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OIT Wireless Telemetry for Industrial Applications

August 19, 2002

Prepared by
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UT-BATTELLE

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Final Report

August 19, 2002

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Executive Summary

The need for advanced wireless technology has been identified in the National Research Council publication (1) *"Manufacturing Process Controls for the Industries of the Future as a Critical Technology for the Future."* The deployment challenges to be overcome in order for wireless to be a viable option include:

- **eliminating interference (assuring reliable communications);**
- **easing the deployment of intelligent, wireless sensors;**
- **developing reliable networks (robust architectures);**
- **developing remote power (long-lasting and reliable); and**
- **developing standardized communication protocols.**

This project demonstrated the feasibility of robust wireless sensor networks that could meet these requirements for the harsh environments common to the DOE/OIT Industries of the Future. It resulted in a wireless test bed that was demonstrated in a paper mill and a steel plant. The test bed illustrated key protocols and components that would be required in a real-life, wireless network. The technologies for low power connectivity developed and demonstrated at the plant eased fears that the radios would interfere with existing control equipment. The same direct sequence, spread spectrum (DSSS) technology that helped assure the reliability of the connection also demonstrated that wireless communication was feasible in these plants without boosting the transmitted power to dangerous levels.

Our experience and research have indicated that two key parameters are of ultimate importance: 1) reliability and 2) inter-system compatibility. Reliability is the key to immediate acceptance among industrial users. The importance cannot be overstated, because users will not tolerate an unreliable information network. A longer term issue that is at least as important as the reliability of a single system is the inter-system compatibility between these wireless sensor networks and other wireless systems that are part of our industries. In the long run, the ability of wireless sensor networks to operate cooperatively in an environment that includes wireless LANs, wireless headsets, RF heating, wireless crane controls and many other users of the electromagnetic spectrum will probably be the most important issue we can address.

A network of units (Figure 1) has been developed that demonstrates the feasibility of direct-sequence spread spectrum wireless sensor networking for industrial environments. The hardware consists of a group of re-programmable transceivers that can act as sensor nodes or network nodes or both. These units and the team that built them are the heart of a test bed development system that has been used successfully in demonstrations at various industrial sites. As previously reported, these units have been successfully tested at a paper mill. More recently, these units were utilized in a permanent installation at a steel mill. Both of these applications demonstrated the ease with which a new network could be installed, and the reality that DSSS units can operate successfully in plants where narrow band transmitters had previously caused interference with plant operations.

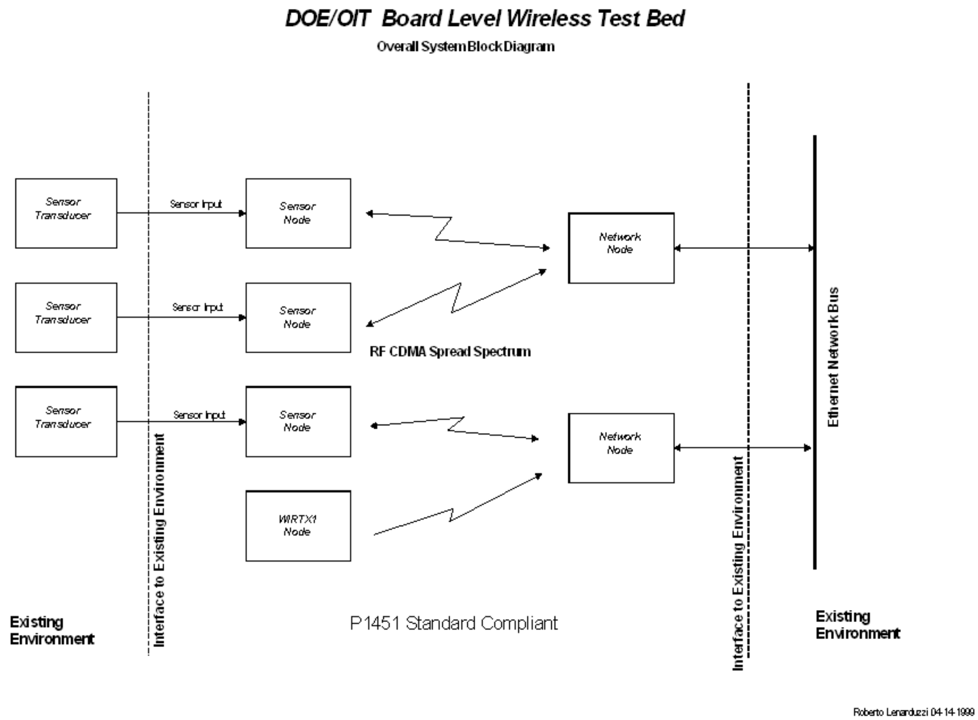

Figure 1 - Wireless Test Bed Supports Legacy and Emerging Standards

In the future the test bed will be used to optimize many data link and physical layer performance characteristics ranging from throughput to reliability. The devices currently use a wall power connection but were designed to migrate to being self powered. Future upgrades will move toward battery power and/or power harvesting. Other upgrades being considered include improved throughput so we can expand the application domain to include vibration (and similar higher bandwidth) sensors. Adding embedded intelligence to the sensor node will also expand the possible applications since pre-processing would support reducing the over-the-air bandwidth required. Ultimately, these devices will be moving toward the ORNL vision for "The Sensor IS the Network" described in an article written for Sensors Magazine (2). Each project benefits from the developments and the expertise gained from related activities. We continue to work with industry to assure the reliable, robust connectivity required while applying the advanced technologies emerging in the wireless marketplace.

Some commercial suppliers are offering proprietary systems that are being used, with limited success in some IOF installations. The test bed described here offers features that differentiate it from these other systems including the use of open standards, the use of direct sequence spread spectrum radio, and the embedded intelligence necessary to support IEEE 1451 smart sensor interfaces.

This test bed has established a new standard for wireless telemetry in the harsh environments common in the Industry of the Future (IOF) sites. We continue to receive requests for test installations to verify individual plant compatibility. Commercial companies are working with us to commercialize the components in the network to make the system available to our industry partners. Future upgrades will make the wireless test bed even more valuable as we integrate power harvesting, embedded intelligence, and improved routing algorithms. The integration of new technologies growing out of the personal communication markets will continue to make the test bed viable for years to come.

I. Introduction

The need for advanced wireless technology has been identified in the National Research Council publication *"Manufacturing Process Controls for the Industries of the Future as a Critical Technology for the Future."* The deployment challenges to be overcome in order for wireless to be a viable option include:

- **eliminating interference (assuring reliable communications);**
- **easing the deployment of intelligent, wireless sensors;**
- **developing reliable networks (robust architectures);**
- **developing remote power (long-lasting and reliable); and**
- **developing standardized communication protocols.**

This project was established by the Sensors and Controls Cross-cut program under DOE's Office of Industrial Technologies to provide wireless telemetry as an enabling technology to the nine industries known as The Industries of the Future. The wireless test bed delivered under this project demonstrated the feasibility of robust wireless sensor networks that could meet strict requirements for harsh environments common to the target industries. It resulted in a wireless test bed that was demonstrated in a paper mill and a steel plant. The test bed illustrated key protocols and components that would be required in a real-life, wireless network. The technologies for low power connectivity developed and demonstrated at the plant eased fears that the radios would interfere with existing control equipment. The same direct sequence, spread spectrum (DSSS) technology that helped assure the reliability of the connection and demonstrated that wireless communication was feasible in these plants without boosting the power to dangerous levels.

The project resulted in the development, design, fabrication, and testing of a wireless test bed network capable of relaying sensor information from the factory floor to the plant-wide Ethernet without the need for dedicated wiring. The interfaces are always industry standard to facilitate integration with existing equipment. Figure 1 illustrates the 4-20 ma sensor interface at the sensor end and the Ethernet interface at the host end. Figure 2 illustrates one of the units ready for deployment.

Several commercial suppliers offer proprietary wireless telemetry packages that are being used, with limited success, in some IOF installations. Some of the specific shortcomings of the technologies offered are detailed in the April 2001 issue of Sensors Magazine (3). The key features that differentiate the Oak Ridge Wireless Test Bed from other wireless solutions are summarized below:

1. CDMA Capable – The Code-Division, Multiple Access-capable system accommodates multiple nodes, uses FCC-compliant modulation techniques, and integrates low-power units with power control capability. The architecture supports multiple (hundreds) simultaneous transmitters without a priori knowledge of how many will be in the vicinity. It uses direct sequence spread spectrum signaling to reduce the power required to achieve the signal-to-noise ratio necessary for reliable communication (process gain). It supports a minimum of 63-chip spreading codes with a migration path to longer codes. The power supply requirements are compatible with battery operation. Also, the units support RF power control to actively control the transmit power to minimize interference and prolong battery life.
2. Open Standards – The system is built around an open standard (e.g. IEEE 1451 for local communications, IEEE 802 for networking and others for sensor interfacing.) This standard, supported by the Institute for Electrical and Electronics Engineers, provides open access to the protocols and specifications and allows multiple vendors to supply components and subsystems.
3. Security – The system provides mechanisms (RF and packet protocols) that address securing the transmitted data against eavesdropping.
4. Install Time – The installation of a few nodes (e.g. a subnet consisting of less than five sensor nodes and one network capable node) takes less than four hours.
5. Networking Adaptability – The architecture supports the capability of re-routing a sensor node through a different network node, repeater node or other node automatically, in the event that its initial communication link is broken.
6. Intersystem Compatibility – The system will not interfere with, or be compromised by other non-cooperating, but FCC-compliant, radio systems.

7. Environmentally Ruggedized – The system operates robustly (achieves at least a minimum throughput) within industry-accepted temperature, vibration and electromagnetic environments.
8. Uses unlicensed bands – The test bed operates in the Industrial, Scientific, and Medical (ISM) bands established for FCC type acceptance without individual licensing required. It does not depend on an FCC "exception permit" for operation.
9. Scalable and Modular – The system design demonstrates both modular hardware concepts and scalable protocols so that installed systems can be tailored to a wide range of throughput, size and power requirements..
10. Throughput – Each sensor node is capable of transmitting at least 100 kbits/sec of "real" data. Each network node supports an aggregate throughput of least 1 Mbps (both in its ability to receive from the sensor nodes and in its ability to re-transmit the data over the plant-wide, Ethernet network.)

The remainder of this report summarizes the work done to fulfill the project goals, how that work was accomplished, where significant advances were made, what benefits exist for industry, and what future opportunities exist for exploiting this work in follow-on activities. The appendices contain project deliverable documentation that details requirements, architecture, design, and the firmware embedded in the microcontrollers.

The Functional Description and Requirements Document (appendix A) illustrates the list of what's important and how important it is. The Architecture Specification in Appendix B details the hardware and software architectures and the embedded protocols implemented. Note that the IEEE 1451 Smart Sensor standard is used throughout the network. The final implementation of the wireless test bed incorporated the Transducer Embedded Data Sheet (TEDS) and command structures. The over-the-air protocol for the radio link is IEEE 1451 compatible but, since no standard currently exists for a wireless implementation, it only approximates the existing standards.[1]

As noted in Appendix A, the key requirements identified were

1. operate in required environment,
2. operate unattended for long periods of time,
3. easy to install and operate, and
4. support legacy interfaces and open standards.

Over the life of the project, we noted that the importance of being self-powered may have been underestimated. The installations where we've demonstrated the test bed have all had access to power but simple household outlets are not very common on the shop floors. As noted under "next steps", the addition of batteries and/or power harvesting technology will make our devices much more useful and easier to install.

The architecture specification, design drawings, and firmware listings are included to allow users who are interested, to copy what we've done, adapt our designs to include new interfaces, or to develop other products that are compatible with the standards implemented here. These detailed documents are made available but are not included in the content of the final report.

II. Approaches

The radios used in this project use the advanced technologies of 900MHz, direct sequence, spread spectrum (DSSS) with code-division, multiple access (CDMA). These technologies allow the transmitted power to be reduced to a lower level and still maintain a reliable connection. The DSSS exhibits what's known as *process gain*. Process gain is computed as

Process gain = 20dB log (chip rate)

where "chip rate" is the number of subsamples taken on each bit being transmitted. The design implemented for this project supports chip rates from 15 to 63 chips per bit.

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[1] Stephen Smith and Michael Moore from our development team, serve on the IEEE 1451 committee and are working to gain consensus on a wireless implementation incorporating the features demonstrated on this project.

Figure 2 - Project Sensor Node ready for installation at Bowater Paper Mill

The overall architecture, as described in Appendix B, emphasizes open standards, in general, and IEEE 1451 in particular. The data structures, command protocols, and even the over-the-air RF protocols are designed to be compatible with existing and emerging 1451 subparts. The diagram below (Figure 3) shows how a wired 1451 bus would be implemented. NCAP is the Network-Capable Application Processor and supports the gateway to the Ethernet. Other information about the details of this project and its implementation are documented in the April 2000 issue of Sensors Magazine (3). The details of the command interface are illustrated in Figure 4.

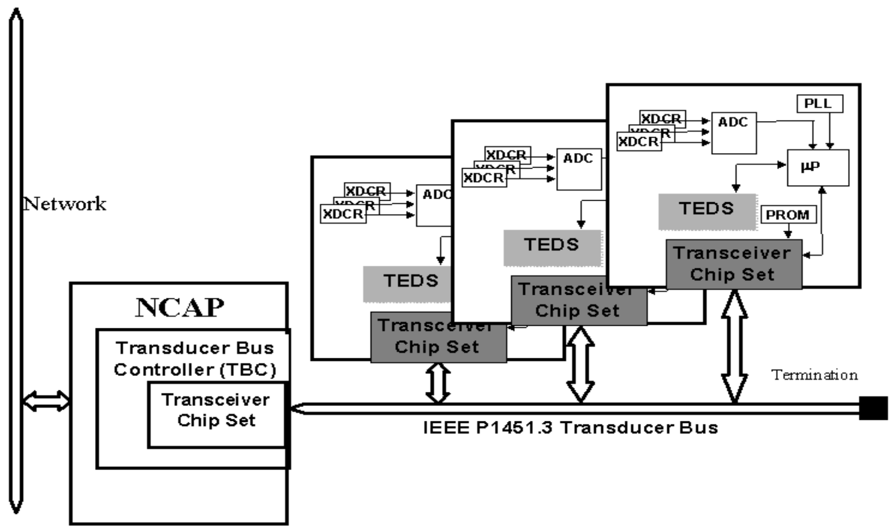

Figure 3 - IEEE 1451 Smart Sensor Standard provides backbone for this implementation.

The RF portion of the design incorporates a fairly standard heterodyne receiver topology and a direct up-conversion transmitter both operating in the 902-928 MHz band. The first version is a QPSK (quadrature PSK) half-duplex system that typically is in receive mode, but disables the receiver for the duration of the burst transmissions.

One of the key elements of the design is a programmable digital synthesizer that will accommodate all typical frequency bands along with a VCO (voltage controlled oscillator) that covers the frequencies of interest utilizing a reasonably small tuning voltage range (0-5 VDC). The front-end RF/analog components obviously have to be linear and reasonably wide bandwidth to handle the CDMA applications. For example, a data rate of 50 kbits/sec and typical spread-spectrum coding length of 63 bits (chips) would require a double-sided RF bandwidth of (50k)x(63)x2, or 6.3 MHz. Also, the AGC (automatic gain control), mixer and other components have to be very linear to prevent distortion of the CDMA signal.

Another key feature of this design is that it is a coherent receiver. While many systems accomplish the coherency via analog means, this process is performed digitally inside a Stanford-Telecom STEL-2000A chip in this design. The final down-conversion from an IF (intermediate frequency) of about 11 MHz to a baseband signal uses a numerically controlled oscillator (NCO) as the final local oscillator (LO). Feedback of the correlator output allows the NCO to be locked to the incoming digitized IF signal. All receiver processing upstream of this is accomplished with an analog LO, mixer and AGC. The downstream processing includes a digital matched correlator that despreads the data, combining the quadrature data into a single stream and performing the differential decoding.

The message-processing portion of the design includes a microprocessor that provides node processing as well as interfacing functions. It also includes an FPGA (field programmable gate array) that is used to parse the decoded stream from the STEL-2000A and determine the quality of the packets before they are passed to the node processor.

The digital portion of the circuit has been set up to accommodate both sensor nodes and network nodes. If the hardware is being used as a network node, a Hewlett-Packard NCAP (network capable application processor) and an ORNL custom daughter-board are attached to the digital circuit developed at ORNL. The daughter-board has parallel STEL-2000A IC's that allow the network to decode truly simultaneous CDMA transmissions from the sensor nodes.

If this same hardware is being used as a sensor node, the NCAP and daughter board are omitted and a small section of the same printed-circuit board is populated to accommodate the 4-20 mA transducer input. The RF section uses a standard, commercial STEL chip set that is available from Intel. This chip set allowed us to program critical parameters like chip rate, chipping codes, and spreading code lengths. The flexibility offered by this chip set outweighed the disadvantages of the relative large footprint needed.[2]

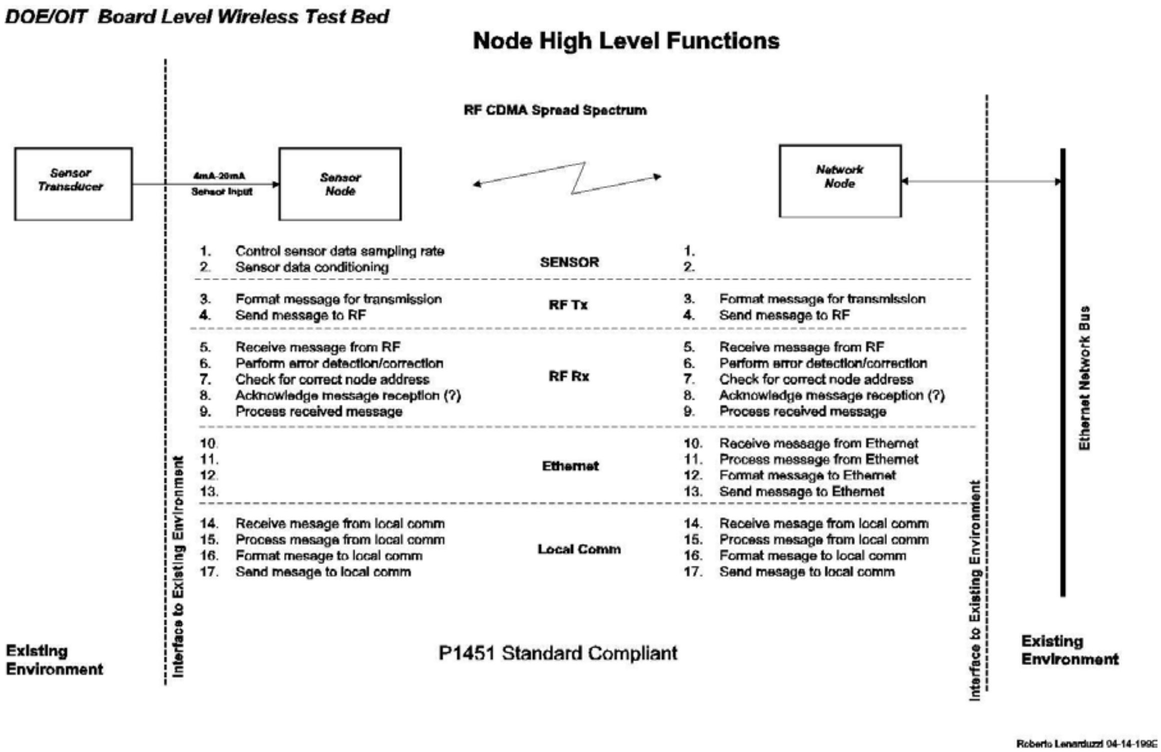

Figure 4 - High level protocols for communication interface.

The modular hardware is implemented so that a sensor node and a network node differ only with respect to a few jumpers and a daughter board. The diagrams in Figure 5, Figure 6, Figure 7, and Figure 8 illustrate the modularity of the design. The CDMA, direct-sequence spread spectrum technology that forms the basis for the design, has been demonstrated to provide improved noise immunity (thought at reduced throughput) in installations where multi-path interference is important. This "process gain" can be computed as 20db x log (chip-rate). Since our systems use a 63-bit chipping code, we get almost 40db of gain over traditional narrow band radio.

The IEEE 1451 protocol used in the interface is particularly important in industrial networks since it allows higher level information to be transmitted so that the low-level data doesn't bog down the network. Wireless 1451, once just a dream, is now being investigated by the standards committee and is benefiting from the research done on this project since some of our team members sit on that committee. Proprietary wireless interfaces carry serious disadvantages because of the potential for interference as well as the cost issue associated in a non-competitive environment.

[2] The chip set continues to be available but production has ceased so anyone interested in duplicating our design should order this chip set before supplies are exhausted.

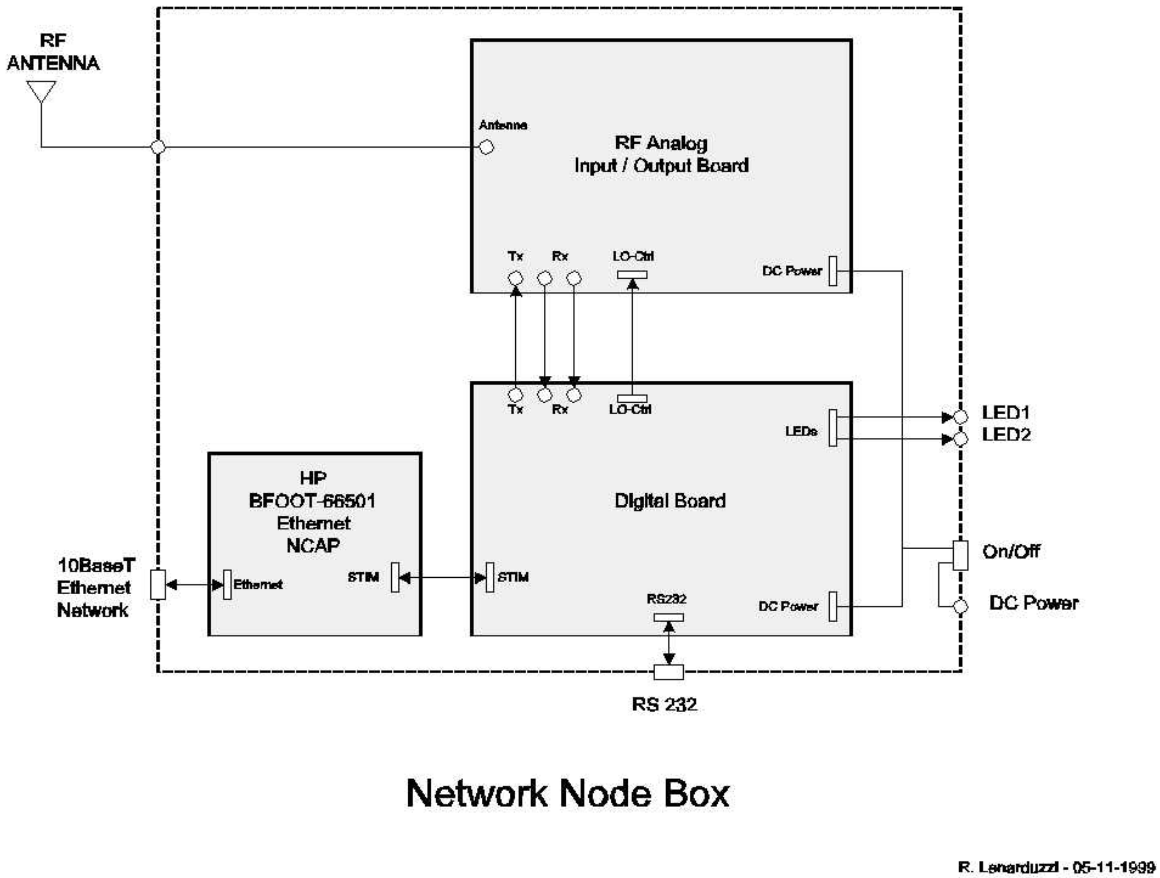

Figure 5 - Network node contains NCAP Ethernet inferface.

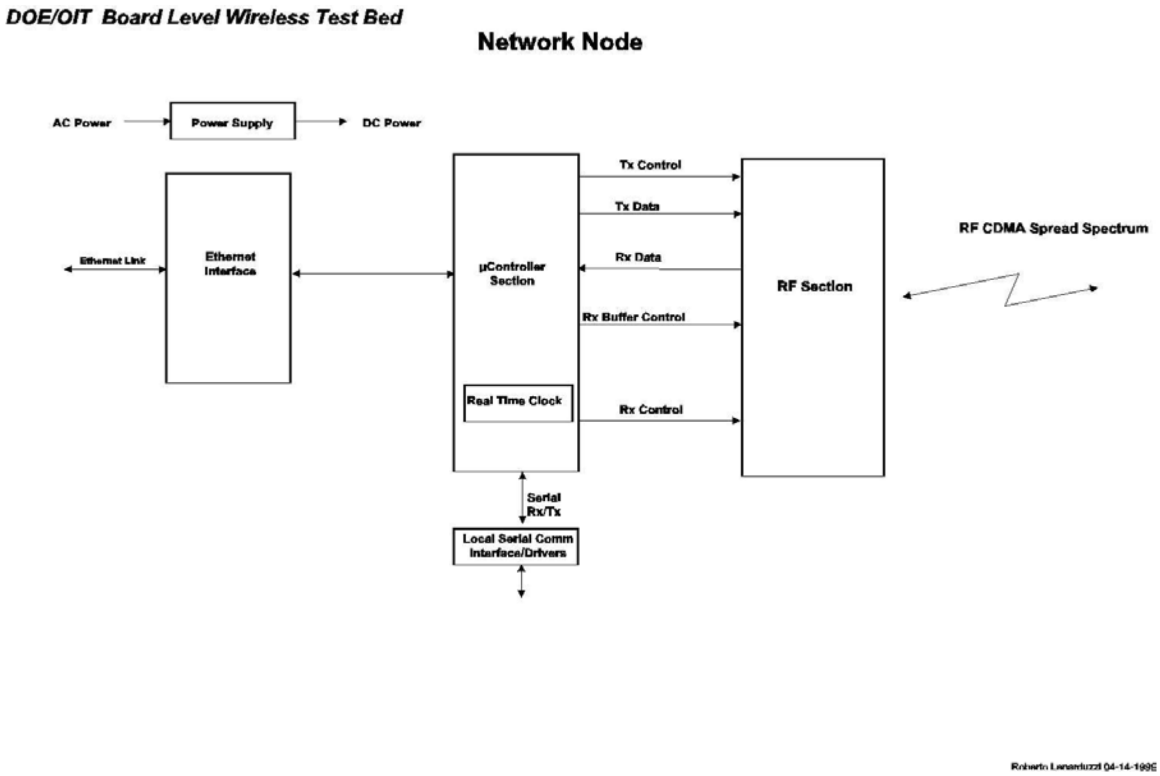

Figure 6 - Node modularity supports reuse.

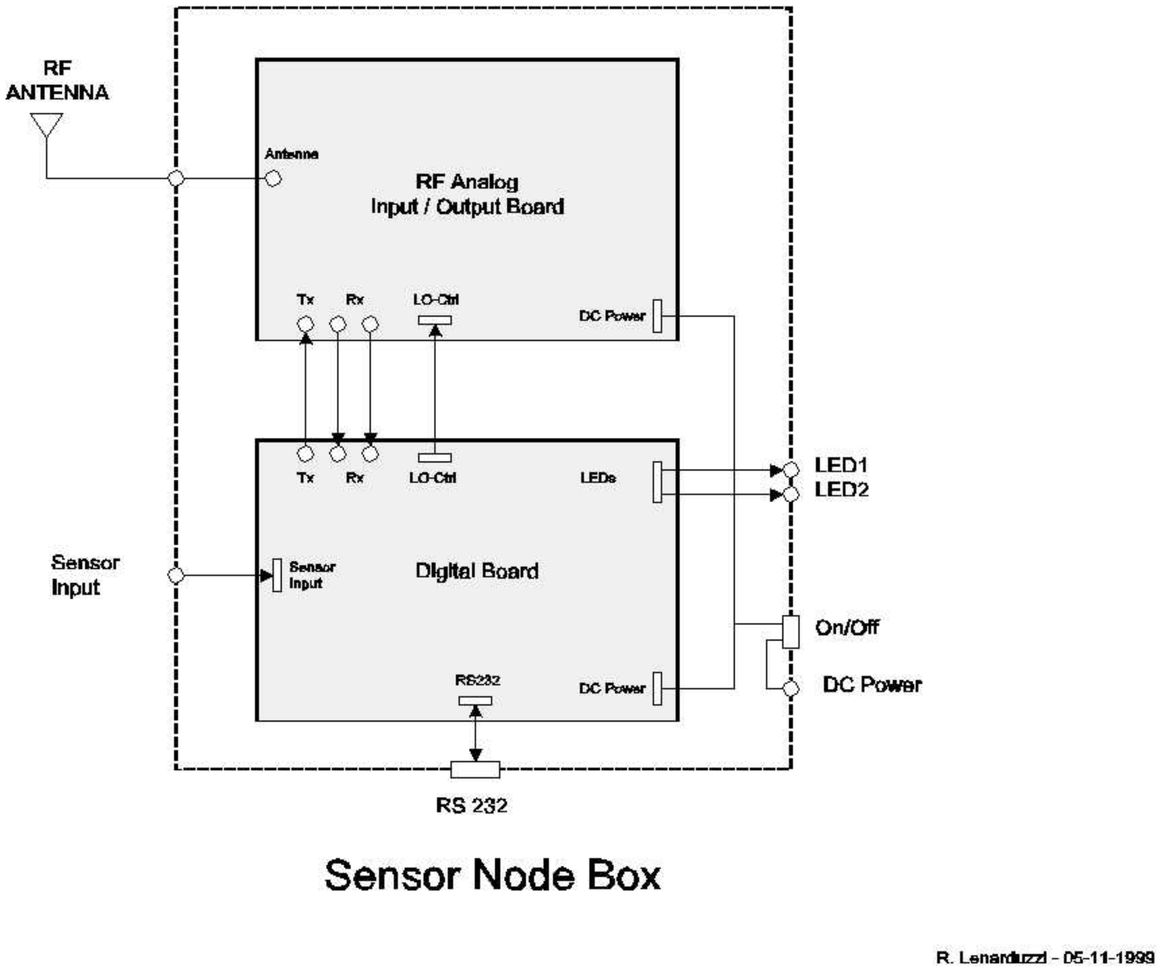

Figure 7 - Sensor Node box uses two of the same modules as the Network Node.

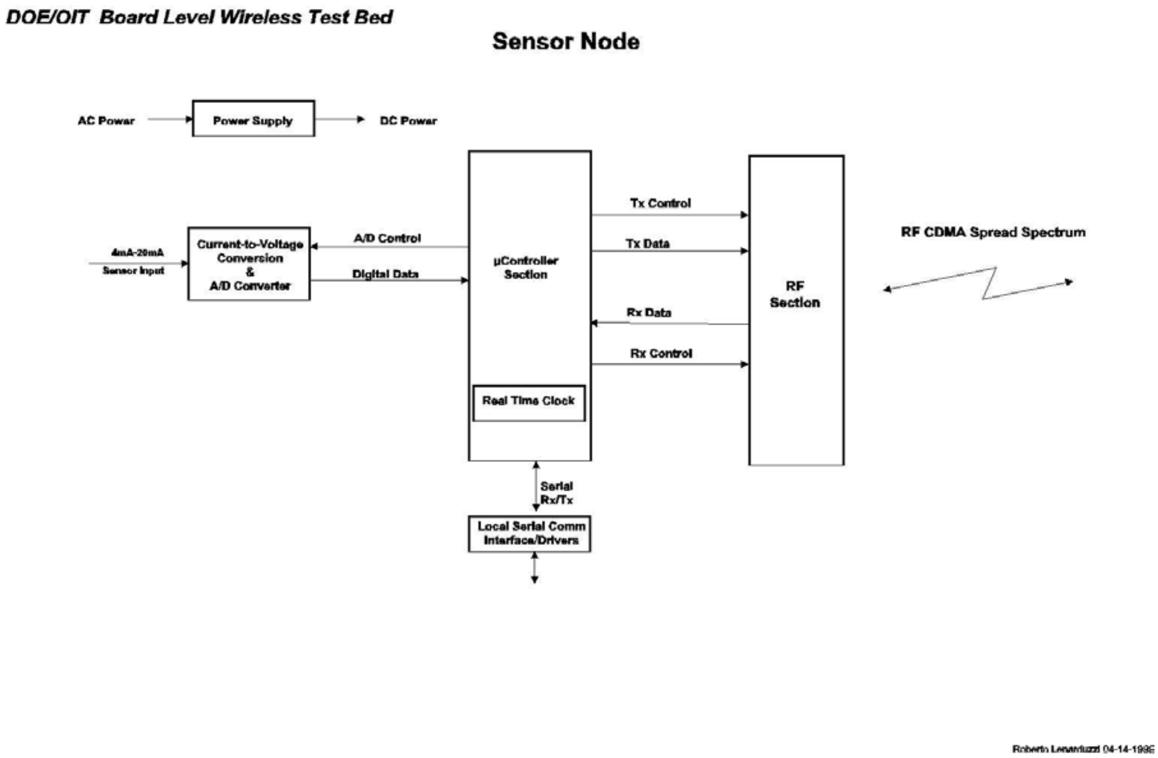

Figure 8 - The node contains sufficient embedded intelligence to support the IEEE 1451 data structures.

III. Results

The test bed was installed for a one-day test at the Bowater paper mill in Catawba, SC. This December 2000 demonstration fulfilled our main project milestone for calendar year 2000. The results of the test illustrated that the DSSS radios could perform as required in the mill without interfering with existing equipment at the plant. A more permanent installation was arranged and continues at a steel mill in Ohio. Both installations were successful and the steel mill installation continues to furnish us with valuable information about performance in harsh environments. Below are the details from these tests.

Figure 9 - Installation at Bowater Paper Mill

A. Bowater Paper Mill

Three of the ORNL devices were tested in the Bowater paper mill in Catawba, South Carolina. The major concern of the plant managers revolved around a previous demonstration where a vendor-supplied, wireless (voice) communication system interfered with the operation of their facility. After spending an hour with plant personnel, whose jobs were on the line, we came to the point that gave them the assurance they needed: the ORNL system is designed to function with one ten-thousandth the power density of most commercial (narrow-band) systems. The power came on around noon and the network came to life without incident. With little to no operator intervention, the system recorded readings from two commercial, off-the-shelf sensors at distances ranging from 3 to 140 feet. A 4-20 ma pressure sensor transmitted finger pressure while a 0-5v temperature sensor simultaneously transmitted air temperature from another location. A laptop tied to the network maintained a real-time display of the readings. The harsh environment of the plant was evident when the spectrum analyzer showed the presence of substantial background electromagnetic interference, which did not affect the operation of the wireless network. The next steps in the research will include the investigation of improving the range and throughput without increasing power, examining options for distributed intelligence to reduce bandwidth, and reducing the footprint and power requirements. A full report is included in Appendix D of this document.

The screen copy in Figure 10 shows the "good packet" rate that confirms the fidelity of the connection. Any bad packets are discarded to prevent corrupt data from entering the data stream.

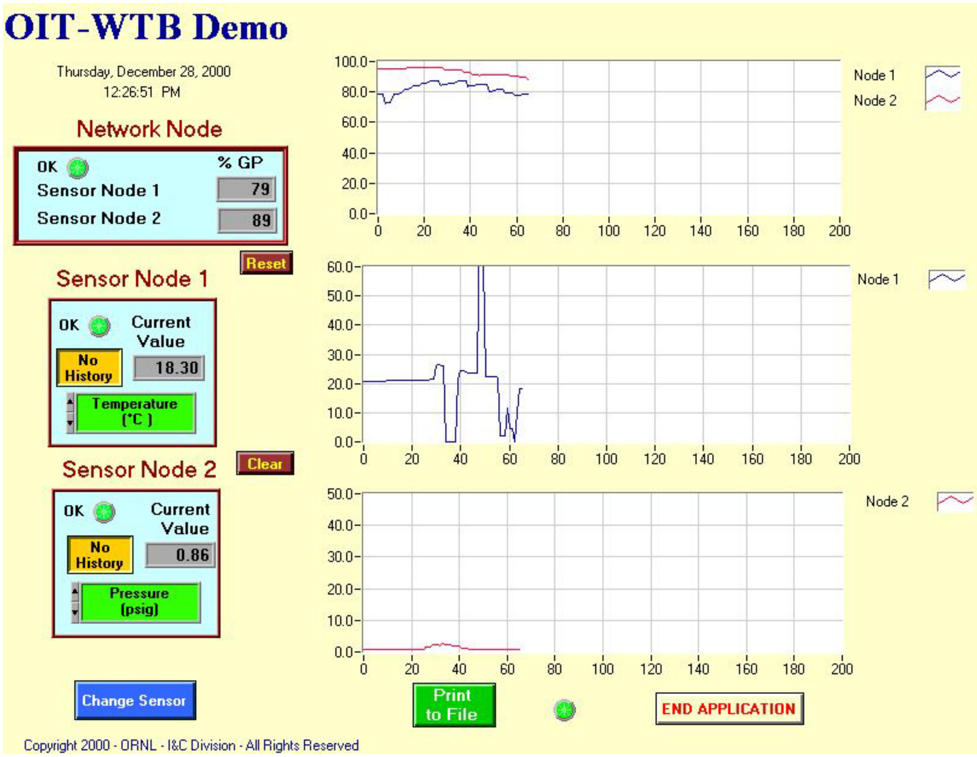

Figure 10 - Pressure sensor and temperature sensor transmit data over 100 feet for display on laptop.

This experiment verified that we could reliably transmit data at 3,000 bytes per second over distances as far as 140 feet and achieve bit error rates such that updates to the screen could occur at least once per second.

Figure 10 above shows that the data transmitted was indeed representative since the plots clearly indicate sensor and telemetry noise. The final system will employ noise and glitch filters so that any readings that represent changes beyond the physical capability of the sensor will be removed from the data stream. Leaving the raw transmitted data visible helps with system troubleshooting. The %GP indication in the upper right shows that we are communicating with 79% good packets to sensor node 1 and 89% with sensor node 2. These numbers are well within acceptable limits (only 10% good packets is required) and commensurate with commercial units running substantially more power. When a bad packet is detected, we simply trigger a retransmission until we get confirmation that valid data has been received. Since our real-time update rates are much faster than what's needed for the user interface, any rejected packets will cause no perceptible delay in the display. We also monitor the time elapsed since the last good packet so we'll know if burst errors are causing problems.

Minor upgrades are expected over the next few months to improve the good packet percentage to 95 – 99% and, thereby, improve throughput. We will also be adding the necessary filters so that the operator display will appear more consistent. The installation proceeded smoothly even though there was some apprehension about having a radio transmitter near the process equipment. Our devices, however, use radio signals that are one-ten-thousandth the power density of traditional transmitters, so we expected and saw no problems. Our research continues on improving the robustness of the connection without raising the transmitted power.

B. Steel Mill

A second installation at Timken steel, though not funded under this project, yielded important new data for our test bed. This wireless system (installed in Summer 2001) consists of a sensor/transmitter unit, an intelligent repeater and a receiver unit that is networked to a computer. This is the first permanent installation of this system that was developed as part of DOE/OIT's cross-cutting technology efforts at ORNL. This installation demonstrated the ease with which a new network could be installed in a working plant operation. Figure 11 depicts the block diagram while Figure 14 shows the overall network configuration for the Timken installation.

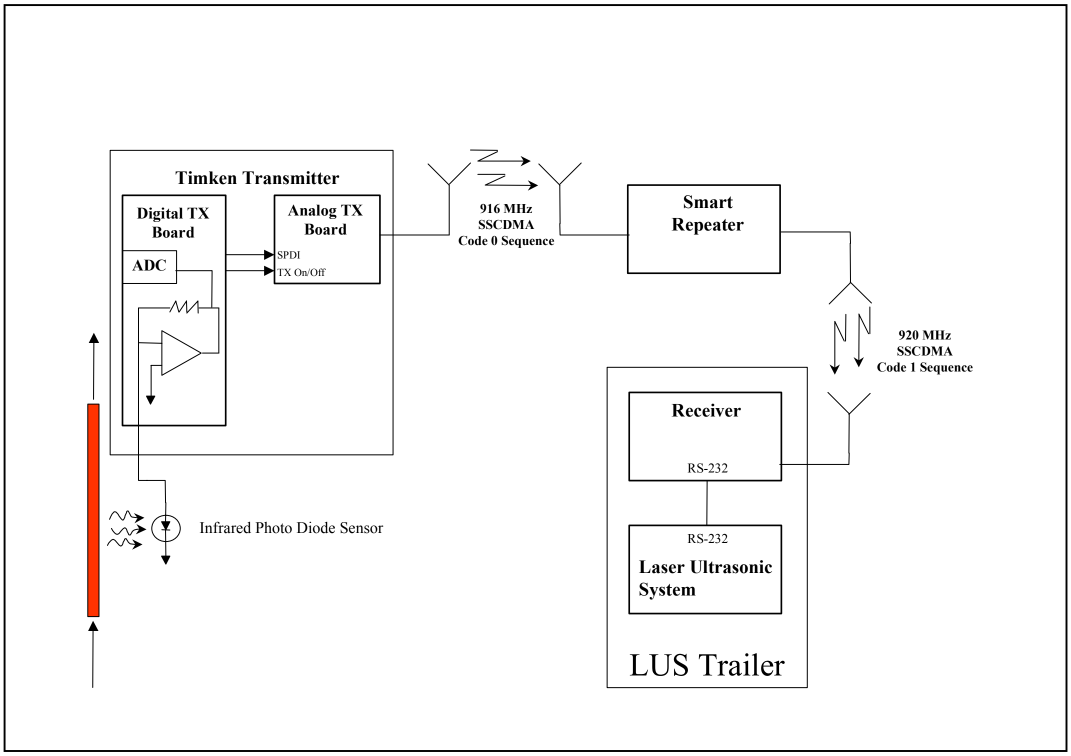

Figure 11 - Timken Wireless Tube Detector Is Used to Increase Laser Life.

The transmitter detects the presence of a tube by optically measuring the temperature (as shown in Figure 12). Every 100 milliseconds, it transmits the actual value of the detector (measured volts) via a Direct Sequence Spread Spectrum (DSSS) RF link with a center frequency of 916.4 MHz. The repeater receives the message from the transmitter (at 916.4 MHz), verifies its validity, and re-transmits it via the DSSS RF link with a center frequency of 904 MHz. The receiver receives the message from the repeater at 904 MHz and processes it. Depending on the mode of operation, it sends messages to the PC and receives commands from the PC via the serial port at 38.4 Kbits/sec. The software in the control-PC relays the information to the Laser Ultra-Sonic control unit where the decision is made to turn the laser on or off. The overall goal is to extend the life of the laser tube by providing a link that allows the laser to be off when no tube is present.

This installation was the first to use the "repeater" function built into the sensor nodes. Since the direct signal path was blocked by the process equipment, the installation required the use of a repeater node positioned high in the room. The repeater then relayed the sensor node signals to the network node outside the building. An external antenna provided even more robustness in the connection.

Figure 12 - Note the photodiode sensor connector on the front of the Timken LUS sensor node.

When the system was first installed, we saw slight interference from a nearby nationwide pager system. Moving the center frequency of our direct sequence, spread spectrum transmitter cleared up any problems that occurred. Exposure to the harsh environments of the steel mill over the long duration of this test didn't seem to adversely effect the equipment. We continue to see glitches in the digital portion of the data processing, though. Our team continues to support the installation and provide upgrades as needed. The future of this installation includes improved start-up and reconfiguration support, as well as better remote diagnostic support so that our team can trouble shoot the installation without traveling to the plant site.

C. The Navy's USS The Sullivans

A prototype direct-sequence spread spectrum wireless sensor (shown in Figure 13) was installed for testing in the Navy ship The USS The Sullivans in Jacksonville, FL. This August 1998 experiment, though not funded under this project, illustrated that the underlying technology is viable for installations where metal walls and equipment would seriously degrade traditional telemetry systems. Our test device, illustrated below, measured air temperature and successfully transmitted the reading to a laptop that was three decks above. The "catwalk" decking provided sufficient transmission for our signal to get through. Even closing the compartment doors failed to completely block our signal since the rubber gaskets on the doors providing sufficient RF leakage that the reading was available 50 feet down the corridor. The Navy's interest in wireless telemetry continues through their relationship with our industrial partner for the test, Aeptec.

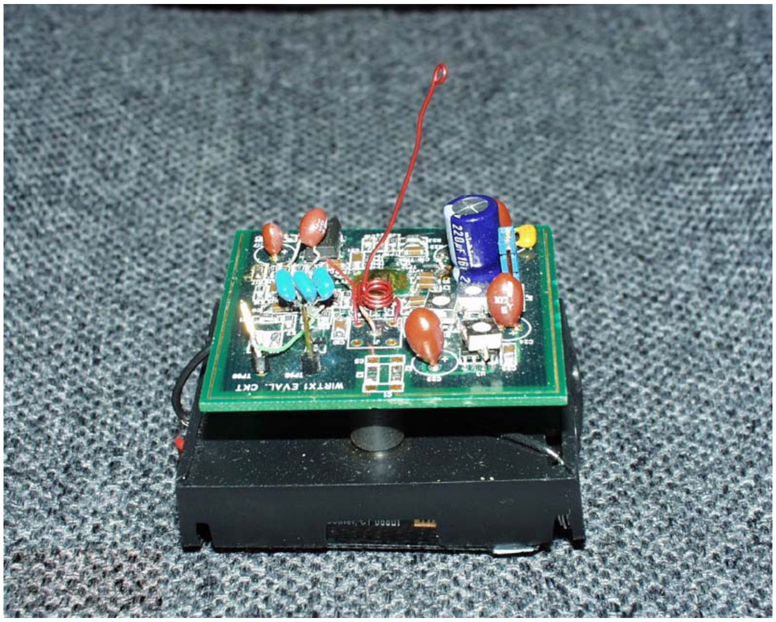

Figure 13 - ORNL's prototype wireless sensor was tested in August 1998 on-board the Navy's USS The Sullivans showing that direct-sequence, spread spectrum telemetry was suitable for these harsh environments.

Table of Field Studies and Results

Plant	Industry	Test Procedures	Results
I. Bowater, Catawba, SC	Papermill Normal operating environment	a. Record data/signals from (2) COTS sensors - 4 – 20 mA Pressure Sensor - 0 – 5.0V Temperature b. Transmit over a range of 3 feet to 140 feet without interrupting plant operations c. Test Configurations - Two sensor nodes - One network node - Laptop with display d. Test Set up : < 4 hours e. Test Duration: 1 day	System successfully transmitted two signals (4-20 mA / 0-5.0V_ for extended period of time with no interruptions and no operator intervention.
I. Timken, Ohio	Steel Plant Tube Production	a. Sense material piece in transition and signal arrival for inspection b. Transmit over range > 200 feet without plant interruptions or operator intervention. c. Field for Configuration: - Sensor/transmitter - Intelligent repeater - Receiver unit networked with computer d. Field Setup < 4 hours e. Field Operational Test > 5 months	System has been successfully deployed in the operational environment for over 5 months (June '01 to Nov. '01) as an integral part of their material flow stream.

Next Step On Current Generation SiGe Chips

Need	Technology / Innovation	Capability	Status
More RF Spectrum and bandwidth at higher frequency	SiGe HBT (heterojunction bipolar transistors)	Operate at 5.8 GHz band	2 chips have been designed and submitted for fabrication – 2 years out for intergration.
Software Tool for IC Layout	Design rule manual for AMS HBT Bicards – NDAw/AMS	Technology file to work with foundries	Complete and working
High Reliable Voltage Control Oscillators (VCO)	a. Complete resonant LCT and circuit on chip b. Off-chip inductors	Synthesize stable frequency for local oscillators and carrier frequencies	Designed and implemented on prototype chips
High Speed Sample & Feedback of VCO to Phase Detector at 6GHz	High Speed Frequency Divider - Series of High Speed Flip-Flop	Divide VCO frequency by factor of 16 and then convert to PELL logic levels to CMOS logic level	Designed and implemented on current prototype chips
Stable Voltage Reference	Temperature Compensated Bandgap Voltage Reference	Frequency, Stability to 100 times better than previous CMOS	Operating on prototype chip.

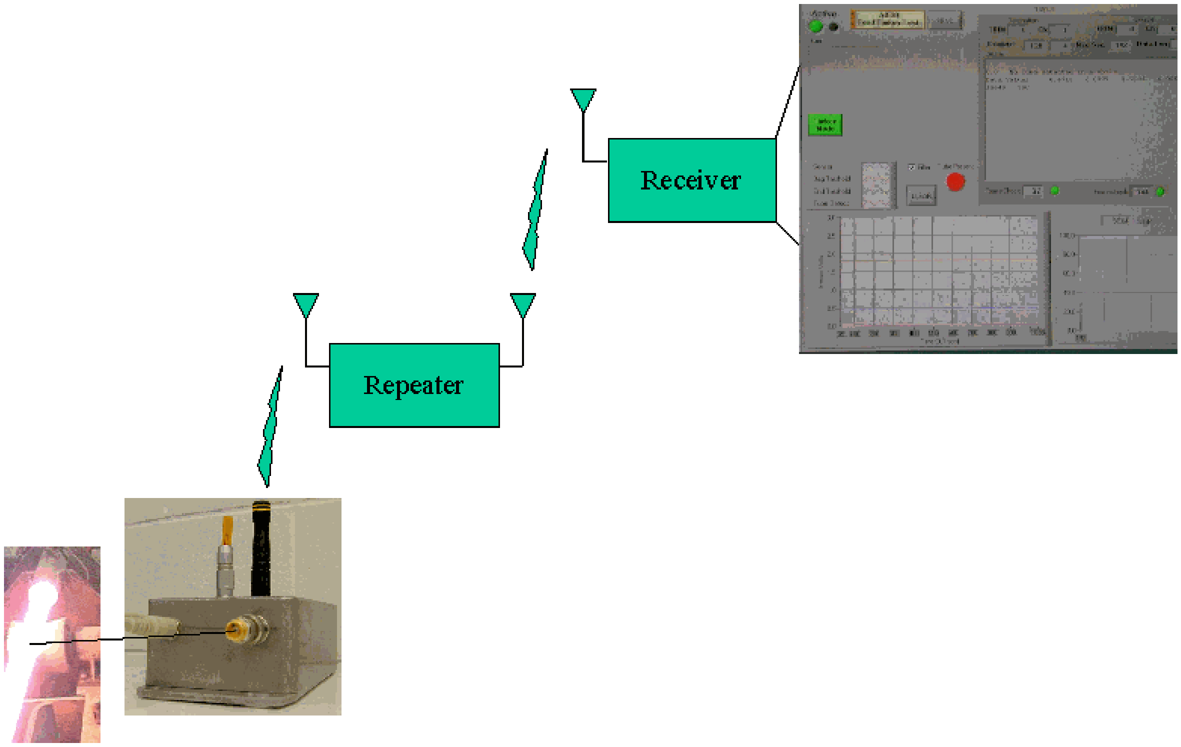

Figure 14 - Test bed installation at Timken steel mill detects and the presence of hot metal and triggers downstream processing.

IV. Advances

This test bed offers industry participants their first opportunity to have advanced radio telemetry integrated into an important measurement in their process. The 63-chip, DSSS radio combined with QPSK (quadrature phase shift keying) and CDMA compatibility provides unique characteristics for harsh environment performance. The demonstrated robustness of the connection with such low power raises the standard in what end-users should expect from wireless systems in their plants.

Other key advances from this project include implementations of the IEEE 1451 smart sensor standard in a completely open wireless network. Our current efforts on IEEE 1451 committee includes assistance in the specification of a wireless hardware interface.

Finally, the beginning of our migration to SiGe (Silicon Germanium) semiconductor technology pushes the state of the art in wireless telemetry for sensors. This new technology promises improved noise immunity, higher throughput, better line-of-sight propagation, and improved multi-path performance. All these are important migration steps in establishing a program that continuously moves wireless telemetry forward for the Industries of the Future. SiGe devices have sufficient f_T to operate efficiently in the 5.8 GHz band. Two SiGe chips have been designed and submitted for fabrication in the AMS process. One chip is designed for characterization and model verification of individual devices. The second chip consists of several of the key RF functional building blocks needed for a 5.8 GHz bi-directional transceiver. Further details are included in the section below.

V. Benefits

The end user community is very familiar with the benefits of a robust, wireless connection for their sensors. They have long struggled with wiring failures caused by flexing of the wires, connector failures due to repeated plugging and unplugging, and the problems associated with making measurements on moving components in their processes. The first installations were in areas where wired systems could be used to verify the connectivity and act as a backup in case the wireless system proved even more unreliable that the wired one. We are currently investigating applications, where wired systems would be too expensive to be practical. Some have tried wired systems and seen so many failures that the sensors were disconnected until a more reliable connection could be established.

Industrial partners in steel, paper, and petrochemical have all expressed interest in the agility provided by wireless networks. Sometimes, troubleshooting their processes could be facilitated by the quick installation of a test sensor. Improvements in efficiencies or reduction in emissions are clear benefits in many of these installations. Some facilities have modular manufacturing lines where subsystems are moved in and out of the production line to meet particular customer requirements for quality or size. Wiring connections for these mobile subsystems are problematic and result in uninstrumented components. Wireless connectivity is viewed as important for making these modular lines more robust.

VI. Next Steps

Our next steps include small ones to improve the test bed in the near future, near term improvements that will move the test bed towards the future goals, and long term steps that establish the goals and roadmaps for our wireless telemetry program. All these are requirements driven to meet the needs of the industries in this market. Near term goals include improving noise immunity for more robust communication, improving data rates to support new sensor types, adding the first stages of embedded intelligence, and upgrading the packaging to provide a more robust installation. Longer term goals include continuing to reduce the power required for reliable communications, advancing the embedding intelligence in the sensor nodes to further reduce bandwidth requirements in the transmission link, and adding degrees of autonomy to the sensor suite to support goal-directed rather than procedure directed configurations.

SiGe – Two Years Out

As the need for more RF spectrum and bandwidth continues to grow, the need for systems operating at ever higher frequencies grows. Bipolar junction devices have historically been the workhorse for silicon technology RF applications up to a few GHz. But as the feature sizes of CMOS (Complementary Metal Oxide Semiconductor) processes shrink the devices have become suitable for RF applications. Currently CMOS circuits are fairly common in RF circuits operating at 1 GHz and below, and CMOS circuits operating up to 2.4 GHz are in development. However, frequencies between 4 GHz and 10 GHz are still largely the domain of bipolar devices, especially silicon-germanium devices.

SiGe HBT (heterojunction bipolar transistors) devices have sufficient f_T to operate efficiently in the 5.8 GHz band. The AMS (Austrian Micro Systems) process is specified for f_T as high as 30 GHz. Two SiGe chips have been designed and submitted for fabrication in the AMS process. One chip is designed for characterization and model verification of individual devices. The second chip consists of several of the key RF functional building blocks needed for a 5.8 GHz bi-directional transceiver.

Adding a little germanium to the recipe for silicon bipolar devices improves the performance of the devices considerably. It will decrease the transit time through the base region making the device faster, decreases the base resistance allowing for lower noise devices, and increase the early voltage which allows better current sources and higher gain. These devices are called heterojunction bipolar transistors (HBT) and the process is referred to as silicon-germanium (SiGe). The process consists of conventional silicon process steps with the addition of one epitaxial layer for the germanium-loaded base layer.

MOSIS, a user facility for Application Specific Integrated Circuit fabrication, has recently added a SiGe HBT process to their list of available foundries. This process is provided by Austria Micro Systems (AMS), and is their 0.8 micron HBT BiCMOS process. This gives the designer a standard 0.8 micron CMOS process, which is preferred for digital designs, along with a SiGe HBT process. This allows the designer a great deal of flexibility and options to optimize a circuit for a specific function.

The software tool for integrated circuit layout used at ORNL is called MAGIC. It provides for the geometrical layout patterns and also checks for design rule violations regarding line widths and spacings. MAGIC also provides netlist extractions with some parasitic capacitance included for circuit simulation and verification. In order for it to work with a particular foundry process, a "technology file" must be created that defines the various layers used by that process, and defines the geometrical rules. Under a Non-Disclosure Agreement with AMS, the Design Rule Manual was obtained for the AMS HBT BiCMOS process which provided the information necessary to create the technology file for MAGIC.

Two different test chips were designed and submitted for fabrication. The first is a device test chip and contains only individual circuit devices and is intended for characterization and modeling purposes. It consists of several sizes and configurations of HBT transistors, some PNP bipolar transistors, several NMOS and PMOS transistors, a voltage-controlled variable capacitor, some spiral inductor variations, and several other types of devices available through this process. This chip will be measured and compared with model predictions for the individual devices.

The second chip, shown in Figure 15, contains several critical RF building block circuits. Most of the functional blocks needed to implement a RF system are present on this chip. For a receiver, one of the most critical blocks is a good low noise front end amplifier (LNA). Two LNA concepts are included on this chip for study. One version is completely monolithic implementation, while the other requires several passive components external to the chip for biasing and impedance matching. A mixer design is implemented on this chip. It is a classic Gilbert mixer topology.

Another important function in RF systems is a phase lock loop (PLL) to synthesize a stable frequency for local oscillators and carrier frequencies. The phase detector section of a PLL is usually a digital circuit consisting of standard logic cells, and as such was not included on this chip. However, the voltage controlled oscillator (VCO) which must operate up to about 6 GHz is crucial. Two versions of the VCO circuit are on this chip. One version includes a complete resonant LC tank circuit on the chip, and so depends on the quality and accuracy of the spiral inductors. Another VCO of the same architecture is present which requires off-chip inductors to complete the resonant circuit.

In order to function in a PLL, the output of a VCO must be sampled and fed back to the phase detector of the PLL. CMOS logic circuits are unable to operate anywhere near the 6 GHz requirements of the VCO, so a high speed frequency divider, or prescaler, is required to reduce the frequency to a range where the CMOS logic can handle it. A prescaler circuit is included on this chip, and connected to one of the VCO circuits internally. The prescaler is constructed of a series of high speed flip-flops made from the HBT devices to divide the VCO frequency by a factor of 16, and then convert from PECL logic levels to CMOS logic levels.

Another important requirement for almost any system involving analog functions is the need for a stable voltage reference. A temperature compensated bandgap voltage reference has been included on this test chip.

Testing of both of these chips will require the layout and fabrication of several circuit boards to attach the chips and needed supply voltages, biasing, and input and output signals. Figure 16 shows a block diagram of a conceptual RF system. The green shaded areas indicate the blocks that are prototyped on the test chip. The red shaded areas are functions that still are needed. Blocks that are not shaded indicate functions that must be implemented off chip, or that will be realized in standard CMOS logic cells. The base-band function will be a separate sub-micron CMOS chip. Not shown in the block diagram, but still important to a high quality RF system, is various filter functions for the RF and IF sections that help reduce the effects of out-of-band interference signals and noise. These filters are typically surface acoustic wave (SAW) devices.

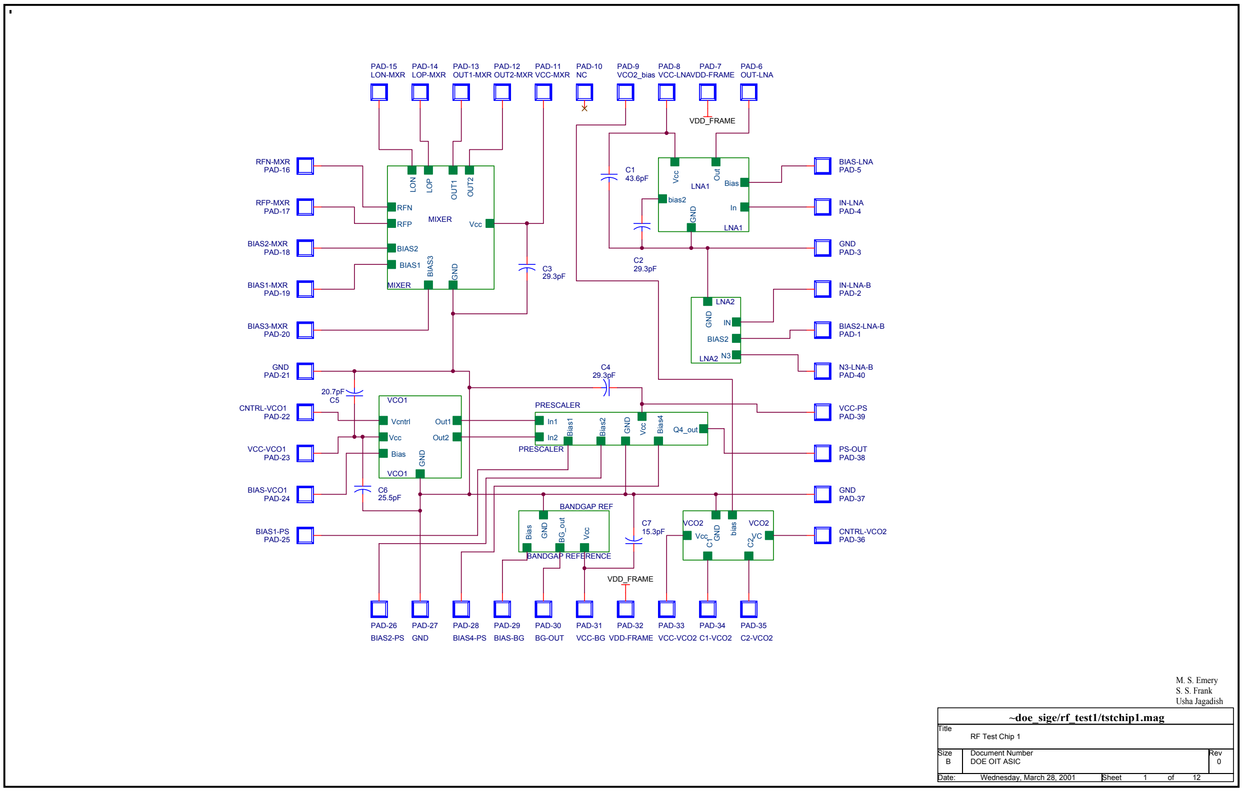

Figure 15- Functional block diagram of test circuits and pin-out of test chip submitted in the AMS SiGe process. The chip contains a mixer circuit, two versions of low noise amplifiers, two voltage controlled oscillators, a frequency divider, and a temperature reference.

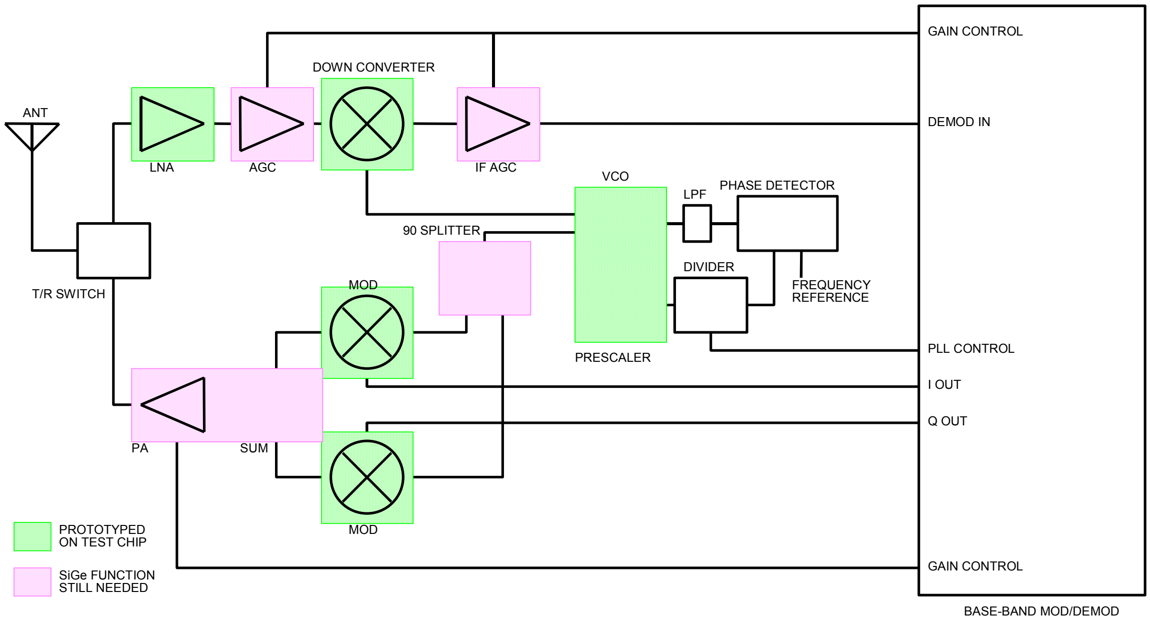

Figure 16 - Conceptual block diagram for RF communication system. Blocks with no shading indicate either functions off the RF chip or standard logic cells.

Long-Term Migration Path

A new paradigm is emerging where sensors are no longer viewed as a discrete combination of transducer, analog signal conditioning, digitization, digital signal processing, information analysis, sensor fusion, information analysis, decision making, telemetry, and sensor verification components (see Figure 17). Instead, the transducer will be integrated with the signal conditioning, digitization, intelligent processing, and communication electronics all on the same silicon substrate (Figure 18). ***This holds the potential for providing a new generation of sensors that get better and cheaper every year*** (tracking Moore's Law like integrated circuits and home computers). The telesensor illustrated (funded outside this project) demonstrates the feasibility of low cost solutions once we understand the requirements and architectural issues needed to address the needs of the IOF markets. The long-range future clearly points to the ORNL vision of "The Sensor IS the Network". This concept has been highlighted in a series of articles in Sensors Magazine and is illustrated in Figure 19.

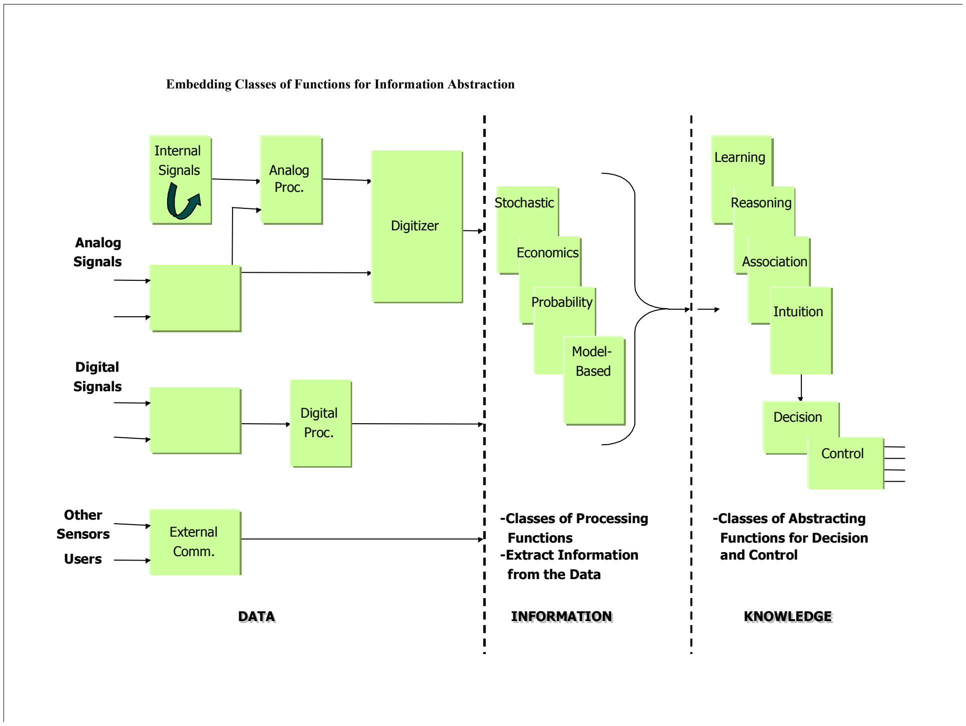

Figure 17 - Embedding all processing in a single package provides powerful driver for a new class of sensor.

Achieving the performance necessary for these new concepts requires a migration to a new semiconductor technology. This SiGe technology discussed above is emerging as part of the commercial wireless marketplace, particularly in cell phones and broadband wireless data networks. Leveraging this technology is an important part of the future of the ORNL program. As the first step towards this future, our project began to explore the possibilities by designing and fabricating some prototypic devices for testing in our program.

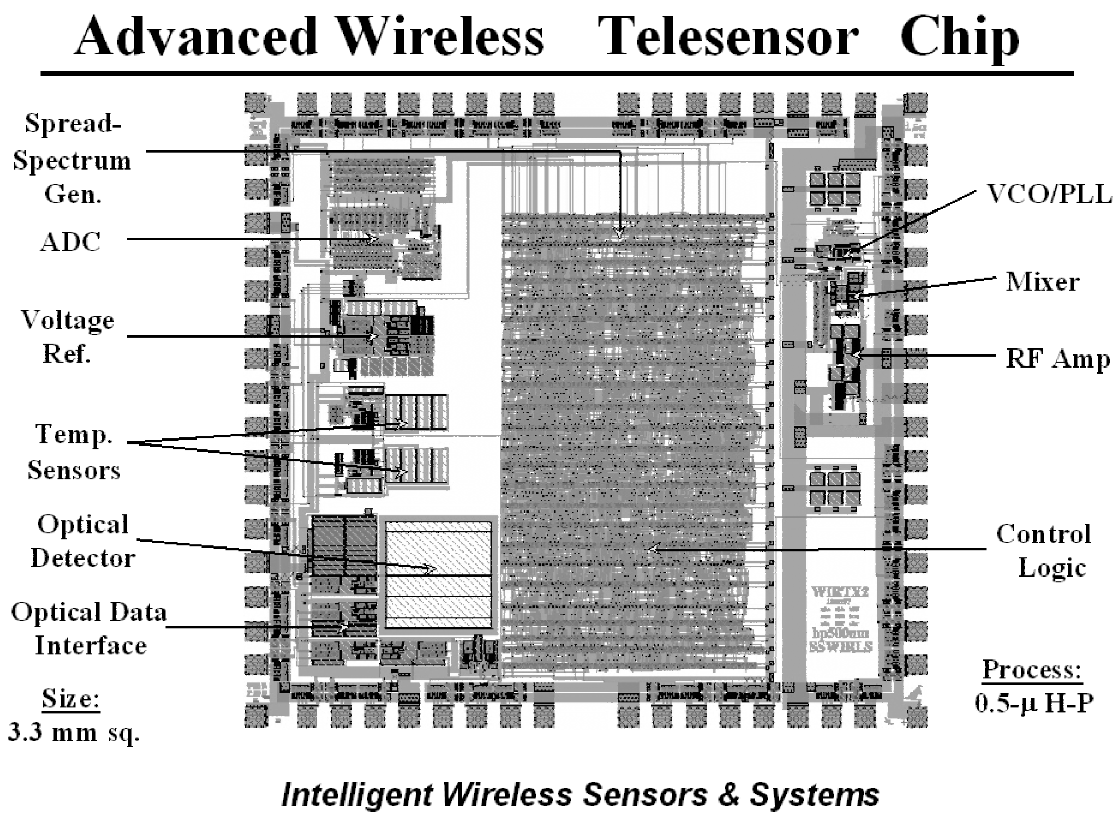

Figure 18 - Fully integrated sensor and telemetry systems will emerge as low cost solutions to ubiquitous sensing.

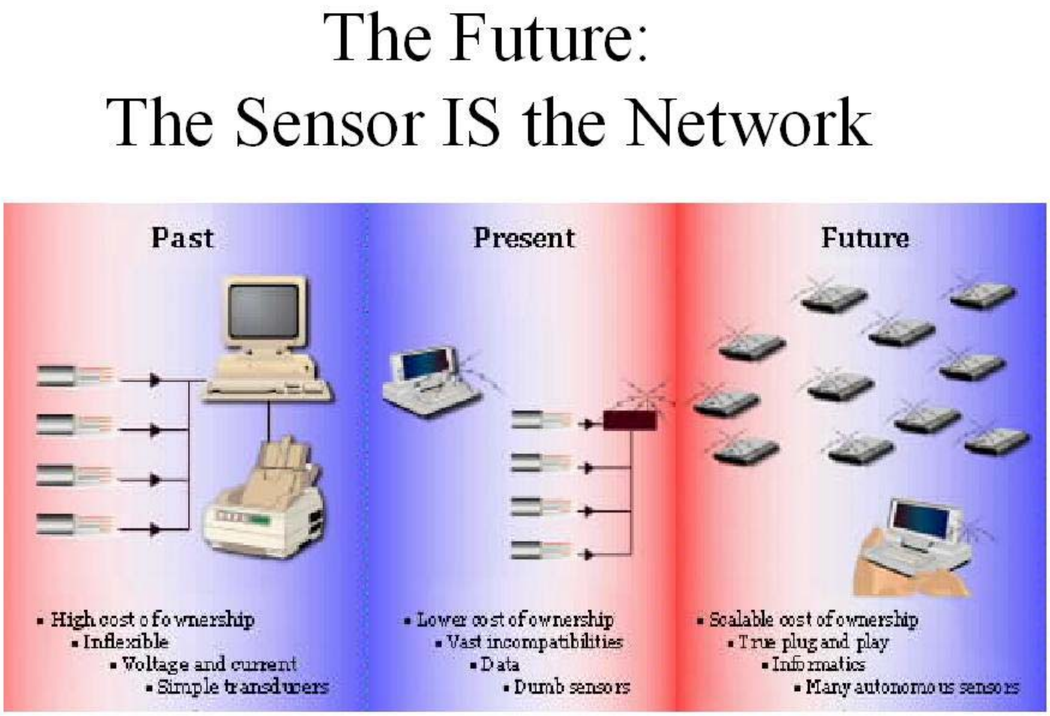

Figure 19 - The migration from a wire per sensor to completely wireless connectivity holds great promise.

Near-Term Improvements Planned

The immediate future for our network includes some of the important steps towards this vision. We are currently working to make improvements in packaging, performance, embedded intelligence, and network access. The improvements planned for packaging include reducing the footprint, integrating the antenna, integrating a self-powering technology, and making the packaging more robust for harsh environments. The performance enhancements include moving to SiGe technology with an increase in the operating frequency to 5.4GHz. Also, we are looking at lengthening the spreading code to 128-bits as well as upgrading the base-band processing to support 1.0Mbit/second transmission. The first implementation was designed to meet the requirements for simple sensors like temperature, humidity, and pressure. Upgrades to the analog-to-digital converter will allow us to look at measurements like vibration, acoustic monitoring, or waveform analysis.

Adding embedded intelligence to the sensor node will also expand the possible applications since pre-processing would be able to reduce the over-the-air bandwidth required. Critical to this would be research and development in power harvesting, power management, and low power electronics as well as the intelligence to extract features from the data stream. Current digital signal processing (DSP) chips use too much power to be effectively integrated into these low power sensor nodes.

VII. Conclusion

The project successfully completed the mission established at its inception, in 1998. The overall goal was to get the emerging wireless technology to the point where end users from the Industries of the Future would have sufficient confidence that they would join in cost-shared partnerships to install prototype systems in their own facilities. We are now getting those kinds of responses. We now have our first commercial partner, Graviton, interested in pursuing the commercialization of the technologies prototyped in this project. In addition, a DOD partner has recently joined our team and will be using ORNL-based wireless technology to supply advanced capability to the US military.

The ORNL base wireless program continues to move forward with the relationship with OIT as a key part of that program. The opportunities available by managing the projects here for mutual benefit continue to offer maximum return on investment for R&D funds invested here. Our experience and expertise continues to be recognized through requested articles in Sensors Magazine and invited conference talks and papers for ISA[3], Sensors Expo, and others.

The technologies developed for this project will continue to mature and grow, exploiting developments in other projects and commercial communications, exploding broadband wireless networking markets. Our continued hope is to help make wireless connectivity a lower cost than wired options and more reliable and secure. Further DOE work is expected as we continue our program.

[3] The International Society for Instrumentation, Systems, and Automation – formerly Instrument Society of America

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(2) Wayne W. Manges, et al, *Intelligent Wireless Sensors for Industrial Manufacturing*, Sensors – The Journal For Applied Sensing Technology, April 2000, volume 17, no. 4, pages 44-55.

(3) Wayne W. Manges, et al, *Wireless Sensors – Buyer Beware*, Sensors – The Journal of Applied Sensing Technology, April 2001, vol. 18, no. 4, pp. 18 – 30.

(4) G. O. Allgood, et al, *It's Time for Sensors to Go Wireless, Part 2: Take a Good Technology and Make It an Economic Success* – Sensors-The Journal of Applied Sensing Technology, May 1999, vol. 16, no. 5, pp. 70-80

Appendix A
Functional Description and Requirements Document

DOE/OIT Wireless Sensor Technology
DRAFT Requirements Document

October 5, 1999
Wayne W. Manges, Glenn O. Allgood,
Timothy J. McIntyre, Stephen F. Smith

I. Scope

This document describes the requirements for the development, demonstration, and deployment of a suite of wireless sensors for DOE's Industries of the Future Program. This requirements document should be viewed in parallel with the other documents defining the project: (1) The Architecture Specification which the architecture for the wireless sensor network, and (2) The Design Strategy which defines an approach to meeting the requirements and the architecture specification.

Requirements, as specified in this document, include functional requirements and design requirements. The functional requirements define what the system has to do and the design requirements define how the system is expected to do it. The relative importance of each of the requirements is critical to a successful design so a chart is included in the conclusion section that lists the requirements outlined here and places a relative weight on each one. The design strategy uses these weighted requirements to evaluate design alternatives.

All the documents in the series describe a solution that is unconstrained by time and funds. The design strategy contains a section describing the actual phase I deliverables. The weighted requirements are used to make the tradeoffs necessary under the time and funding constraints imposed at the time of the scheduled deployment.

The overall goal of the project is to provide a path that results in a series of demonstrations leading to a deployable system that can be used to interface existing (wired) sensors to a wireless network that can then relay the data to the existing plant backbone. The most critical system requirements for this project are that it must operate in the IOF environment (electromagnetic, temperature, vibration, etc) and it must operate with little or no attention from operators. The wireless units must fit, as smoothly as possible, into the existing plant infrastructure including training, deployment, troubleshooting, and repairing of the units and the network.

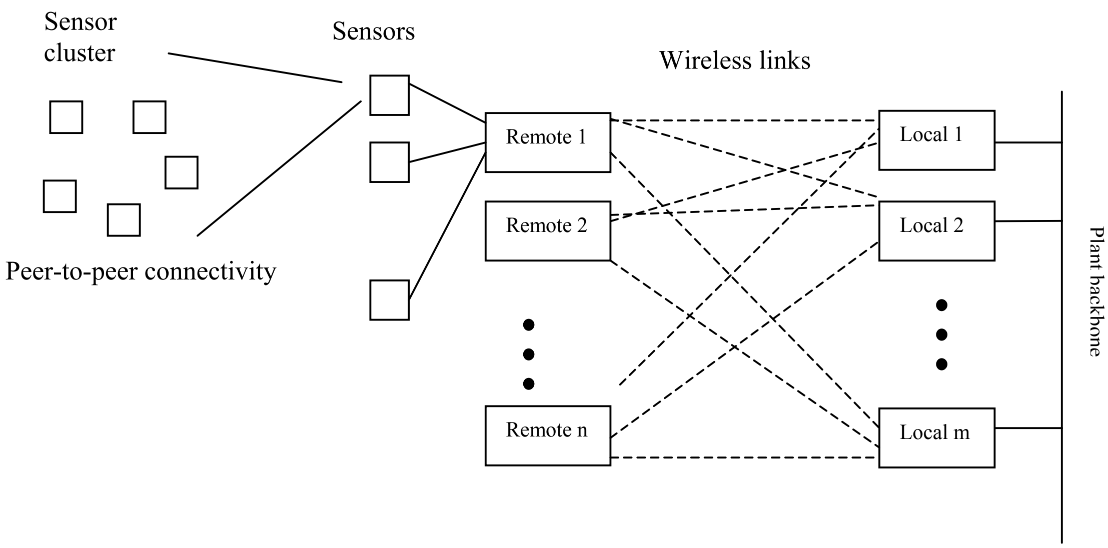
The design of the system is constrained to include only open systems that can be supported by a number of vendors. The IEEE 1451 standard is being used as a template for the design. Compliant data structures and communications protocols will be used wherever possible. The maturation of IEEE 1451 is expected to incorporate a wireless link, which can be integrated with the design as the project, progresses.

The remainder of this document details the requirements listed above and describes some of the derivative requirements that come from the main ones listed here. The conclusion outlines a path forward based on the requirements included here.

II. Systems Requirements

The ultimate vision for the system includes a wireless network that can be configured to have individual sensors act as nodes or to have cooperating sensors interact to form an intelligent subsystem or a group of subsystems interact to form an intelligent process unit. The requirements listed here emphasize the initial demonstration but also reflect the needs for the final system vision. The weights included are on a scale from 1 to 10 with the higher scores representing those that are most important. Compromises necessary during the design and fabrication are evaluated against these requirements to determine a reasonable path.

The requirements are divided into functionality, performance, and utility-related requirements. The functionality-related requirements specify what the system must do in order to fulfill its intended purpose. The performance requirements specify how well the system performs the required functions from a process perspective. The utility-related requirements specify how easy the system is to install, configure, use, troubleshoot, and repair.



Functionality:
1) Human Interface supports three modes of operation - (weight =5) - The three modes are User, Superuser, and Developer. This drives the design issues related to security, data integrity, and ease of use.
2) Analog Inputs (weight = 9) - This drives the design for the process interface requirements: a typical (for the IOF) analog signal will be connected to the field device.
3) Discrete Inputs (weight = 5) - This drives the design for the field input interface for sensors that have only two states - on/off, open/closed, etc.
4) Digital Inputs (weight = 2) - This forces consideration for serial and parallel sensor interfaces: RS232, RS485, IEEE 488, etc).
5) Supports Legacy Sensors and Systems (weight = 9) - The system must accept standard (existing) sensor interfaces and data bus backbones.
6) Y2K Compliant (weight = 5) - The system must support time and date codes consistent with the year 2000 and beyond.

Performance:
1) Update Rate ≥ 100 samples/second (weight = 6) - Each sensor can be sampled at a rate of at least 100 samples/second.
2) Time Jitter ≤ 100 ms (weight = 6) - Sensors sampled around the network must be correlated with a timing standard accurate to within 100 milliseconds.

3) Error Probability < 1:10,000,000 (weight = 7) - The communications protocols must produce accurate transmissions with the corrected bit error rate less than 1 in 10^9 in the operating environment.

Utility:

1) Low Deployment Cost - (weight = 2) - A clear path to a low deployment cost should be evident in the design, packaging, and architecture.
2) Low Development Cost - (weight = 7) - The design can be developed, prototyped and tested for a reasonable cost.
3) Synergism (weight = 5) - A clear opportunity exists for sharing costs and technologies with related projects.
4) Operate Unattended for a year (weight = 9) - Once installed, the system can continue to operate, within the defined level of performance, without major intervention for a year.
5) Operate in IOF typical environment (weight = 9) - This drives design requirements for robustness with respect to temperature, humidity, vibration, electromagnetic considerations, and power.
6) Install 1 in 5 minutes (weight = 2) - Installation should be simple enough that a single person can install, configure, test, and integrate a single additional device in 5 minutes.
7) Install 10 in 30 minutes (weight = 4) Installation of a group of devices should be straightforward - again including installation, configuration, testing, and integration.
8) Matchbox size (weight = 5). The physical size of the devices must be consistent with their use in the IOF environment.
9) Less than TBD hrs of training rqd (weight = 5) Installation, configuration, troubleshooting, and replacement should take little or no training.
10) Modularity at IOF standards (weight = 5) - Field replaceable unit repair and functional modularity should be consistent with other IOF sensor devices.
11) Low Risk Factor - (weight = 5) - Likelihood that the system will meet the expectations.
12) High Wow Factor (weight = 5) - Likelihood that the system will impress industry, DOE, and other lab personnel.
13) High Probability of Working (weight = 5) - Likelihood that the system will actually work, when deployed, in a real plant.

III Conclusion:

The requirements listed above are used to evaluate various design alternatives. As described in the Kepner Tregoe Decision Making procedure, each alternative considered is rated (1 to 10) on how well it achieves each of the requirements. The score in each category is the product of the weight and the rating (a score of 100 is perfect). Each column is then summed to determine which options are most likely to meet the highest weighted requirements. The Excel table below contains the requirements listed above and our assessment of the four alternatives considered.

DOE/OIT Wireless Sensors

30-Mar-99

W. W. Manges, T. J. McIntyre,
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Option A = chips on a board, Wirtx2 optional
Option B = new receiver chip, updated Wirtx
Option C = Updated Wirtx, COTS receiver
Option D = Lance's Receiver, updated Wirtx

The attribute and weights apply to the requirements for the demo
with a path to long term goals.

Attribute	Weight	Option A	Option B	Option C	Option D
Low Development cost	2	5	5	2	2
Low Deployment Cost	7	9	2	2	2
Synergism	5	5	5	2	5
Operate unattended 1 yr	9	9	5	2	3
Operate in IOF typical env.	9	9	5	2	3
Error prob. <1:10000000	7	8	5	2	4
Update rate > 100samples/s	6				
Time Jitter < 100ms	6				
Human IF 3 modes of ops	5	9	2	2	2
Install 1 in 5 minutes	2	8	9	2	9
Install 10 in 30 minutes	4	5	5	2	3
Supports legacy sensors & sys.	9	9	5	5	5
Y2K compliant	5	9	9	2	5
Matchbox size	5	4	9	2	5
Discrete inputs	5	9	5	5	5
Analog inputs	9	9	9	9	9
Digital inputs	2	5	3	3	3
< tbd hrs training rqd	5	5	9	2	9
Modularity at IOF stds	5	9	3	2	4
Low risk factor	5	2	6	10	10
High Wow factor	5	6	10	2	2
High prob of working	5	10	3	2	2
Total Score		**839**	**624**	**407**	**512**

As this chart shows, Option A is a clear winner. The design for this option must take into account the constraints imposed by the Architecture Specification. The Design Document contains the detailed description of how the system will be built. The reader is referred to those documents for related information.

Appendix B

DOE/OIT Wireless Project
Architecture Specification

Wayne Manges, Glenn Allgood, Tim McIntyre,
Steve Batsell, Mike Moore, Roberto Lenarduzzi

Introduction

The purpose of this document is to provide sufficient detail about the proposed architecture for the DOE/OIT Wireless Testbed so that interested organizations can begin to design and build components that can be integrated and tested on the testbed. This document (and the architecture) will evolve, however, as the project and technology mature toward a final solution. With that in mind, individuals should be careful about committing to some of the details before a firm understanding of the consequences has been ascertained. We expect extensive conversations, test results, and other documents will be used to keep interested parties informed regarding the current status of the architecture and the testbed.

The remainder of the document describes the attributes of a consistent, robust architecture and some level of detail on the approach being proposed for the first and subsequent implementations. Where decisions (and trade-offs) are required, we tried to furnish sufficient information to allow readers to track the decision process. Please let us know if you have any suggestions for improvements to the document.

Attributes Of A Successful Architecture

A viable architecture for this project should be extensible, flexible, open to third party implementations, support phased implementation, support multi-level hardware and software, be robust, and have RAM attributes consistent with other industrial systems. This section details each of these attributes and describes the specific criteria that will be used to evaluate the architecture's potential.

To the extent possible, this implementation will be a wireless implementation of the IEEE 1451 family of standards. These standards address extensibility, flexibility, etc pertaining to transducer busses. However, the multi-drop RF sensor network member of this family (IEEE P1451.3) is still in draft form and is specifically written for tethered communications. Therefore, some of the details of this implementation will be different and may be reflected in a future (yet undesignated) wireless version of IEEE 1451.3.

I Extensibility

A sound architecture will support the easy interface of additional nodes, smarter nodes, and more integrated nodes. The architecture should have no hardware limit to the number of nodes supported. The additional nodes may require additional hardware and/or software but will not require the wholesale replacement of existing nodes. The addition of smarter nodes would provide more distributed intelligence in the system and should not be restricted by the architecture. The more integrated nodes might include functions that were once segregated due to hardware or software limitations. As the technology matures, the integration of more functions into the same package becomes more feasible. Again, no architecture limitation should interfere with this natural process. Functionality and performance should not be hardwired in the architecture. Functional and performance modules should be able to be remapped into different packages to improve overall system performance.

II Flexibility

Remapping functional or performance modules among the nodes in the system should be feasible without compromising the architecture. Remapping could include moving the module to a Host (external), to a Sensor Node (SN), or to a Network Node (NN). Remapping may be required to accommodate failures, to avoid bottlenecks, or to address performance issues.

III Open Standards

The over-the-air (OTA)interface will be completely specified and consistent with the IEEE P1451.3 to facilitate the interoperability of the testbed network.

IV Phases

The architecture must support the implementation of defined phases in the testbed. Early phases will emphasize feasibility while later phases will push performance assessments. The architecture should support the phased implementation without serious degradation and without the wholesale replacement of hardware or software.

V Hierarchical Structures

The implementation will support hierarchical hardware, software, and information. Distributed intelligence provides the mechanism for converting data into information at the appropriate level. Simple master-slave or totally distributed (single layer) systems will not be suitable.

VI RAM Issues

The reliability, availability, and maintainability of the network are viewed as an architecture consideration, not just hardware modules. The network must be robust, secure, predictable and verifiable.

Interface Specification

This section contains the details necessary for devices to interface to the components in the network. Internal interfaces describe how components communicate within the bounds of the network included in this project. The external interfaces describe connections between this network and the outside world.

I Connectivity

This section describes how the devices defined in the diagram below interconnect in such a way as to assure the viability of the measurement system architecture. The baseline requirements for the connectivity require that the connection be verifiable and scalable in performance. This scalability includes data rate, EMI (and EMP) resistance, security, number of simultaneous connections supported, and protocols implemented. Early prototypes will implement selected portions of the connectivity specification but will support upgrades to full compliance without major cost or impact.

Maintaining connectivity in the plant environment requires attention to the temperature, vibration, electromagnetic, and humidity conditions during both storage and operation of the devices being deployed. The dynamic nature of the environment also impacts the design constraints since changing conditions are inherently more difficult to predict. Critical assumptions must be made about the environment must be made to permit a fieldable design. Those assumptions are based on representative conditions found in existing facilities.

Connectivity within the network is insufficient to assure a viable system. The connectivity, like many other aspects of the operational system, must be verifiable without major impact on the performance of the system and without significant training or additional tools. The verifiability of the connectivity must address issues like headroom, error rates (corrected and uncorrected), and latencies. In User mode, only data coming from the Host, SN, and NN are available to the user. In Super User mode, the device (SN or NN) can be interrogated and forced into a mode that stresses the network for diagnostic purposes.

Unidirectional SN devices must implement a protocol (publish/subscribe) that allows the user to verify the operation of the sensor. The maximum latency in the verification protocol is application dependent and is set when the sensor is deployed. Bidirectional SN devices support protocols that provide faster verification of operational status. Master/slave is the preferred protocol for bidirectional SN devices. In this protocol, the maximum latency is set by the master.

The connectivity can be impacted by accidental or purposeful interference either by internal staff or external individuals. Designing for adequate security requires that all these potential interactions be addressed. Security implementations will be graded and role-based. Users have less authority than Super Users with Developer at the highest level of access. Developer access is not allowed during operational status. The device must be set off-line for developer access to be allowed. All security implementations will focus on providing cost-effective protection against the most likely scenarios. Additional security can be added, as necessary, with a commensurate impact on performance. The implementation of the security measures will be as transparent as possible so that normal, authorized access to the system continues unimpeded while unauthorized (or unintended) access gets immediate and terminal actions. Super User access can override automatic security features.

Data encryption between SN and NN depends on the application. The natural encryption provided by the CDMA protocol implemented in the OTA link is the minimum supported. Additional encryption can be added, as necessary, to meet the needs of the application. Specific error detection and correction protocols will be implemented to meet the required 1 in 1,000,000,000 bit error rate (corrected). Dynamic adjustments of BER for maximum throughput will be permitted if suitable procedures are in place to meet the standards under all conditions.

Configuration management must be simple and fast. Temporary interruptions of connectivity must be immediately (within 1 second) mitigated through reconfiguration and rerouting. Human intervention is not required for reconfiguration initiated by the normal dynamics of the environment or the system. Failed devices (SN or NN) should be reported quickly. A failed SN could result in loss of sensor data unless a different SN can derive the measurement from other sensors and provide the new measurement as a substitute. A failed NN will cause the existing NNs to reconfigure to intercept the signal from the orphaned SN and provide the sensor data to the network. Notification of the event will be controlled so that a flood of events doesn't result in a flood of network activity reporting the event.

II External Interfaces

The first sensor interface supported will be the 4-20ma analog signal. This allows a certain load that can be used to power the SN device, if desired. The IEEE 1451 protocol will be implemented in the SN device with suitable data structures to be defined. The first NN devices will implement an ethernet interface to the plant backbone. The actual hardware implementation (thin-wire, thick-wire etc) will be determined later.

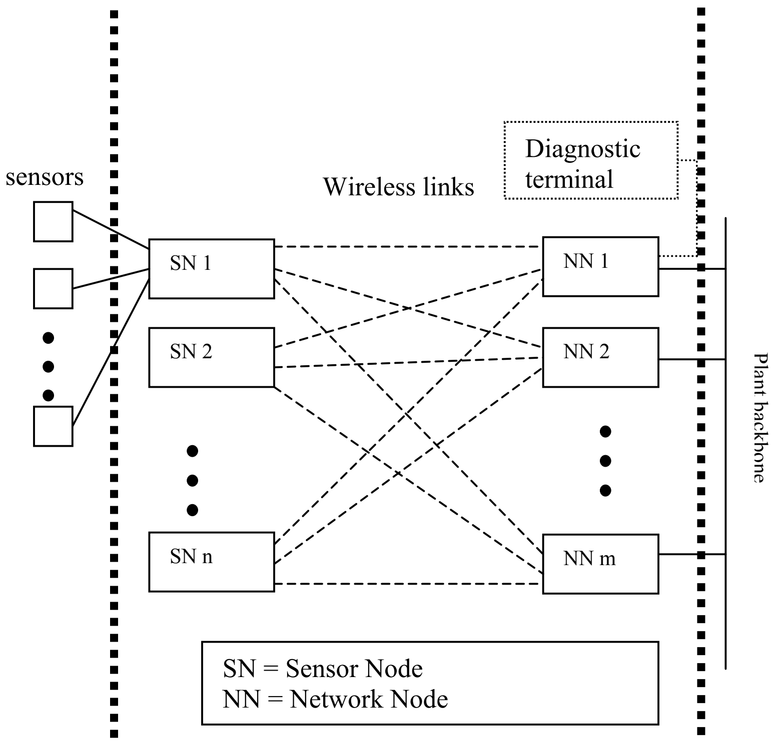

Figure 1 – System Overview

III Wireless Interface

The following figure and paragraph describe the IEEE P1451.3 bus structure. The testbed will implement a wireless version of this.

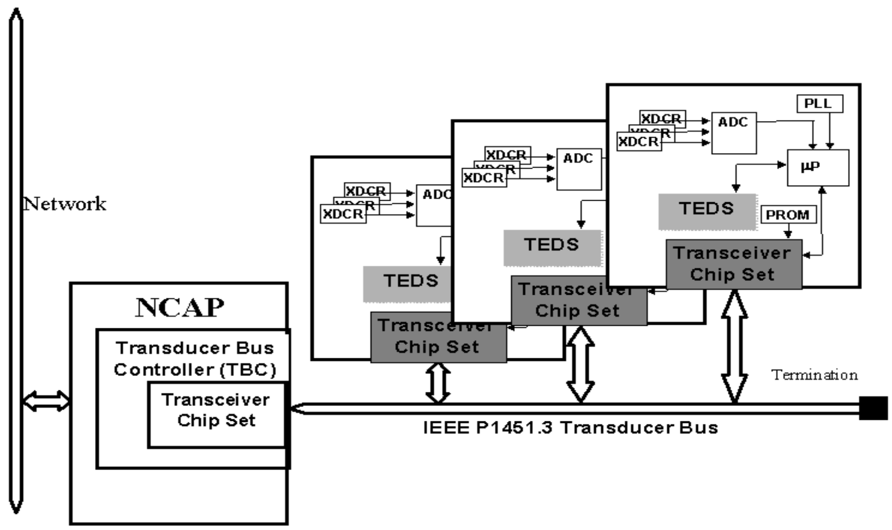

Figure 2 – System Overview of IEEE P1451.3 System

The distributed multidrop system (See Figure 2) consists of one or more Transducer Bus Interface Modules (TBIMs), a Transducer Bus Controller (TBC), and the actual physical transducer bus. A TBIM consists of one or more transducers and contains the means for storing or associating a Transducer Electronic Data Sheet (TEDS), a real-time clock (RTC) for time-stamping data, a microprocessor for formatting the data and a transceiver chip setor CDMA and/or FDMA purposes. The TBC will control the transducer bus and could be a part of an NCAP, an IEEE standard 1451.2 interface, or any other acquisition system. (Note that the NCAP/TBC in IEEE 1451.3 nomenclature is roughly equivalent to the Network Node discussed above and that the TBIM is equivalent to the Sensor Node.)

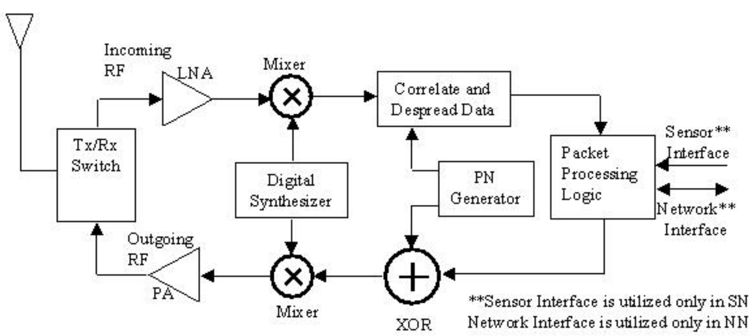

Figure 3 – Block Diagram of Spread Spectrum Transceiver

The hardware block diagram is shown in Figure 3. As shown, the packet processing logic generates and processes commands using the protocols shown in Table 1. The PN Generator is used both for spreading and despreading the OTA signal. For this implementation, a set of Gold codes generated by the polynomials $f_A = 1 + X + X^6$ and $f_B = 1 + X + X^2 + X^5 + X^6$ were utilized. This generator produces a set of 65 different codes each of which are 63 bits (chips) in length. Therefore, the effective OTA bandwidth is 63 times greater than would be required by the unspread packet described in Table 1.

The protocol and structure of the communication over the wireless interface adheres to the current definition of the 1451.3 standard (tethered RF communication). The communication is based on Spread Spectrum (SS) CDMA RF technology with carrier frequency, SS code, SS code length, and transmission data rate definable for the installation.

The transmission packet used in the Wireless Test Bed is derived from the current definition in the IEEE P1451.3 standard as

Byte Position	Value	
0	0x7e	Start Byte
1	0-255	Destination address (byte 1) 0 = all Nodes 1-254 = Nodes 255 = This Node
2	0-255	Destination address (byte 0) = Channel address 0 = all 1-255 = transducer
3	1 – 254	Source address (byte 1) SubNet
4	0-255	Source address (byte 0) 0-255 = Node
5	0-255	Command Class
6	0-255	Command Function (Command Class related)
7	0-255	Message ID (sequence)
8-9	0-65535	# of data bytes
10-11	0-65535	format field check sequence
12-m	(command dependent)	0 to 65535 bytes of data or parameters associated with the command
m+1-m+2	0-65535	Frame Check sequence
m+3	0x81	end Byte

Table 1 – Packet Structure

Each transmission adds a header to this packet for frame synchronization. The hexadecimal representation of the Test Bed header is “FF FF 0F”.

Some of the values in the destination address and their use have been predefined to indicate special conditions. Normally the first byte (MSB) addresses the node in the particular wireless subnet, while the second byte addresses the transducer or sensor attached to the node.

Source address includes the “subnet” which identifies the portion of the wireless network the nodes belong to, and the Node address. Note that there is no distinction in addressing between “network” nodes and “sensor” nodes to allow for future peer-to-peer expansion.

Similarly, the command is structured into two bytes: the first one indicate the “class” or category of commands, where the second byte indicates the particular command function within that class. Some commands are defined by the standard. Other are defined by the manufacturer.

Error detection/correction will only be partially designated by IEEE P1451.3. Additional EC/ED coding will be added on an as-needed basis.

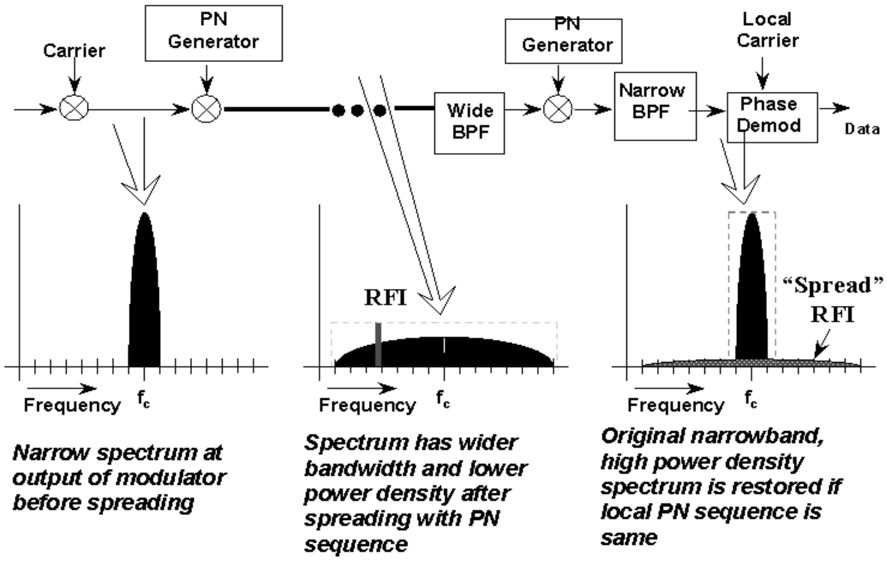

Figure 4 - Spectral representation of spread spectrum interference rejection.

As shown in Figure 4, spread spectrum uses orthogonal pseudo-random noise (PN) sequences to widen the spectrum of an otherwise narrowband signal. By spreading the signal over a wider frequency spectrum, this method rejects narrowband interferers. The spreading of the signal also reduces the probability that the signal of interest will interfere with other receivers. The correlation process of the receiver despreads the desired communication signal and effectively spreads out the energy from the interference signal.

As described earlier, this implementation will utilize the appropriate portions of the proposed IEEE P1451.3 standard and the general concepts of IEEE 1451.1. The IEEE P1451.3 standard is targeted for tethered RF communications and not wireless applications, but the adaptation for our testbed is straightforward. In the future there will probably be a wireless version of IEEE P1451.3. The testbed will evolve to match that standard and, in fact, will probably help drive it.

Conclusions

This architecture specification defines a system that provides early functionality, adherence to existing and emerging standards, while providing robust, secure communication in the harsh environments common to the Industries of the Future. Clearly, future implementations will integrate intelligence, mobile ad hoc networking, intelligent agents, and other technologies currently being demonstrated in the laboratories around the nation. The architecture defined here will accommodate these new technologies without major rework.

Critical to the ultimate success of this project will be the maturation of the commercial partnerships already started. Vendors are beginning to embrace the open standards, robust protocols, and distributed intelligence described here rather than the TCP/IP models being used in some of the wireless networking protocols. A combination of TCP/IP and intelligent sensor buses may turn out to be the commercial path emerging from these projects integrating sensors with the internet.

A clear attribute of this architecture is the scalability required to support the implementation for both large and small applications. The architecture requires simple "ring-up" of new sensors and dictates that hard limits in numbers of sensors be avoided where ever possible.

Appendix C – Bowater Test Results

Results of Bowater Test on 12/28/2000

This is a brief account of the results from a field test of 2 wireless sensor nodes and 1 network node conducted at the Bowater Coated Paper Division facility in Catawba SC on December 28, 2000 by Wayne Manges, Roberto Lenarduzzi and Mark Buckner. Figure 1 is a sketch of the Number 3 mill where the tests were conducted. S1-x indicates sensor node 1 at location x, S2-x indicates sensor node 2 at location x, and Nx indicates the network node at location x. The results are summarized in Table 1. Figures 2 through 10 are captured images of the results screens for the various tests.

The components did not operate properly when first powered up. We believe this was related to the temperature difference inside the facility (~29°C or 84°F) and outside (~1°C or 34°F). The equipment was left in the van overnight and the temperate dropped to about 1°C or 34°F. Once the components acclimated to the conditions in the mill they functioned properly.

Communication could not be established between sensor node 1 at location S1-8 and N2. We observed –50 dbm of noise at location S1-9 so its possible sensor node 1 was not able to "hear" a request for transmission from N2.

We were able to achieve successful communication between sensor 1 and 2 (S1-7 and S2-7) and the network node at N1 only when the network node was placed in line of sight of S1-7 and S2-7 via a window in the control room.

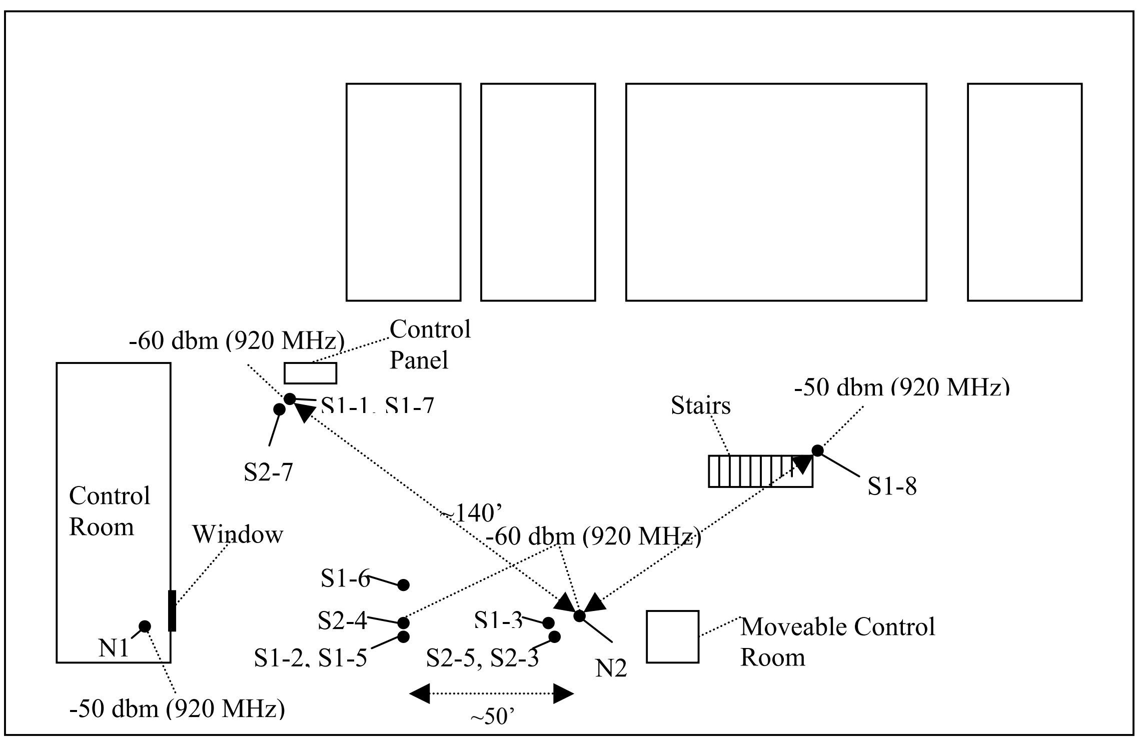

Figure 20 Sketch of Mill #3 facility with sensor node locations, distances and background readings.

The “Tests” column in Table 1 indicates the following scenarios: (1) for S1 or S2: after communication was established between the network node and both sensor nodes, each sensor node was individually turned off and back on again and communication was re-established with out user intervention; (2) for the network node: after communication was established between the network node and both sensor nodes the network node was turned off and back on again and communication was re-established with both sensor nodes without user intervention.

Table 1 Summary results of test.

Node[a]	Distance[b]	Figure #	Conditions	Noise	Tests
N2(1)		Figure 2	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-3(0)	5			-60 dbm (920 MHz)	On/off
S2-3(0)	5			-60 dbm (920 MHz)	On/off
N2(1)		Figure 3	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-3(0)	5			-60 dbm (920 MHz)	On/off
S2-4(0)	50			-60 dbm (920 MHz)	On/off
N2(1)		Figure 4	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-5(0)	50			-60 dbm (920 MHz)	On/off
S2-5(0)	5			-60 dbm (920 MHz)	On/off
N2(1)		Figure 5	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-5(0)[c]	50			-60 dbm (920 MHz)	On/off
S2-4(0)	50			-60 dbm (920 MHz)	On/off
N2(1)		Figure 6	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-6(1)	50			-60 dbm (920 MHz)	On/off
S2-4(0)	50			-60 dbm (920 MHz)	On/off
N2(1)		Figures 7 & 8	29° C 31 % RH	-60 dbm (920 MHz)	On/off
S1-7(2)	120			-60 dbm (920 MHz)	On/off
S2-7(2)	120			-60 dbm (920 MHz)	On/off
N2(1)		Figure 9	29° C 31 % RH	-60 dbm (920 MHz)	--
S1-8(1)	50			-50 dbm (920 MHz)	--
N1(W)		Figure 10	29° C 31 % RH	-50 dbm (920 MHz)	--
S1-7(2)	50			-60 dbm (920 MHz)	--
S2-7(2)	50			-60 dbm (920 MHz)	--

[a] The number in parentheses indicates the approximate elevation off the floor.
[b] The distance in feet between the network node and the sensor nodes.

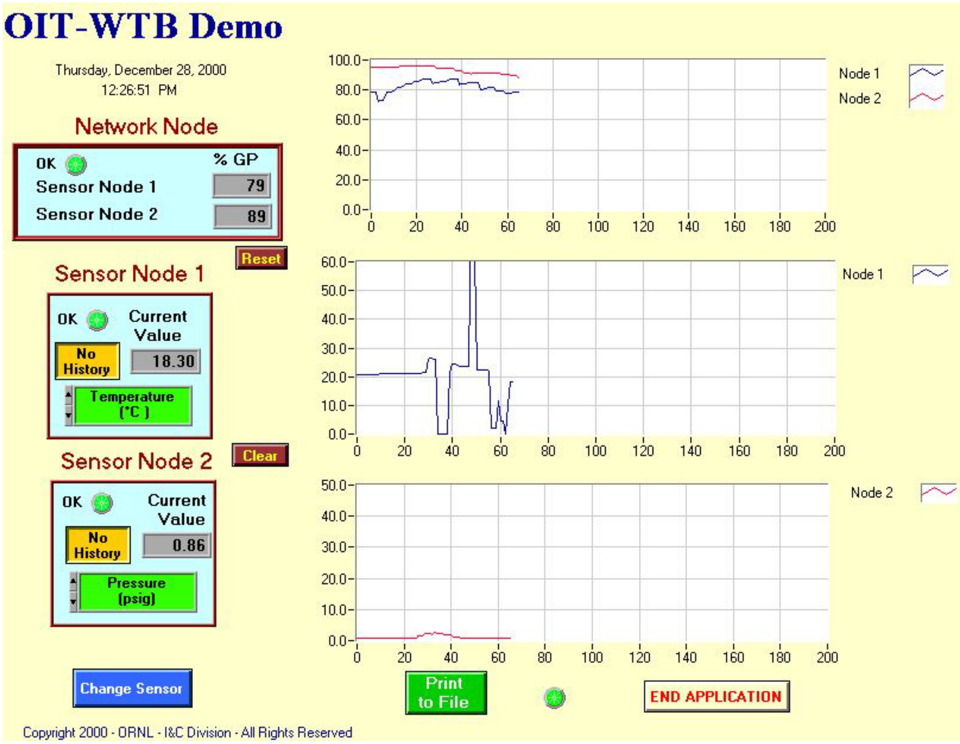

Figure 21 Screen dump showing results of test at locations N2, S1-3, S2-3.

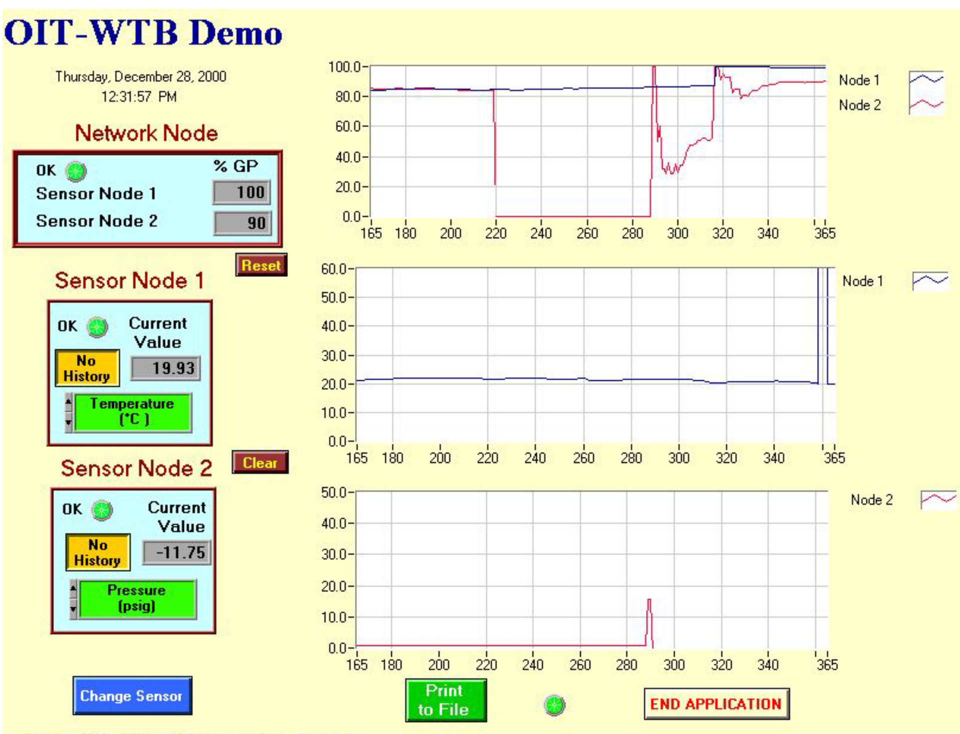

Figure 22 Screen dump showing results of test at locations N2, S1-3, S2-4 (pressure transducer was disconnected from sensor node 2 at ~ '290' on the x-axis).

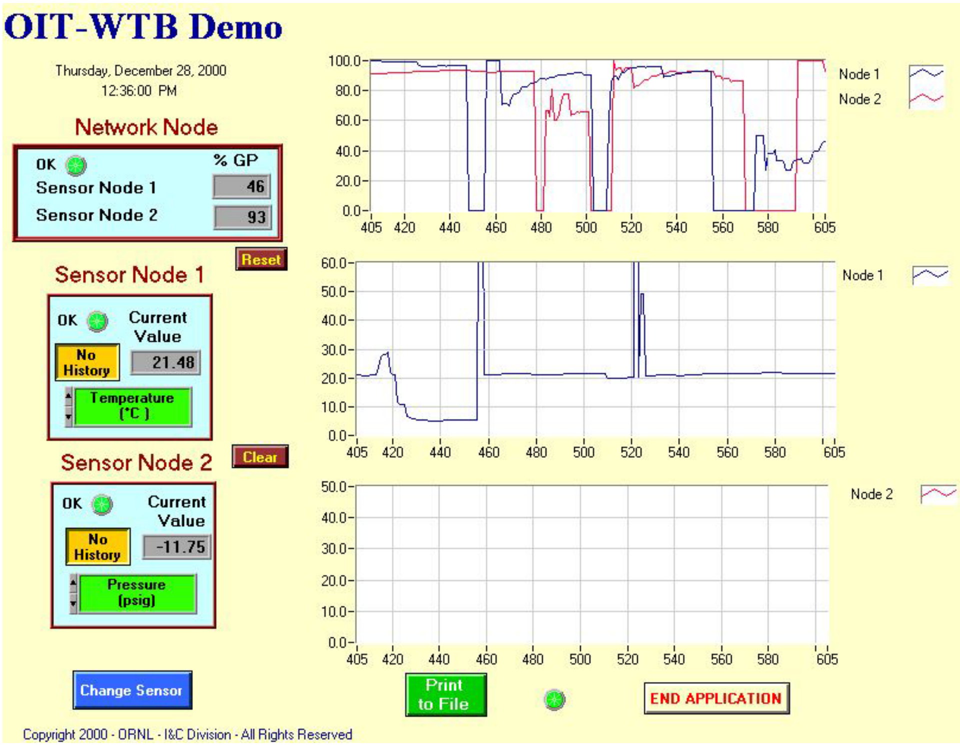

Figure 23 Screen dump showing results of test at locations N2, S1-5, S2-5 (pressure transducer is not connected to sensor node 2).

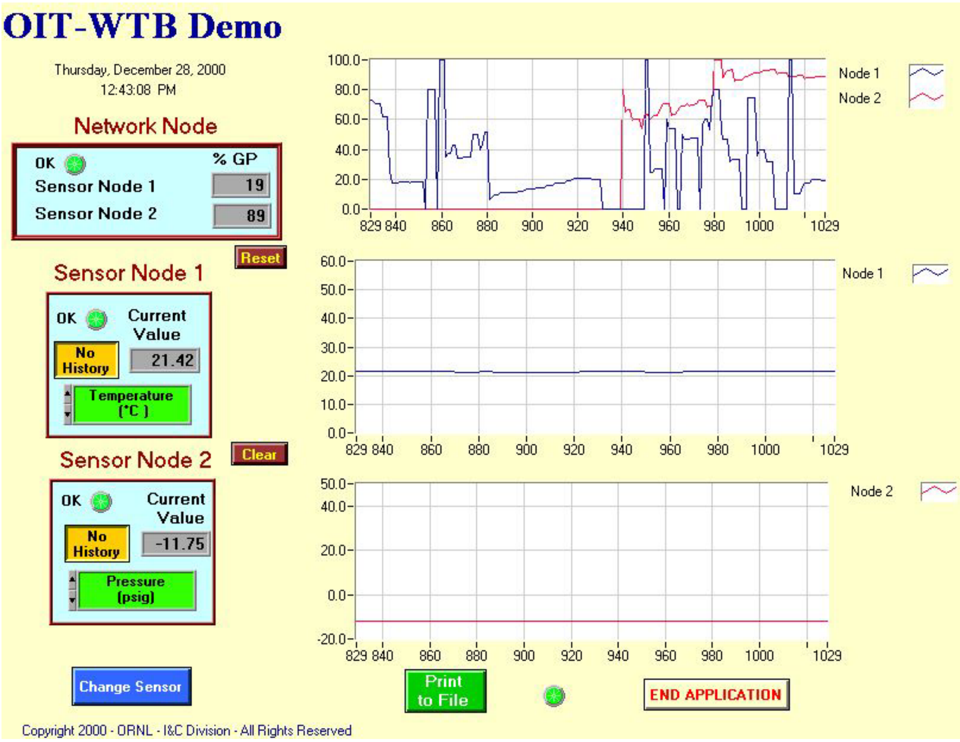

Figure 24 Screen dump showing results of test at locations N2, S1-5, S2-4 (pressure transducer is not connected to sensor node 2).

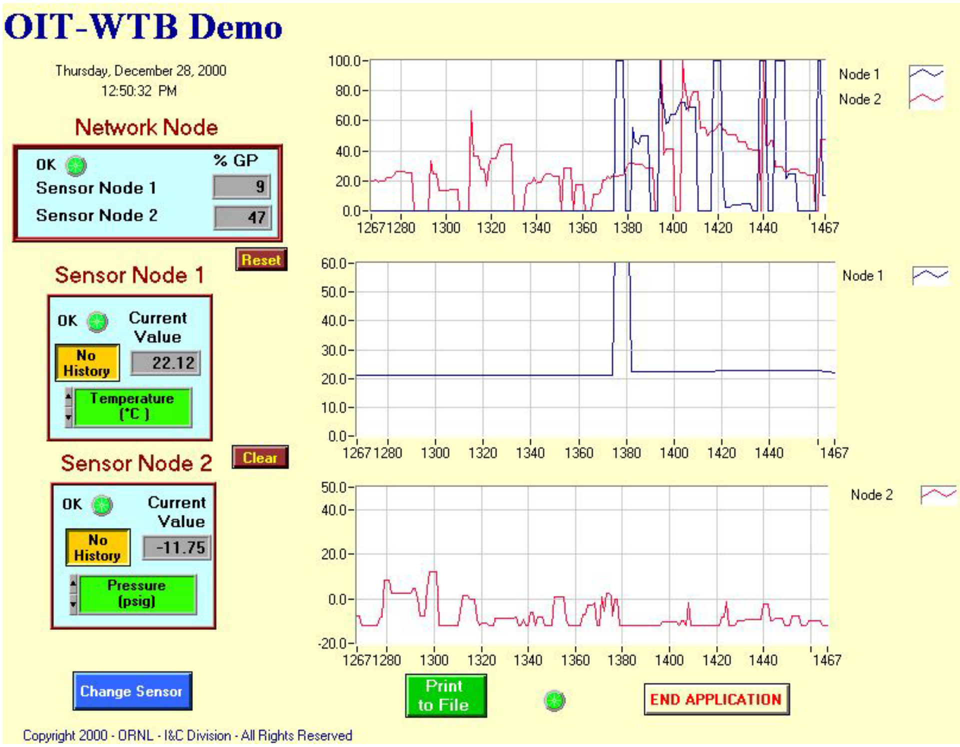

Figure 25 Screen dump showing results of test N2, S1-6, S2-4 (pressure transducer is not connected to sensor node 2).

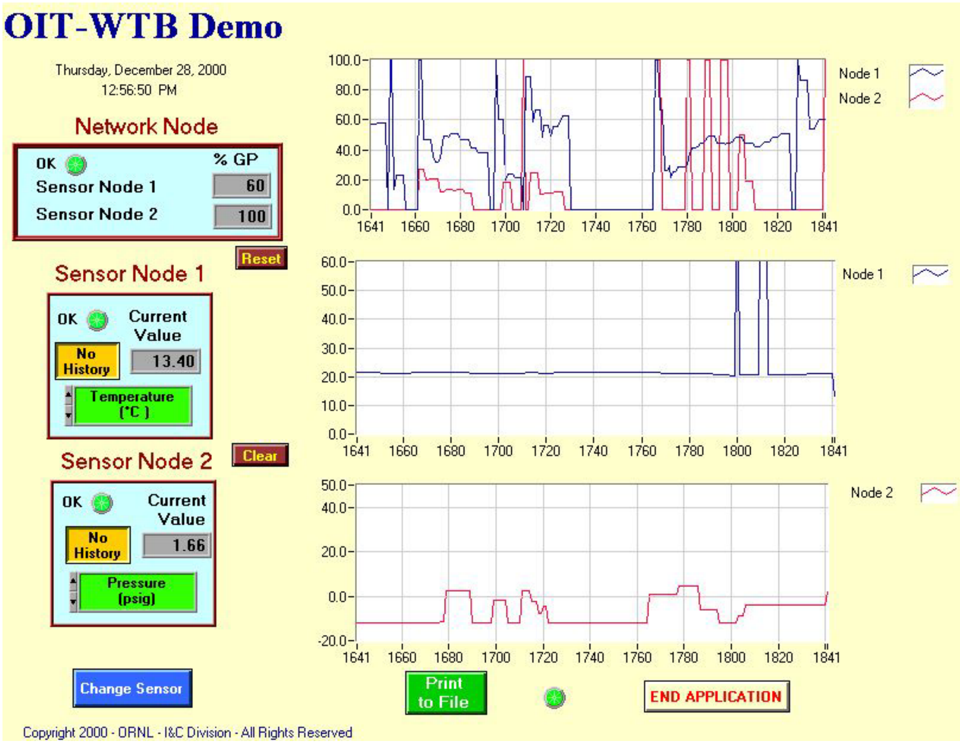

Figure 26 Screen dump showing results of test at locations N2, S1-7, S2-7 (pressure transducer is reconnected to sensor node 2 at ~ 1841 on the x-axis).

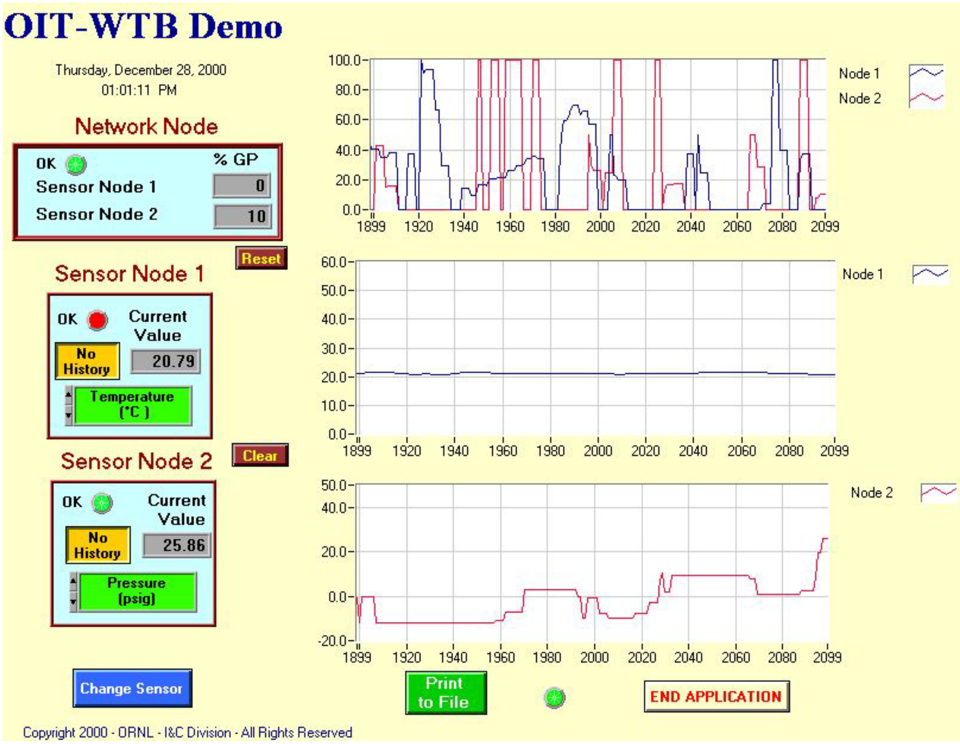

Figure 27 Screen dump showing results of test at locations N2, S1-7, S2-7.

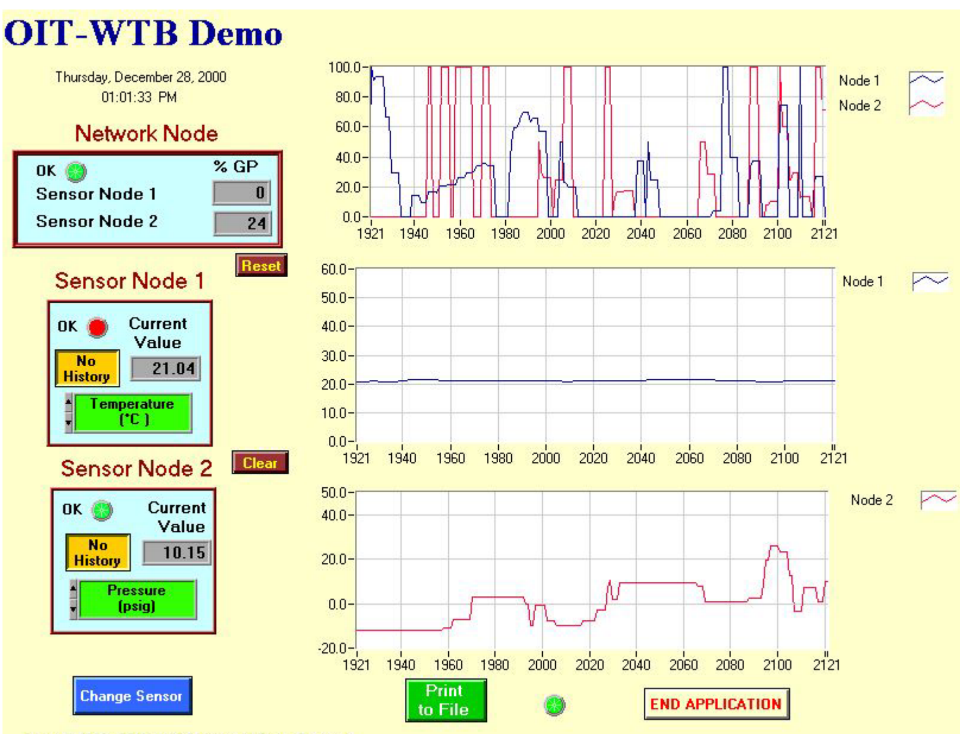

Figure 28 Screen dump showing results of test at locations N2, S1-8, S2-7.

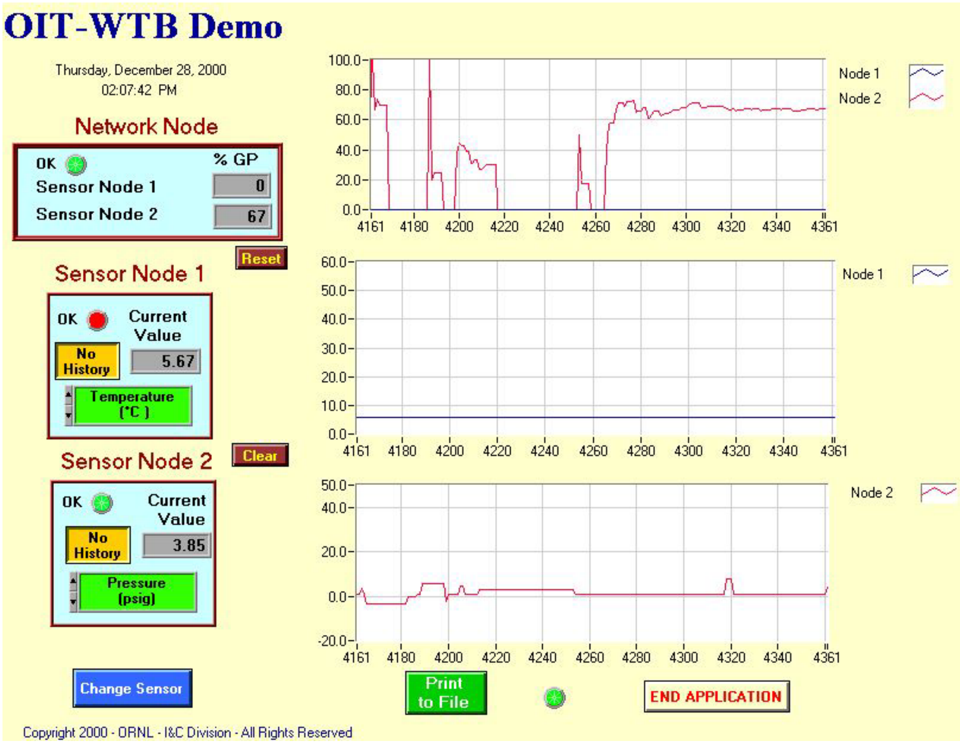

Figure 29 Screen dump showing results of test with Network node in the control room (N1) and sensor node at location S2-7.

Appendix D
Timken Steel Trip Report Summary

Subject: Trip To TIMKEN
Date: August 28-29, 2001
Participants: R. Crutcher, R. Lenarduzzi
Report author: R. Lenarduzzi

Richard and I visited the Timken facility in Canton, OH to apply some changes to the Wireless Tube Detector system to alleviate minor problems encountered during initial operation. It should be noted that when we arrived and prior to the changes made, the system was correctly detecting the tubes and the wireless transmission had a 97% reception of packets. Note that the RF links have a great amount of redundancy and even getting 10% of the packets through is sufficient (as long as there is at least one transmission while each tube is present.)
The two problems addressed were:

1. the RF interference caused by a 930 MHz pager system, and
2. the rise of the sensor signal baseline above the lower tube-detection threshold during heavy tube traffic, causing the laser lamps to always be ON (which is OK). The laser lamps are turned off about 1 minute after the end of the last tube is detected. If tubes are more frequent, the laser lamps stay ON constantly. It takes the laser lamps 30 seconds to warm up. It takes ~40 seconds for the tube to reach the laser after it has been detected. During the operation we observed a 15-20 second gap between tubes for typical batches.

For problem 1, we changed the transmission carrier frequency between the repeater and the receiver from 920 MHZ to 904 MHZ and we added a bandpass filter centered at 904 MHz. With the filter in place the amplitude of the 930 MHz interfering carrier was decreased by about 20 dB. After the change, the communication continued to have a 97% reception of packets.

We speculated that the cause of problem 2 was the heating of surrounding metal guards due to the heavy traffic of tubes. Our solution was to add a short cylinder around the sensor to reduce the angle of view and an optical filter to reduce the effect of cooler temperature items. The optical filter introduced some attenuation to the sensor and its corresponding output, about 2.0 V vs 2.2 V for the tubes running at the time. We observed this value change during operation and we learned that the temperature of the tube differs from run to run in the range from 1400 F to 2000 F. We have seen the detector signal from ~1.5 V (1600 F) to 2.5 V (2000 F) which is the top end of the A/D converter. We changed the thresholds to 1.1 V (turn-on) and 0.9 V (turn-off). The tube traffic was very sporadic so we could not test the effects of the modifications relative to a high duty cycle of tubes. When the tube traffic increases, the thresholds may need to be adjusted. Christian Neron has been instructed in using our software to adjust thresholds.

Post-trip Problem.

Christian Neron called today (9/3) saying that the receiver unit was not receiving any packets. After verifying with the spectrum analyzer that the 904 MHz carrier was present, we verified that a configuration bit in the microcontroller had been reset. I stepped Christian through a software correction. We also are sending a new EPROM for the receiver with the correct code word preprogrammed.

Appendix E - Glossary

4-20 mA – An industry standard electrical interface for sensors in harsh environments. An analog signal that varies from 4 mA to 20 mA to indicate the value of the sensor signal.

A/D – See ADC

ADC – This is the analog-to-digital converter segment of a data acquisition system. It accepts the analog voltage (or current) from the field wiring and converts it to a digital signal that can be processed by a computer.

AMS – Austria Micro Systems is a semiconductor manufacturer specializing in SiGe deivces for use in radio circuits.

Bandgap voltage reference – A semiconductor structure used in microelectronics to supply a standard voltage reference on the integrated circuit without the need for external components.

BiCMOS – Bipolar CMOS combines bipolar (PNP and NPN) devices on the same silicon substrate (chip) as CMOS devices.

Bi-directional – A communication network node where the traffic can be both transmitted and received (but not necessarily simultaneously).

Bit – The finest breakdown of information in a digital computer. The value of a single bit is either zero (off) or one (on).

CDMA – Code-Division, Multiple-Access is a transmission protocol used to transmit data on a shared line. It can be wired or wireless but is most often used in wireless communication including cell phones. This is one of the only communication technologies that allows all transmitters to be "on" at the same time and not interfere with each other.

Chip – The term "chip" is used to designate a single silicon die (about 0.1 inch square) on which a complete, monolithic integrated circuit is fabricated – as in "a single chip implementation of a spread spectrum radio. It can also represent each subsample taken on an individual bit to accomplish the spreading in a spread spectrum radio – as in "IEEE 802.11 uses 11 chips per bit in its spreading code".

Chip Rate – The number of subsamples taken on each bit in the transmission.

CMOS – The Complimentary Metal Oxide Semiconductor technology is most common in fabricating low cost, low power semiconductor integrated circuits for use in modern electronic equipment. It uses PMOS and NMOS devices in tandem.

DSP – Digital Signal Processing is used to perform functions like spectral analysis and filtering in modern radio systems. Older analog processing is only used in the portions of the radio where the frequencies are high enough that processing the signals digitally is economically infeasible.

DSSS – Direct-Sequence Spread Spectrum is a communication technology where each bit in the transmitted signal is exclusive-ored with a higher speed chipping pattern before being modulated onto an RF carrier for transmission. The resulting RF signal has significantly wider bandwidth than the original "baseband" signal had. This has some advantages in high EMI environments. Their "process gain" is equal to 10db log (chip rate).

Early Voltage – This is a measure of the variation in collector current (in a bipolar junction transistor) with V_{CE}.

ECL – Emitter Coupled Logic is a semiconductor technology used for high frequency applications.

EMI – Electromagnetic Interference is the electrical noise that gets into transmission that causes the electrical or radio signals to be difficult to comprehend. EMI in the industrial environment can be caused by light dimmers, electrical arcing, computers, cell phones, or many other digital electronic devices.

EMP – An electromagnetic pulse causes broadband interference (EMI) since it acts as an impulse function. High energy EMP (such as caused by a nuclear weapon detonation) can damage transistor circuitry because of the high current spikes induced in the circuits.

FCC – The Federal Communications Commission regulates the radio transmissions in the US. They authorize specific types of transmissions in specific radio bands for the overall welfare of the nation as well as international treaties.

FHSS – Frequency Hopping Spread Spectrum is a communication technology where the transmitter and receiver change frequencies every so often so that the entire bit stream is not on a single frequency. The transmitter and receiver are synchronized so that they can stay locked and the bit stream is retrieved. This technology has some advantages in a high multi-path environment. All currently available FHSS systems are "slow hoppers" meaning that they output more than 1 bit per hop so they have no "process gain" like DSSS systems.

FPGA - A field programmable gate array is a special purpose (semi-custom) integrated circuit that contains many individual circuits that can be tied together in an application specific way (programming the FPGA) to achieve a desired result. These are more flexible than simple, hard-wired, CMOS integrated circuits but are far easier to use than Application Specific Integrated Circuits (ASICS) for low volume and prototype applications.

F_t – The transition frequency of an electronic device is where the gain is equal to one. At lower frequencies, the circuit exhibits gain greater than one. It is a "figure of merit" for radio devices. The higher the F_t the easier the device is to use in high frequency applications.

GHz – A 2.4 GHz radio transmission is an electromagnetic signal that oscillates at 2.4 $x10^9$ cycles per second. These ultra high frequency (UHF) signals have very good noise immunity but are useful for line of sight transmissions only. In general, the higher the frequency, the more the radio signal is like visible light – line of sight, sensitive to fog, immune to most electrical interferers.

Gilbert Mixer - The classical Gilbert Cell Mixer comprises three stacks of transistors to provide mixing. It is used as a standard cell in many micro-electronic circuits.

HBT – A heterogeneous bipolar transistor structure used in SiGe circuits.

IEEE – The Institute of Electrical and Electronic Engineers is a professional society involved in establishing standards for various technical areas. See www.ieee.org.

IEEE 1451 – This smart sensor standard defines the electrical and logical interfaces for communicating between industrial sensors and computers.

IEEE 802 – This is the standard for computer local area networks (LANS). "Regular" ethernet (802.3) is included in this standard as well as 802.11, the wireless ethernet standard. Bluetooth wireless communication is defined under 802.15.

IF – The intermediate frequency stage in a radio is where the carrier frequency, usually higher, is beat against a local oscillator to create a lower frequency that is easier to filter and amplify.

IOF – The Department of Energy's Office of Industrial Technology sponsors a program to assist a collection of industries that are historically high energy consumers. These "Industries of the Future" are listed on the DOE web site and include steel, glass, petrochemical and others.

ISM – The FCC has allocated a collection of frequencies in the radio spectrum for use by "industry, science, and medicine". Radios in these bands don't require licenses but are "type accepted" under FCC regulations so that individual transmitter licenses are not required. The 900 MHz, 2.4 GHz, and 5.8 GHz bands are the most commonly used in wireless sensor networks.

LAN – A Local Area Network (as opposed to a Wide Area Network – WAN) usually comprises a collection of computers tied together over some network technology (like Ethernet) and managed by a single organization to provide compute services to a community of users such as at a university or company.

LC Tank Circuit – The inductor (L) and capacitor (C) form the part of the oscillator that determines its natural frequency.

Line-of-sight – In radio, line of sight refers to the need for transmission between transmitter and receiver to occur without intervening structures or obscurers. Lower frequency radio transmissions (like commercial AM broadcasts) can "bend" around buildings and even the horizon or bounce off the ionosphere but higher frequency transmissions (like TV) require that the transmitter tower be able to "see" the receiver antenna.

LNA – A Low Noise Amplifier is required in radio designs to get the level of the received signal up to a point where the circuits following don't swamp the signal with their own internally generated noise.

MAGIC – The software tool for integrated circuit layout used at ORNL is called MAGIC. It provides for the geometrical layout patterns and also checks for design rule violations regarding line widths and spacings. MAGIC also provides netlist extractions with some parasitic capacitance included for circuit simulation and verification.

MOSIS - MOSIS (MOS Implementation Service) is multi-user service that allows manufacturers and researchers to develop IC based product prototypes at a fraction of the fabrication cost by sharing a lot with other users instead of paying for a dedicated lot at a commercial IC foundry.

MHz - A 900 MHz radio transmission is an electromagnetic signal that oscillates at 900 $x10^6$ cycles per second. These ultra high frequency (UHF) signals have very good noise immunity but are useful for line of sight transmissions only. In general, the higher the frequency, the more the radio signal is like visible light – line of sight, sensitive to fog, immune to most electrical interferers.

Mixer – The oscillator in a radio where two signals are beat together to lower the frequency of the transmitted signal to a more manageable frequency for amplification and filtering (see IF).

Monolithic – Monolithic integrated circuits are electronic components that integrate all elements necessary for operation on a single substrate (usually silicon).

Multi-path – Radio signals arriving at the receiver along a trajectory that includes reflections are said to exhibit multi-path. This can be troublesome in many systems but DSSS systems actually rely on multi-path to reduce restrictions on line-of-sight constraints.

NMOS – The N-channel, metal oxide semiconductor device is used in microcircuits

Noise –Unwanted signals combining with the desired signal in such a way as to make the desired signal more difficult to discern are contributing to the noise. Noise can be acoustic, electromagnetic, or just random.

OIT – The Department of Energy's Office of Industrial Technology sponsors research and development in areas supporting the nation's industries in improving energy efficiency, improving raw material utilization, and reducing emissions. See www.oit.doe.gov.

ORNL – The Oak Ridge National Laboratory is one of the DOE's multi-purpose R&D labs located in Oak Ridge, Tennessee. See www.ornl.gov.

Packet – Packet radio implies that the data being transmitted into bundles before being transmitted. This allows multiple users to access the physical media simultaneously. Traditional phone lines have been line switched implying that the line is allocated to the connection until the connection is broken. Packet switched networks (as are now used for phone service) actually break the data up for transmission and then reassemble it for delivery.

PECL – This semiconductor technology (positive-referenced ECL) is used for high frequency applications.

PLL – A phase-locked-loop is a critical component in modern radio (and other) electronic circuits. It compares the output phase of a signal with a reference and adjusts the frequency of the oscillator to bring the phase into alignment. This is used to lock a high frequency oscillator in phase with a low frequency (high precision) standard. This keeps the radio on the correct frequency without requiring a separate stable oscillator for every frequency**..**

PMOS – The P-Channel, metal oxide semiconductor device is used in microcircuits.

PNP – A bipolar transistor structure that sandwiches the N-type (excess electrons) material between two P-type (excess holes).

QPSK – Quadrature phase-shift keying is an update to the older RF modulation technique known as binary phase shift keying. Phase shift keying varies the phase of the RF carrier to represent the information desired. In binary, phase shift keying on phase would represent a zero and another phase a one. In quadrature phase shift keying, each sine wave in the carrier can be shifted to four different phases representing the data to be transmitted.

Repeater – This type of radio receives a signal and retransmits it in such a way as to extent the range of the transmission.

RF – Radio Frequency is usually considered to be any electromagnetic signal above 30 Hz.

Rx – This is the abbreviation sometimes used to represent the receiver in a radio.

SAW –Surface Acoustic Wave devices are now used as electromechanical filters in many radios and other applications. They are electrical components that have a thin film of a special material layered onto a substrate. The electrical signal excites (vibrates) the thin film in such a way that only signals that meet certain frequency characteristics are transmitted along the film.

SiGe – This is a new type of semiconductor fabrication technique using a combination of silicon and germanium that is replacing standard silicon in certain high frequency (RF) applications.

Signal-to-noise – This ratio, usually expressed in db, represents the relative strength of the desired signal to the undesired noise. The expression for signal to noise ratio (SNR) is signal/(signal+noise).

Spread Spectrum – Telecommunications techniques in which a signal is transmitted in bandwidth considerably greater than the frequency content of the original information. This can improve the signal to noise properties of the transmission.

Standard logic cell – In semiconductor design, a standard cell is one that exists in the library and is well understood with respect to performance, power demands, and has a viable circuit model for simulations.

Sub-micron – In semiconductor fabrication, submicron fabrication implies that the feature sizes in the device are less than 1.0 micrometer (10-6 meter). Today's microprocessors and memory chips are typically built using 0.35 and 0.25 line widths. Recently, a 0.18 micron line width has been achieved and is being used in the latest processors from Intel and AMD. A human hair is said to be about 50 microns wide.

Telesensor – The name given to a device (at ORNL) that combines sensing and telemetry on the same silicon substrate (chip).

Transceiver – A transceiver is a single unit that combines the functions of transmitter and receiver.

Tx - This is the abbreviation sometimes used to represent the transmitter in a radio.

VCO – The voltage controlled oscillator is a critical part of the PLL that allows the frequency of the oscillator to be varied with a controlling voltage that represents the error signal from the phase measurement.