WIRELESS TECHNOLOGY COMING TO HARD, INDUSTRIAL APPLICATIONS

Wayne W. Manges, Glenn O. Allgood, Stephen F. Smith, Timothy J. McIntyre,
Michael R. Moore and L. Curtis Maxey
Instrumentation and Controls Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6006

I. INTRODUCTION

The need for advanced wireless technology has been identified in the National Research Council (NRC) publication *"Manufacturing Process Controls for the Industries of the Future."* The deployment challenges to be overcome are:

- **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.**

A new paradigm is emerging where sensors will be integrated with the signal conditioning, digitization, intelligent processing, and communication electronics all on the same silicon substrate (Figure 1). ***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).

This article describes ORNL's research (under Department of Energy sponsorship) to address the issues associated with intelligent wireless sensors for industry. We start with a brief history of wireless industrial systems, then a synopsis of current market offerings, and, finally, details about the ORNL project. Our first-year effort focuses on establishing the fundamental operational requirements, the specification of a viable architecture, and a proof-of-principle prototype demonstrating the feasibility of the approach. Potential research in the out-years will be aimed at reducing the size, power, and cost to assure a viable market segment for commercialization.

II. HISTORY

This project, of course, draws on a long history of wireless systems R&D in various fields. There have been many attempts to eliminate cabling in the manufacturing environment. The high cost of installation, the high failure rates of connectors, and extreme difficulty in trouble shooting connections are just some of the drivers that encouraged end users to investigate alternatives. The current use of bus architectures (like ethernet) is an attempt to address some of the inherent problems in wiring in a plant. Many installations are simply impossible without

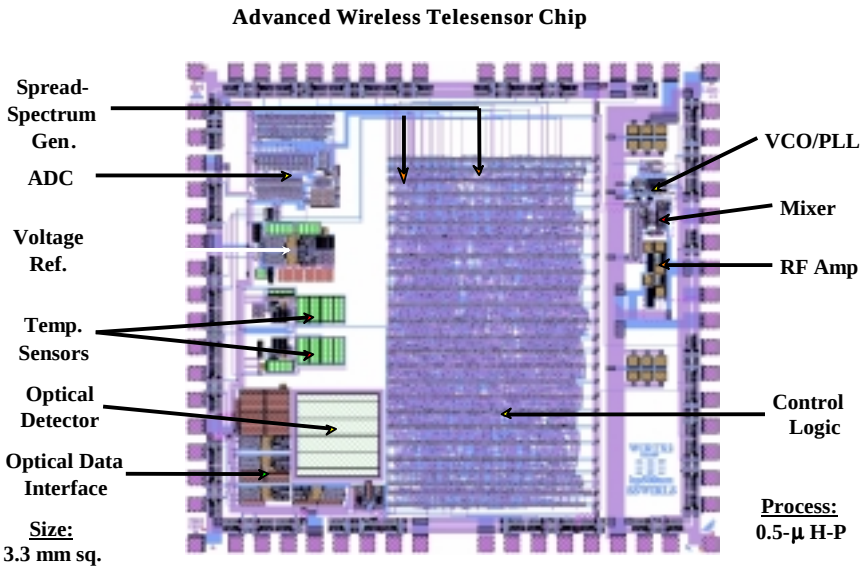


Figure 1. ORNL's second generation integrated wireless sensor provides both on-chip and off-chip sensor capabilities.

eliminating the tether of the communications and power lines. Other applications require such widespread and diffuse sensor placement that running wires makes the entire installation not cost effective. The fantasy of ubiquitous, high quality, robust sensors continues to evade the manufacturing marketplace.

Almost all these early attempts at wireless connectivity were point-to-point architectures. The simple RS-232 radio frequency (RF) modems, were the first exposure most engineers had to wireless connectivity. Most experience with these was less than satisfactory. The problems associated with untethered power, electromagnetic interference generation and rejection, and maintaining integrity of the RF signal path caused most of these early adopters to have a bitter taste for wireless solutions. Recent technological innovations and consumer market dynamics have caused many to reevaluate the viability of wireless solutions in industry.

The technology push coupled with the market pull of reducing costs is resulting in remarkable opportunities in the marketplace for entrepreneurs and investors. The technology push, driven by the advances in RF semiconductor (silicon) technology and the tremendous cost reductions sweeping through the consumer marketplace as wireless technology begins to yield to Moore's Law, has caused many of us to dare to imagine a world of low cost sensors unencumbered by wires. The market pull of wiring costing as much as $2000 per foot (in a nuclear power plant) and the lure of a sensory-aware Next Generation Internet have prompted many to reconsider the business opportunities in wireless sensors. Whether or not these forces can be brought together and harnessed to produce useful, viable, and cost effective products is the question we are all waiting to have answered.

Several government agencies have invested in attempts to make wireless technology a viable option for their mission. The Defense Advanced Research Projects Agency (DARPA) probably has the oldest program focused on the development of wireless sensor technology for use by the military. Their web site can be found at www.darpa.mil. Rockwell is a key industrial partner with their Wireless Intelligent Network of Sensors (WINS) program. They can be found at http://www.wins.rsc.rockwell.com/. The Department of Commerce, through their National Institute for Standards and Technology (NIST, formerly NBS) has a program called Smart Spaces. ORNL's wireless work with the Department of Energy is directed through their Office of Energy Efficiency/Renewable Energy under their Office of Industrial Technology.

Wireless sensor technology has been identified as an important part of a US Department of Energy program to help identified industries become more efficient (1). As part of the Sensors and Controls Crosscut Technology Program, wireless sensors are viewed as an enabling technology for increasing industrial process efficiency. The DOE started its Industries of the Future (IOF) Program a number of years ago, as a thrust area within the Energy Efficiency and Renewable Energy (EERE) Office of Industrial Technologies (OIT), to focus government-assisted R&D activities on the energy-intensive and waste-intensive industry sectors to achieve the following objectives:

- Lowering raw material and depletable energy use per unit output,
- Improving labor and capital productivity, and
- Reducing the generation of waste and pollutants.

The Sensors and Controls Crosscut Program has as its mission the development and deployment of integrated measurement systems for operator-independent control of manufacturing processes in support of the IOF agenda.

Based on the 1994 Manufacturing Energy Consumption Survey, about 82 percent of all energy used in manufacturing was consumed by the pulp and paper, primary metals, chemicals, petroleum refining, and stone, clay and glass industries. These are the primary industry sectors targeted by the IOF Program to establish government/industry partnerships for developing and delivering advanced science and technology options to improve resource efficiency and competitiveness. Such partnerships now exist between the OIT and the following nine industries: Agriculture, Aluminum, Chemicals, Forest Products, Glass, Metalcasting, Mining, Petroleum, and Steel.

Our current project is designed to demonstrate the feasibility of wireless sensors in a real manufacturing environment and to provide a test bed for third-party suppliers to evaluate their products in a consistent way. As an enabling technology, we are initially developing a robust scheme for achieving reliable data telemetry in industrial environments. As the architecture and hardware matures, integration of various sensor technologies including legacy systems as well as emerging technologies such as MEMS based micro-sensors will be implemented.

The utility of wireless sensor technologies is expected to impact many aspects of plant operation. Most notably will be those applications that benefit from the ability to deploy a large number of sensors or networks of sensors. Concepts such as context dependent anticipatory maintenance and system health monitoring can now be addressed at the plant or enterprise level of integration by eliminating the tremendous infrastructure costs associated with wiring. Finally, the door will be opened to paradigm shifts in sensor deployment philosophy including process flow-through sensors (inside-out sensing vs. outside-in), peel-and-stick devices, and embedded-and-shipped systems that can be remotely called up on the internet.

III. CURRENT SYSTEMS

A number of organizations, besides the government, are pursuing wireless solutions for the industrial environment. For details in how modern wireless technology is changing the way we think about radio and sensors, see *It's Time for Sensors to Go Wireless, Part I: Technological Underpinnings* in Sensors magazine, April 1999. In this section, we'll take a brief look at some of these so that the reader can assess where they might fit and where additional information might be available. Bluetooth, though not an industrial network standard, is discussed because of its potential impact in the consumer marketplace.

A. Bluetooth

As stated in *Wireless Systems Design*, "Bluetooth stands to become the fastest-growing de-facto standard ever." The projection is that, before the year 2002, Bluetooth technology will be built into hundreds of millions of electronic devices. This can exert formidable pressure in the industrial marketplace. Just as ethernet was once thought to be inappropriate for industrial networks, Bluetooth may emerge as an industrial standard, as well as a home and office networking standard. This section describes the technology to help industrial users make more informed decisions.

The original Bluetooth consortium comprised Nokia, Toshiba, IBM, Intel and Ericsson. With major players like Motorola, Philips, and Hewlett-Packard joining the current 1100 participants, most people agree that the emerging Bluetooth standard will have a huge impact in the marketplace. An evaluation kit is currently available from Ericsson (www.ericsson.com/microe) for about $15,500 for those who want to get started developing products immediately. The first real products, based on an Ericsson 2.4 GHz radio module, are just now coming available. Crossbow is now beta testing Crossnet, a wireless sensor network based on Bluetooth. Total Bluetooth sales are projected to be over $2 Billion by 2005.

The Bluetooth specification (which builds on the IEEE 802.11 wireless LAN standard) represents a key milestone in providing open standards for wireless communication. The T2901 transceiver (samples available) implements the standard with 1.0 milliwatt output power in the 2.45-GHz Industrial, Scientific, and Medical (ISM) band. The 1600 frequency hops per second among 79 channels provides a gross data rate of 1.0 Mb/s. Full duplex operation is achieved through a time-division multiplexing scheme. Performance in an industrial environment is yet to be investigated. More details about the Bluetooth specification can be obtained from the web site – www.bluetooth.com. Some Bluetooth competitors exist who also exploit the existing IEEE 802.11 wireless ethernet standard. HOP and SWAP are the two closest competitors challenging the Bluetooth consortium.

B. Proprietary Industrial Solutions

Computational Systems, Incorporated (CSI), a small company in Knoxville, Tennessee, recently announced the availability of the first fully integrated, wireless sensor for use in the rugged environments common to manufacturing. Their device, about the size of a soda can, monitors critical parameters about electric motors and reports them to a central host that integrates information from a number of the sensors and provides reports. The CSI architecture, though fully proprietary, addresses many of the critical issues that characterize a viable industrial network. Devices can act as repeaters and can coexist with a large number of cooperating sensors. CSI, now a wholly owned subsidiary of Emerson Electric, can be reached through their web site: www.compsys.com.

Grayhill, a traditional supplier to the manufacturing marketplace, has partnered with an OEM radio supplier to provide a wireless network interface compatible with their product line. Their device, known as the EZCom Wireless LAN Transceiver, offers wireless Modbus connectivity in a ruggedized package suitable for the manufacturing environments. The 900 MHz transceiver incorporates many of the spread spectrum techniques that make the new generation of wireless interfaces robust enough for manufacturing. Their web site is at www.grayhill.com/products/ezcom.

Robertshaw offers a wireless sensor (figure 2) designed to report the level of material in storage tanks. Several options are available for the sensing technology but the radio links are all compatible and robust. Their communication protocol uses direct sequence spread spectrum, CDMA, with a spreading code suitable for industrial use. Their product line can be seen at www.centeron.net.

C. Consultants and Job Shops

A number of companies and individuals are available to assist companies with integrating wireless technology into their existing product lines. Some "niche" companies serve a specific market. A company called CellNet makes "dumb" devices that are used to enable parking, electric and gas meters to communicate with passing service vehicles (www.cellnet.com). They currently have over 2.5 million "end points" on-line.

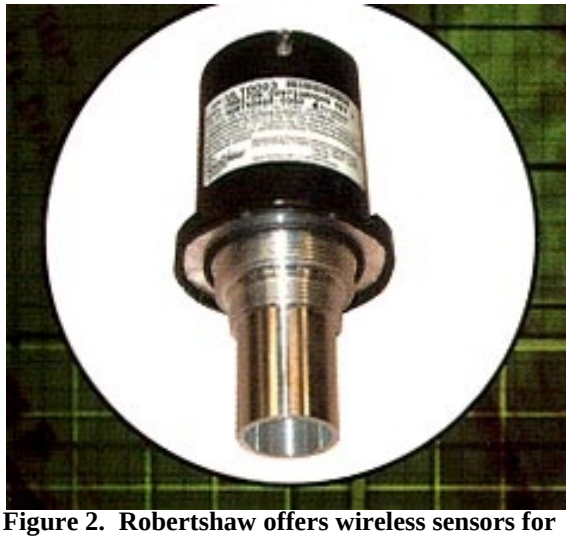


Figure 2. Robertshaw offers wireless sensors for harsh industrial environments.

Voyager Technologies, a spread spectrum RF technology development company, has been serving OEM clients since 1995. They can be reached at www.digitalrf.com.

HiTech Equipment Corporation offers wireless modems and other components to help companies develop wireless sensors for their markets. They can be reached at 858-566-1892 or through the Sensors magazine link on the World Wide Web.

The best way to keep up with what's happening is to periodically search the Web. A number of on-line newsletters are available as no-cost subscriptions including www.wirelessdesignonline.com. Tutorials are maintained at various websites including ours at http::/orcmt.oakridge.org/wireless and one maintained by a group in Colorado at www.oldcolo.com.

IV. CRITICAL ISSUES

A number of critical issues influence the potential for success in a particular implementation. Among these critical issues are adherence to existing and emerging standards, inherent reliability, current and potential costs, and the architectural extensibility. This section investigates these issues and how they might be addressed.

A. Standards

The Bluetooth standard is discussed elsewhere. It can be layered on top of the IEEE 802.11 standard that will be discussed here. The IEEE 1451 Smart Sensor standard is designed to allow communication over various hardware connections (including IEEE 802.11) for industrial applications of smart sensors.

IEEE 1451 Smart Sensor Standard

IEEE P1451.3 is a tethered multidrop sensor bus standard for transducers using IEEE P1451 TEDS (transducer electronic data sheet) methodology, thus enabling a large number of transducers that require power and synchronous sampling. Spread spectrum methods are used (in the higher capability systems) to simultaneously communicate with a large number of nodes and to provide a more robust channel. It enables large arrays of physically separated sensors to be coordinated both regarding the timing of the samples and the delivery of the sampled data to the user's host computer for analysis.

The tethered bus provides the means for several functions:

1. synchronizing data acquisition of a large array of transducers
2. simultaneous communication with a large array of TBIMs
3. power for operation of TBIM

This DOE project described in this paper is the first attempt to implement the protocols of P1451.3 wirelessly. Of course, this implies that no significant power will be distributed by the bus. Otherwise, however, the architecture of this project adheres to the P1451.3 standard.

In this scheme, time-synchronized data transmissions are accomplished by a combination of code division multiple access (CDMA) and frequency division multiple access (FDMA) carrier-modulation formats. Sensor nodes called transducer bus interface modules (TBIMs) and network nodes called transducer bus controllers (TBCs) each include RF transceiver functions that allow several hundred combinations of frequency selections and code modulations. The length of codes, number of distinct carrier frequencies, and other transmission parameters can be dynamically reconfigured through the TBC to accommodate changing sensor-network information requirements. The TBCs handle several simultaneous RF links.

The architecture is of course open, which offers a significant advantage over proprietary protocols. The plug-and-play compatibility offered allows several manufacturers to supply individual pieces or cooperate with partners to provide entire systems. This vastly improves the longevity of a system, since it can be upgraded seamlessly and the user is not dependent on a single manufacturer.

There are several significant contributors to the family of IEEE 1451 standards including sensor developers such as B&K and Eaton, manufacturers such as EDC, system developers/users such as Boeing, and government groups such as NIST and ORNL.

IEEE 802.11 Standard

The development of new technologies for physical media access via wireless techniques, to encourage broad acceptance and achieve conformity with regulatory requirements (e.g., by the Federal Communications Commission [FCC] in the U. S.), have usually resulted in formal industry standards. In the wireless data-networking arena, perhaps the most significant benchmark is the ANSI/IEEE Std. 802.11, which in 1999 was also formally adopted as an International Standard, ISO/IEC 8802-11. This evolving suite of related technology definitions has been based on the foundation of the reliable (deterministic) transport of packetized data, in similar fashion to the 802.3 Ethernet protocol, but in the much more difficult and unpredictable wireless medium. The chief obstacles to high wireless data-transmission rates are the lack of available allocated RF bandwidths and the inevitable link quality limitations due to noise, interference, and multipath. The latter problems have been addressed in the 802.11 Standard via the use of spread-spectrum techniques, including both frequency-hopping (FH) and direct-sequence (DS) methodologies. These are specified for the worldwide 2.45-GHz unlicensed ISM band, originally for a maximum of 1- and 2-Mb/s data rates. The FH mode uses 79 hopping channels (for North America) and employs 2- and 4-level Gaussian FSK modulation. The DS option in the Standard utilizes an 11-bit Barker spreading code, with either DBPSK (differential binary PSK) or DQPSK (differential quadrature PSK) signaling. Unfortunately, the 11-bit code length, optimized for highest data throughput, often fails to provide adequate protection from powerful interferers in the band such as microwave ovens. As a result, several technical improvements were added, including complementary-code keying (CCK) modulation, to produce an updated but compatible extension to the standard, 802.11B, to provide improved robustness and much higher data rates (5.5 and 11 Mb/s), while still maintaining full spectral and operational compatibility with the original 1- and 2-Mb/s formats. The improved capabilities in 802.11B should vastly expand the application of WLAN devices worldwide and concurrently drive down hardware prices and boost performance.

B. Reliability

The reliability of the network is, quite often, more important than any particular sensor. Attempts to reduce wiring by incorporating bus architectures have resulted in reduced wiring but increased risk since single point failures can now eliminate the signals from a large number of sensors. Attempts to compensate through redundancies have increased cost while marginally improving reliability. Since the most unreliable part of any wired connection is the connector, the key seems to be to eliminate the connectors.

The most desirable wireless network results in a “web” architecture where all devices can

communicate with all other nodes (like the world wide web). A robust routing algorithm is required so that, if one of the nodes becomes unavailable, a new connection can be established without severe penalty in either time or throughput. Implementing such algorithms continues to be on the research agenda of many private and government organizations.

If the wireless network is less reliable than a representative wired network, the systems will not be implemented in the real world. Research, development, and deployment strategies at many organizations (like ORNL) continue to strive for wireless systems that, not only match wired systems, but surpass them.

C. Cost

The same strategy applies to cost as was discussed under reliability. That is, any wireless system that doesn't compete, in cost, with representative wired systems, will succeed only in niche markets and will never have the impact promised. The first successes will undoubtedly come where wired solutions are most difficult or impossible, the overall goal must be to replace wires with ever-increasing market share. The article in Sensors magazine (3) describes the economic issues associated with deploying wireless solutions.

Early successes will lead to greater market share which will lead to increase production which will begin to drive wireless sensors toward the holy grail: Moore's Law. How the market will shake out as sensors become cheaper and more effective over time remains a critical unknown.

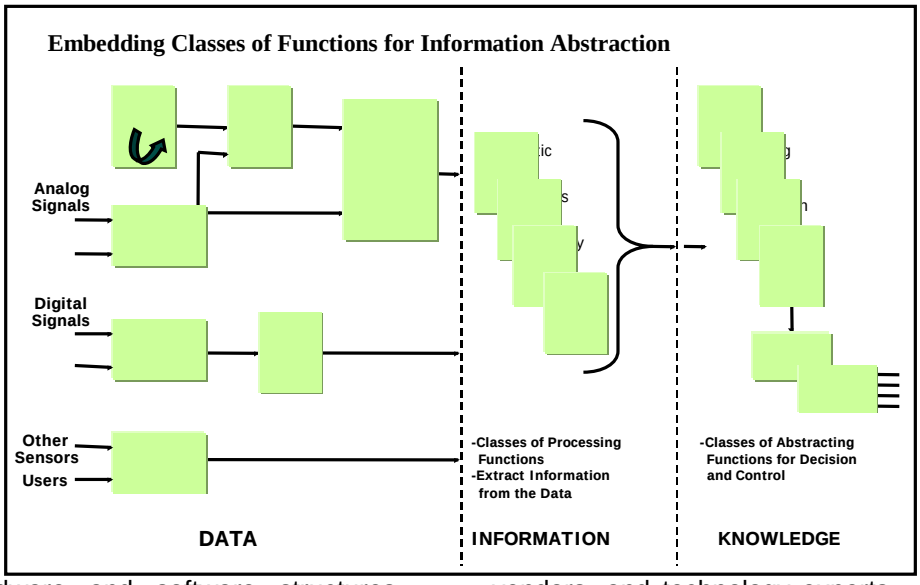
D. Extensibility

Wireless systems, like any other system installation, must provide a migration path that solves the current problem with a cost effective implementation but leaves options open to extend the solution to expected future problems, as well. Early wireless implementations worked adequately for single sensors or perhaps two or three. But the difficulty of multiple sensors in the same RF environment has represented a significant technical challenge that must be addressed for viable wireless networks. For sensors, extensibility also includes integration of classic dumb sensors all the way through the expected integration of intelligent agents that advise operators on the state of the process and the equipment.

One of the main objectives of this research for DOE is to provide the enabling technology required for deploying intelligent (smart) wireless systems into manufacturing environments, especially those identified by the DOE as Industries of the Future. Accomplishing this will require embedding novel innovations complimentary to human cognition and new hardware developments into the hardware and software structures that will allow the acquisition and processing of data at speeds that can now only be met by expensive systems.

The novel innovations adapted from human cognitive skills will provide the system with consistent, self-reasoning mechanisms for making decisions. These innovations include an ability to extract motive and intent from its surroundings, survive in a dynamically changing environment, respond and evolve in conflict, mimic, understand complex organizational behavior, and understand the concept of competition and 'best suited' for the job. The emergence of such abject behavior in the DOE OIT sensor would be difficult at this time since computational equivalent-cognitive algorithms do not necessarily exist in forms to support such reasoning. There are algorithms, though, that can act as precursors to enable certain elements or traits of human reasoning. These are identified in Figure 3 below. As shown, there are two distinct functional groups envisioned for the intelligent (smart) wireless sensor. One is for information and data abstraction and the other for implementing the reasoning and control task. These embedded functions will not be found in the current prototype but are expected to be developed in the next generation sensor/system suite.

Figure 3. The hierarchy of information abstraction must eventually be implemented in intelligent, wireless sensors.



The novel hardware and software structures mentioned in the first paragraph are needed to provide the foundation that will support the embedded functions. These novel structures include high speed data acquisition network acting as an autonomous nervous system for sensory input, a wireless information structure that allows groups of sensors to exhibit complex organizational behavior, and a supporting structure that allow the sensors themselves to form computing structures, i.e., computable computers.

V. DOE/OIT WIRELESS SENSORS PROJECT

The project was conceived to demonstrate the feasibility of a robust, wireless network of intelligent sensors and to provide a test bed where prototypes could be tested. This section describes this ongoing program, how we have attempted to address the issues detailed earlier, and where it is headed.

A. Goals

The success of this project is to be judged on how follow-on work is facilitated by the work begun under this activity. DOE continues to sponsor research focused on improving efficiency, reducing emissions and reducing waste streams from the industries they have identified as the "Industries of the Future". This project is meant to provide sufficient confidence in these industries that wireless technology offers potential solutions to many of the problems associated with deploying sensors in areas or in quantities previously thought unsuitable or too expensive for a network of sensors. To be successful, partnerships will need to be formed that integrate end-users, vendors, and technology experts. This article is part of our mission to facilitate such partnerships.

B. Deliverables

The original deliverables for this project included a requirements document that confirmed the conceptual, functional and design requirements for the project and attempted to assign priorities so that compromises necessary during the research could be intelligently made. The second deliverable in the first phase was an architecture specification that would allow third-party organizations to participate in the program. The final deliverables include actual prototypes capable of demonstrating the architecture and the ability to meet the key requirements. The final deliverable also includes a test bed capable of confirming the performance of the prototypes as well as any third-party devices where a level of compliance testing is desired.

C. Requirements

The key requirements identified for this project are those familiar to most people who have worked with measurement systems designed for industrial applications. Systems installed must be capable of operating with minimum operator intervention. For this wireless network, this translates to a system that is self starting, self configuring, and self healing. The second most important requirement was the support for existing (legacy) sensor systems. Our approach here is to embrace existing standards like smart sensors (IEEE 1451) and ethernet (IEEE 802). The architecture is designed to embrace other protocols as necessary. The third critical requirement was that the system operate, as required, in the harsh environment common to these industries. Key factors include temperature extremes, dusty atmospheres and vibrations.

Other requirements are included in the DOE document but are not listed here.

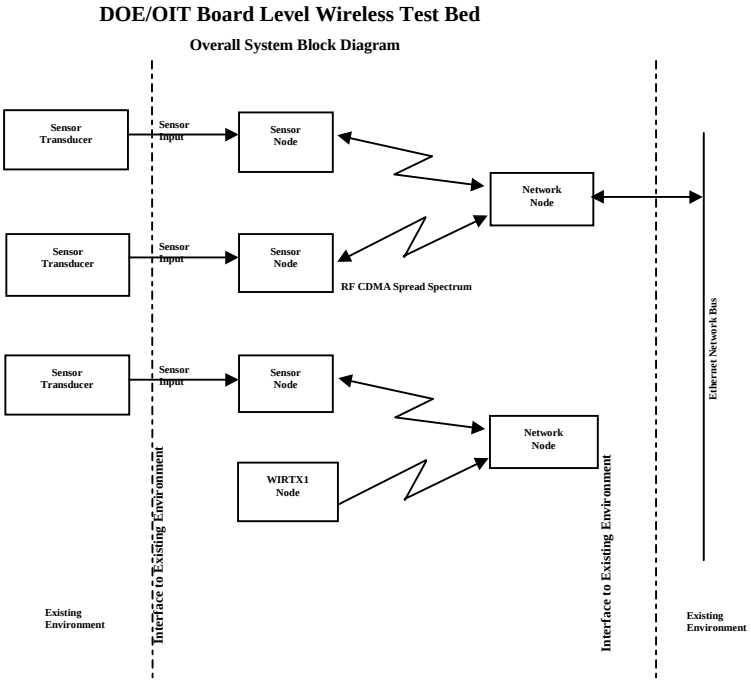
D. Architecture

The purpose of the architecture specification 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. Figure 4 below illustrates the basic connectivity supported in the project. 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.

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 to permit a field-able design. Those assumptions are based on representative conditions found in existing facilities.

Demonstrated 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 sensor nodes (SN) or network (NN) nodes are available to the user. In Super User mode, the device (sensor node or network node) can be interrogated and forced into a mode that stresses the network for diagnostic purposes.

Unidirectional sensor-node 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 sensor-node 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.



P1451 Standard Compliant

Figure 4. ORNL's project must support connectivity from existing transducers to legacy networks in the plants selected for demonstration.

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 over-the-air 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 NN 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.

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.

E. Design

The design criteria for this project require that we start with simple devices that meet the critical requirements described elsewhere but ultimately have a migration path (as shown in figure 5) to devices fully implemented in one (or a very few) Application Specific Integrated Circuits (ASICs). This approach has been successful on other projects while approaches that produce single-chip solutions early provide important research but are not as useful to the customer since critical testing was never done on the underlying architecture.

The telemetry portion of this project was designed to be modular and adaptable, so that developers of IEEE P1451.3 systems could use it as a reference design for future applications. Both the software and hardware have been designed in a fashion that allows rapid prototyping of tailored applications. In fact the design of this system is helping to drive the details of the IEEE P1451.3 protocol by allowing committee members to see the effects of protocol decisions as they are being made.

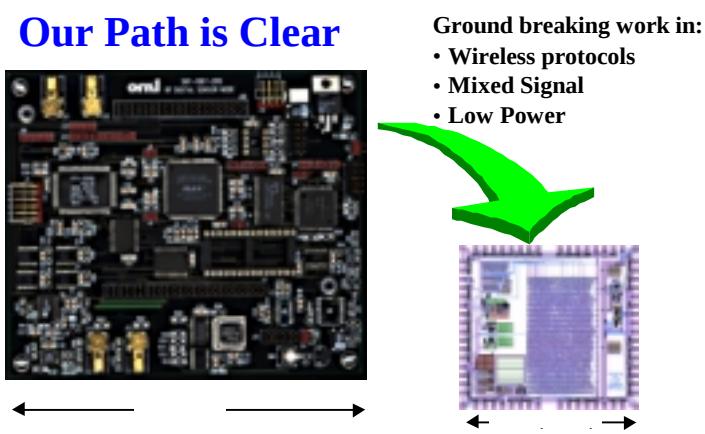


Figure 5. Migration from board to chip requires careful design at the board level so the transition to the chip meets the desired power, size, and functional goals.

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 ISM (industrial, scientific and medical) band. The first version is a QPSK (quadrature, phase-shift keying) 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*63*2 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 the Stanford-Telecom STEL-2000A IC in this design. The final downconversion 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, combines the quadrature data into a single stream and performs the differential decoding.

The message processing portion of the design includes a microprocessor that provides node processing as well as interfacing functions. Also, it 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 setup to accommodate 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 left off and a small section of the same printed circuit board is populated to accommodate the 4-20 mA transducer input.

F. Performance

The first implementation of the wireless communication module is expected to operate at a level of performance consistent with the basic needs of the IOF candidate industries. Net throughput of 50 Kbits/second over the untethered distance of 50 meters will meet the initial needs. As the design matures, the throughput is expected to improve to over 1 Mb/s over about the same distance. The power demands will decrease as the design moves from discrete components to more and more dedicated ASICS. The architecture requires that any link experiencing difficulties should be remapped to maintain connectivity suitable for the real-time needs of our target industries.

VI. CONCLUSIONS

The final deliverables for the DOE/OIT project will provide prototypes that verify the feasibility of moving toward wireless connectivity for the target industries. The overall goal is that industrial partners joining the project will carry on the commercialization of the products providing commercial devices, components, and systems suitable for industrial applications at reasonable cost. This will open new markets and opportunities that will, in turn, motivate improved technologies and, if properly designed, decreasing costs. The Moore's Law model for sensors can, at least, be envisioned, based on these assumptions. The ultimate outcome will depend, however, on many technical, social, and marketing forces.

Our deliverables for this project will first see the factory floor by the end of calendar year 2000. Once we've demonstrated the viability of the architecture and protocols we will begin to migrate toward more integrated (compact) solutions. We are currently soliciting partners who want to test and/or adapt the networks for use in their own facilities. We will (under suitable financial

arrangements) have the devices we've prototyped duplicated, installed and tested in a partner's site and provide written reports on the performance. The underlying architecture and protocols will remain open with special licensing available for any other intellectual property included in the implementation.

The next generation components, available in 2001, will provide improved performance, lower power demand and improved dynamic remapping performance. The ORNL testbed will continue to be available for use by third party suppliers or end users to verify operation of new devices or systems.
The longer-term solutions will include more embedded intelligence so that cooperating sensors can assume more of the responsibility for process optimization. The first new devices will use new techniques to provide feature abstraction, then information and finally knowledge level abstraction. The key will continue to be to implement these technologies in a way that is feasible for use in the industrial environments required.

The key to success is to continue to build partnerships that bring end users (industry), suppliers (instrumentation and systems houses), and technology brokers (labs and universities) together for viable solutions. The economics remains a critical success factor since no technology can provide a solution without a sound economic foundation (reference 3). We can be contacted at the e-mail addresses listed below if anyone is interested in pursuing such partnerships.

References

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Contacts

Wayne W. Manges – mangesww@ornl.gov
Steve Smith – smithsf@ornl.gov
Glenn Allgood – allgoodgo@ornl.gov
Tim McIntyre – mcintyretj@ornl.gov
Mike Moore – mooremr@ornl.gov
Curt Maxey – maxeylc@ornl.gov