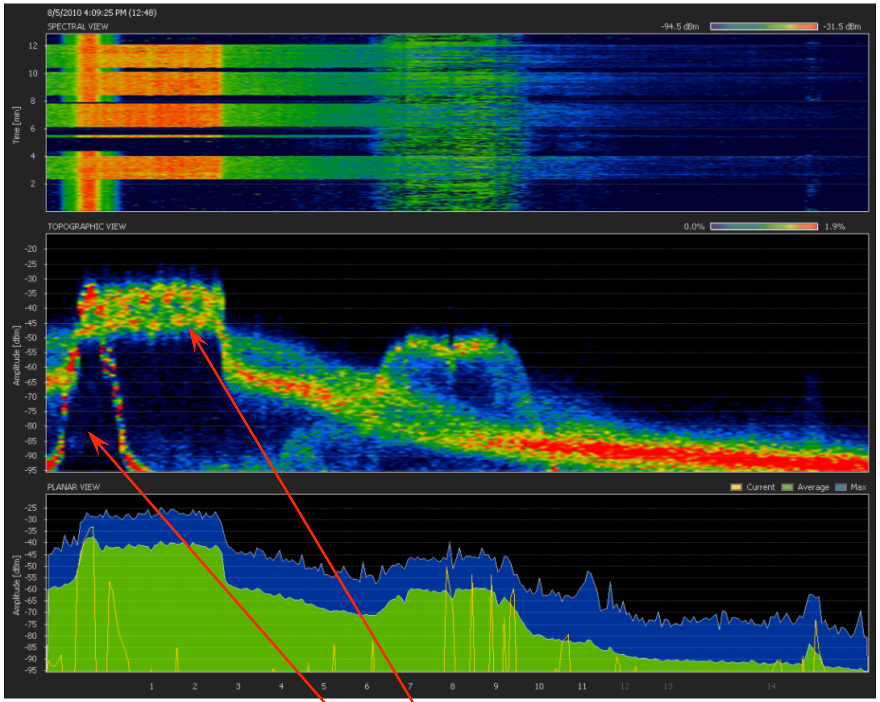
Failover from router to alternate router

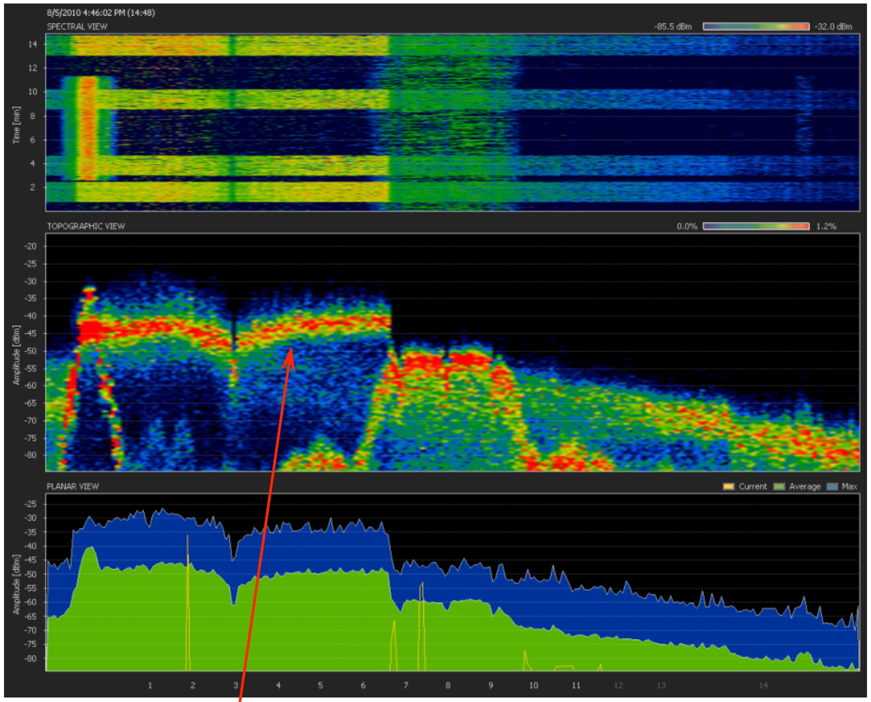
Two-Hop PAN Association and Reconstruction Times



- Two second data cycle time – paces the association and reconstruction
- Scales well, but PAN reconstruction time increase as number of nodes increases
- Reasonably fast and consistent, fully reliable.

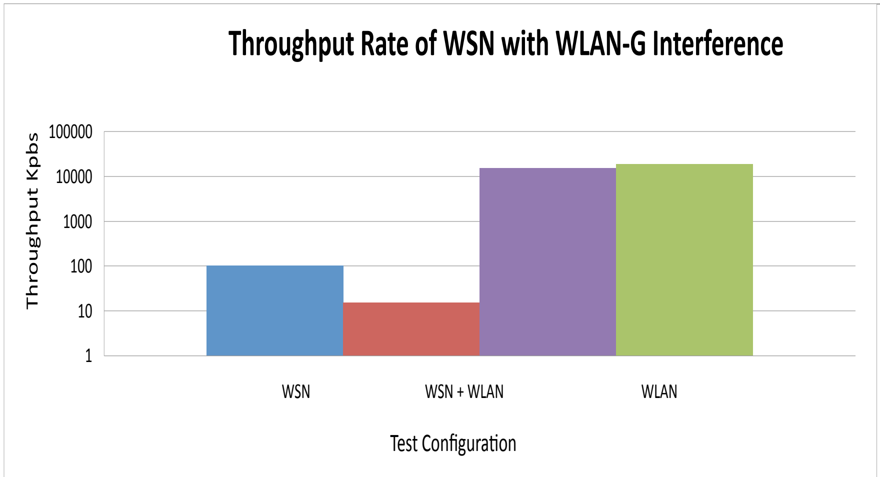
WLAN G and N Mode Interference Spectrum

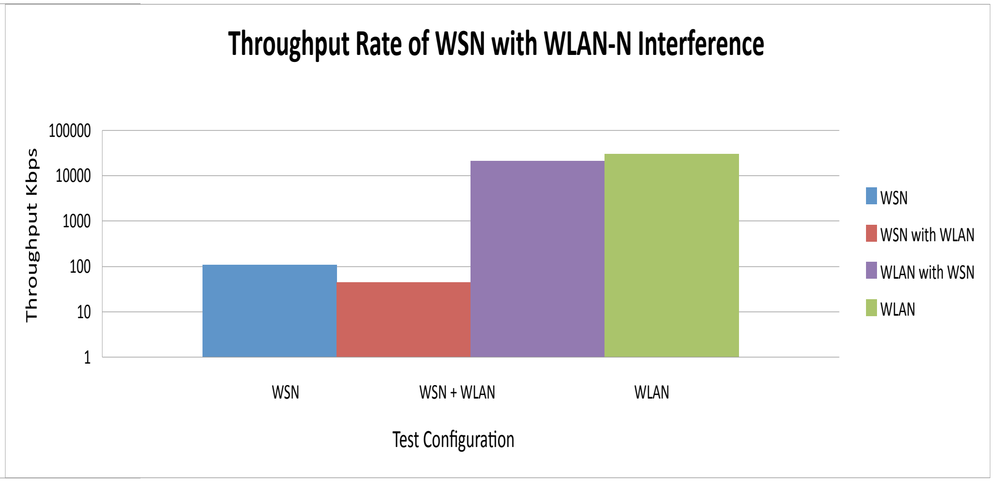




- 802.11g on Chan 1 (100 mW)
- ZigBee on Chan 11 (1 mW)
- 802.11n on Chan 4 (100 mW)

Throughput Rate with WLAN-G and WLAN-N Interference





- Zigbee Throughput - 104 Kbps to 15 Kbps with interference
- WLAN Throughput - 18.8 Mbps to 15 Mbps with interference

- Zigbee Throughput - 106 Kbps to 45 Kbps with interference
- WLAN Throughput - 30.5 Mbps to 21 Mbps with interference

Proposed Payload Shroud Flight Test Monitoring

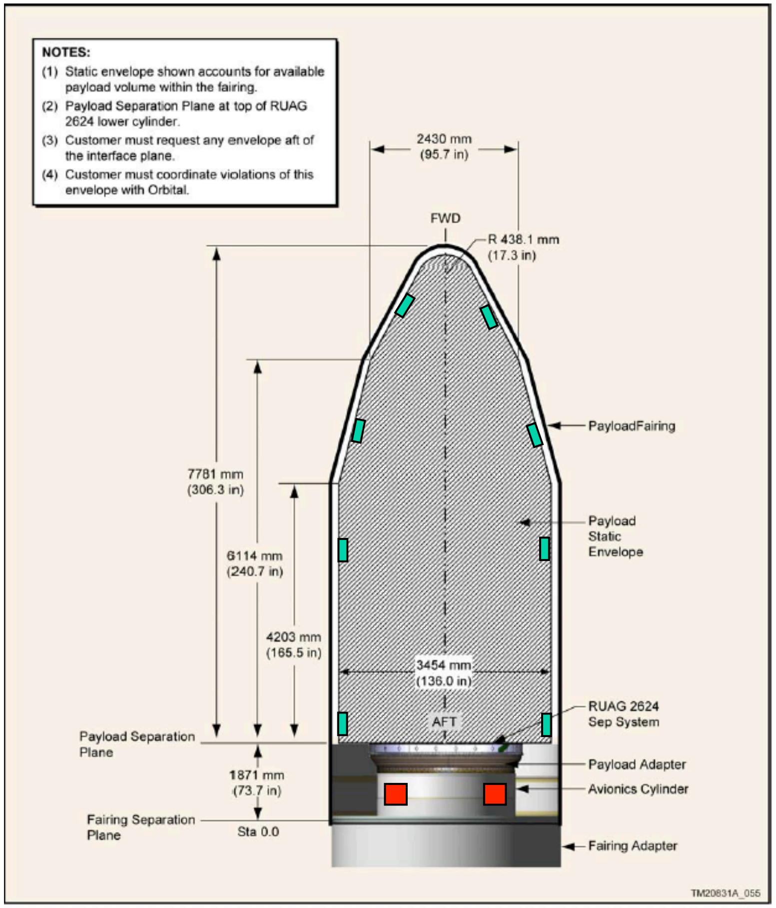


Figure 5.1.2-3. 2624 Separation System Payload Static Design Envelope

- Measure air temperature and pressure
- Measure acceleration and vibration
- Measure force and strain
- GOAL: Characterize ascent environment and structural response including separation mechanisms

Internal Shroud Sensor Module

Gateway to Telemetry Downlink

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Conclusions

- Wireless sensor products are available from a large number of vendors and are used for building systems and energy management (SmartMeters)
- NASA is evaluating the technology for use on-board aerospace vehicles
  - Appropriate application area – non-critical monitoring
  - Applicable standards and features
- The WSN was successfully characterized for fail-over performance and RF susceptibility and interference in various environments
  - Redundant modules and routers provide reliability – failover is quick and sure
  - Conform to NASA standards for spectrum management and RF transmitters
- IEEE 1451 provides a necessary method for embedding key meta-information in each module for sensor descriptions and module identity
- Information architecture with NCAPs bridging PAN and TCP/IP networks allows standardized information access and distribution
- Several working groups are active in advocating wireless sensor networks to aerospace Programs
  - Aeronautics Sensors Working Group - Hunter
  - Wireless Connections in Space - Winterhalter
  - Wireless Avionics Community of Practice - Studor